Evaluation of rain water management practices for sediment load reduction in the (semi) humid Blue Nile basin
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Abstract: With the construction of the new Renaissance Dam at the Ethiopian Sudan border, reducing sediment load in the Blue Nile is becoming increasingly important. Past attempts of decreasing sediment concentrations have been only partially successful. In this paper, we will examine the temporal distribution of sediment generation within small watersheds and systematically compare this with the observed sediment concentration at various watershed scales using the Parameter Efficient Distributed (PED) model. The model is based on the concept that runoff and erosion are generated mainly from areas that become saturated during the rain storm. These runoