Magnitude and Dynamics of Runoff and Sediment Transport in the Geba River Catchment, Northern Ethiopia

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1. Abstract

The Northern Ethiopian Highlands are a fragile environment, characterised by steep slopes, intense rainfall and a sparse vegetation cover. The extreme poverty, stagnating technology and high population and livestock densities induce intense soil erosion and degradation problems in these Highlands. This not only leads to lower crop yields but has also important off-site consequences: the life expectancy of many reservoirs (used for power generation or water supply in the dry season) is threatened by massive sedimentation. Although these problems demand for a thorough solution, little is known about the magnitude and dynamics of sediment transport in the Northern Ethiopian Highlands. Therefore, an intensive measuring campaign was conducted during the rainy season of 2006 in ten subcatchments of the Geba (drainage area: 5180 km²), a tributary of the Tekeze river. The catchments had drainage areas between 120 km² and 4330 km² (mean: 1068 km²) and represented a range of environments. Annual rainfall ranges from 700 mm to more then 1200 mm. The estimated area-specific sediment yields (SY) varied between 400 and 2500 ton/km²/yr (average: 1404 ton/km²/yr). These values were obtained with rating curves, based on manual runoff discharge and suspended sediment concentration measurements. The error on these yields was assessed by Monte Carlo simulations and varied between 6 and 48 %. In some cases, however, the uncertainty is larger, since our sampled population was not always fully representative for all events. A dominant part of the sediment is transported during short but intense flash floods at night. Sampling these events is very difficult and often even dangerous. A few flash floods were, however, monitored in detail. The results showed a clear positive hysteresis effect. To explain variation in SY between the catchments, a semi-quantitative model (FSM) was adapted. Topography, soil cover, lithology and the presence of gullies explained a large part of the observed variance (63%). Insufficient information on soil and water conservation practices (SWCP) was available. Nevertheless our results strongly indicate that SWCP might be a relevant factor in explaining SY. Although further refinement is needed, semi-quantitative models are a promising tool for predicting SY in a cheap and efficient way when no detailed data is available.

2. Introduction

The Northern Ethiopian Highlands are a fragile environment, characterised by steep slopes, intense rainfall and a sparse vegetation cover. Poverty and stagnating technology in this vulnerable environment induce severe soil erosion. This leads not only to lower crop yields and higher food insecurity, but also to important off-site effects: e.g. flooding and the deposition of sediment in Reservoirs. In Tigray (Northern Ethiopia), significant achievements were made, mainly from 1994 to 2002, on the development of agriculture through irrigation by using seasonally harvested runoff using earth dams. However, most of the implemented schemes are not serving the intended purpose well because of these sedimentation problems. Many reservoirs are filled with sediments much sooner then expected (Haregeweyn et al., 2006). Without these water reservoirs irrigation becomes impossible, which leads to lower crop yields. Moreover, the increasing population leads also to higher energy demands. More then 90% of the Energy demand is still fulfilled by the use of biomass. The high demand for firewood has lead to massive deforestation in the region, which also induced severe soil erosion. Nevertheless, Ethiopia has a large potential to generate electricity by hydropower. However, the large sediment yields are a threat for the life expectancy of many reservoirs used for hydropower electricity generation (Zenebe et al., 2008). On the Tekeze, for instance, the construction of a dam (height: 188 meter; Crest length: 420 meter) started in 2002. It is planned that the dam will start functioning in 2008. However, the life expectancy of this construction is not well known, since sediment data for the Tekeze catchment is very limited (Nyssen et al., 2007). Detailed sediment discharge data is needed for this type of projects.

Although some research on sediment export in the Ethiopian Highland has been conducted (e.g. Haregeweyn et al., 2006), there are still large gaps in our knowledge about sediment yield at the basin scale. This is clearly illustrated in Figure 1 (Nyssen et al., 2004). This Figure shows the relationship between the area-specific sediment yield and the drainage area for different catchments that drain the Ethiopian Highlands. Apart from the rather large scatter around the regression line, there are almost no observations for medium-sized catchments (i.e. 200km² - 5000 km²). This emphasizes the need for more sediment yield data, especially at this medium-sized scale. Reliable and sufficient data is needed, not only to make realistic estimations of the life expectancy of reservoirs (both for hydropower and irrigation purposes), but also to improve our knowledge about the impacts of erosion at larger scales so effective erosion control measures can be applied.

Therefore, the aims of this study were to: i) to assess sediment export for ten tributaries of the Geba, a representative river catchment of the Northern Ethiopian Highlands; ii) to gain insight in the temporal and iii) spatial variation of sediment export in the Northern Ethiopian Highlands.

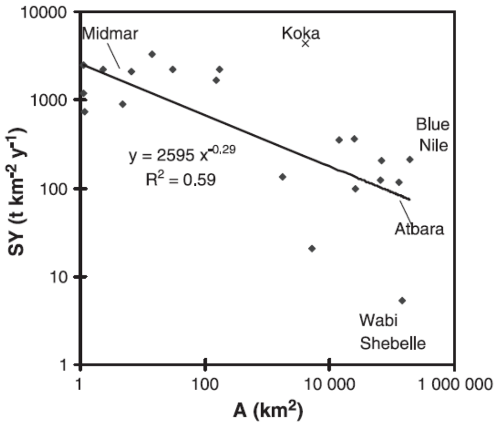

Figure 1 Area-specific sediment yield (SY) versus drainage area (A) for different catchments draining the Ethiopian Highlands. Koka data are probably overestimated and were not taken into account in the regression analysis (After: Nyssen et al., 2004)

3. Materials and Methods

An intensive measuring campaign was conducted during the rainy season of 2006 (12 july – 10 september). Around 80% of the annual rain falls in the rainy season. The ten measuring stations were installed beforehand and were all situated at the outlet of tributaries of the Geba Catchment. Figure 2 gives an overview of the tributaries and the monitoring stations.

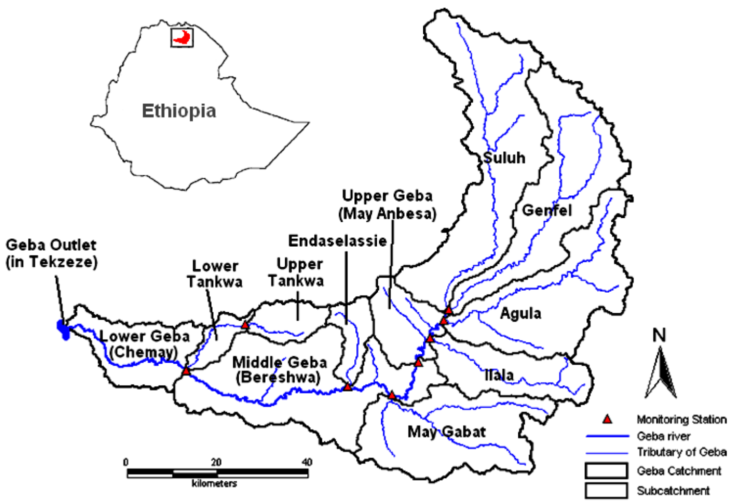

Figure 2 Overview of the Geba Catchment, its tributaries and the installed measuring stations

Each station consisted of a scaffold from which suspended sediment concentration (SSC, kg/m³) samples could be taken. Digital pressure transducers were installed in the stages. These automatically recorded the flow depth (d, m) on a continuous basis. Flow velocity (u, m/s) was measured, together with SSC, at least daily plus each time a large difference (±50 cm) in flow depth was noted. In all monitored catchments, flash floods occurred. These events were of major importance for the sediment export. However they occurred mostly at night, happened very fast, were often dangerous and were therefore difficult to sample for SSC. Six of the ten measuring stages were destroyed by flash floods during our campaign. As a result, continuous flow depth data was lacking for some periods. Nevertheless, a few flash floods could be monitored in detail. The cross-sections of the rivers at the measuring stations were measured before and after the measuring campaign. From these, the area of flow section (A, m²) could be derived for each flow depth. These measurements allowed calculating the runoff discharge (Q, m³/s) for each specific flow depth (since Q=A*u with A=f(d)). Hence, the continuous flow depth series could be converted to continuous runoff discharge series by means of rating curves. Also the continuous suspended sediment concentration was estimated by developing rating curves between Q and SSC.

4. Results and Discussion

It was observed that the SSC was highest at the start of the rainy season and lowered towards the end of the season for comparable runoff discharges. This could be related to the depletion of sediments and the development of a vegetation cover through the rainy season. Therefore, it was decided to split the rainy season in three arbitrary chosen subperiods and to use a different Q-SSC-rating curve for each period. This enhanced our predictions significantly. Also during flash floods, significant differences in SSC were noted. Two floods could be monitored in detail. During both floods, a positive hysteresis was found: for equal runoff discharges, the SSC was higher during the rising then the falling limb. This was probably related to sediment depletion, however more data will be needed to confirm this. On the other hand, runoff discharge increased during the rainy season. A hypothesis to explain this, are the vertic properties of the soils. Large areas of the studied catchments have soils with vertic properties (FAO, 1998**)**. At the start of the rainy season these soils are completely dry and cracked. After several rain showers, however, these cracks close and form a less permeable surface. Hence, a larger part of the rainfall runs off and reaches the river.

Table 1 gives an overview of the measured runoff and sediment yield in the measuring period. The uncertainties on these were assessed by a Monte Carlo simulation. However, as mentioned above, at several stations the digital pressure transducer was washed away by flash floods. In most cases, new transducers could be installed. Nevertheless, at many station continuous diver data is lacking for some periods. For these periods, total daily runoff and SY were estimated, based on available rainfall data. Validation of these predictions was not possible, however. The share of the total calculated runoff and sediment export that are based on these predictions are also indicated in table 1. Further, estimations of the area-specific sediment yield during the measuring period are given.

Table 1 Overview of the Total Runoff and Sediment Export during the measuring period (12/07/2006-10/09/2006) and their uncertainties. 'Error' refers to the relative error on the calculations and was assed by Monte Carlo simulations. '% predicted' refers to the share of the total runoff/SY that was predicted, based on rainfall data. These predictions could not be validated. Values for Middle Geba are probably overpredicted.

Catchment Name (Abbreviation)	Catchment Area, km²	Total Runoff, m³	Error and % predicted of Total Runoff)	Suspended Sediment Export, ton	Error and % predicted of Total SY	SY, ton/km²
Suluh (S)	942.6	1.06E+07	6,3% / 0%	6.65E+05	13,5% / 0%	705
Genfel (G)	660.2	3.30E+07	5,4% / 0%	1.64E+05	31,0% / 0%	248
Agula (A)	667.2	5.12E+07	7,2% / 27,7%	9.01E+05	? / 29,2%	1350
Ilala (I)	270.9	3.85E+07	6,5% / 0%	2.42E+05	9,3% / 0%	893
Upper Geba (OB)	2763.3	1.50E+08	7% / 2,9%	1.73E+06	47.7% / 1,4%	626
May Gabat (M)	584.7	5.74E+07	8,6% / 0%	4.24E+05	? / 0%	725
Endaselassie (E)	121	6.73E+06	26,3% / 24,0%	5.79E+04	13,3% / 20,4%	479
Upper Tankwa (UT)	127.5	1.35E+07	5,9% / 41,8%	1.72E+05	6,2% / 36,2%	1349
Lower Tankwa (LT)	213.5	2.18E+07	13,3% / 25,3%	1.93E+05	12,1% / 28.2%	904
Middle Geba (MG)	4330.9	*4.20E+08*	9,7% / 70,2%	1.10E+07	13,1% / 79,4%	*2540*

Table 1 indicates clear differences in SSY between the different tributaries. To explain these differences, a semi-quantitative model, FSM (Factorial Scoring Model; Verstraeten et al., 2003; de Vente et al., 2004), was adapted. This model was originally developed for Spanish conditions (Verstraeten et al., 2003; de Vente et al., 2004; de Vente et al., 2005) but proved also its success in Italy (de Vente et al., 2006) and small catchments in the Ethiopian Highlands (Haregeweyn et al., 2006). In these studies, FSM proved its potential to assess SY in a quick and fairly reliable way. The model works by attributing scores (1, 2 or 3) to factors that are expected to be relevant in the studied area. The factors that were considered in this study were: topography, lithology, soil cover and the presence of gulies. A score of 1 was attributed if this factor was expected to contribute little to the sediment export, while a score of 3 was given if this factor was expected to contribute a lot. Scores were assigned by mutual agreement between three persons, based on available maps and expert knowledge of the area. A Total index was calculated by multiplying the scores of all considered factors and confronted with the actual sediment export. The result of this regression is given in Figure 3. Middle Geba was excluded from this analysis, since the sediment export of this catchment was unreliable. Although the number of observations in this regression is low, the high R² indicates that the evaluated factors are indeed significant: around 63% of the variance could be explained by these four factors. Moreover, it was found that most catchments plotting below the regression line are catchments where many soil and water conservation measures were applied. Haregeweyn et al. (2006) also noted the importance of soil and water conservation practices on sediment yield and proposed to include a factor that considers these measures. Unfortunately, insufficient data was available to include this factor in our analyses.

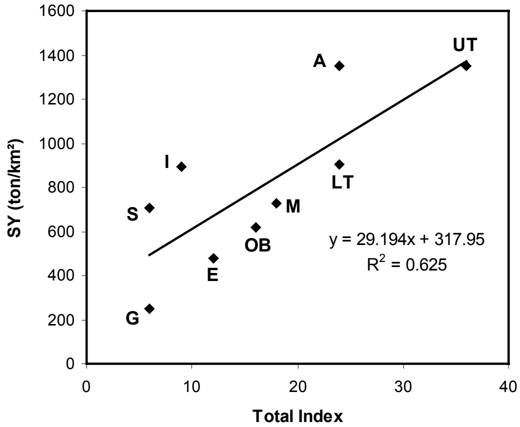

Figure 3 Calibration of the Applied FSM Total scores with the available SY data. Middle Geba was excluded from this analysis, since SY was most likely over predicted. For symbols: see Table 1.

Despite the low number of observations, the limited data-availability and the fact that no real model validation could be made, the results of this analysis seem promising. Semi-quantitative models can be a useful tool to predict sediment export in a quick and inexpensive way, especially in ungauged basins where no detailed spatial data is available. Nevertheless further refinement will be needed.

5. Acknowledgments

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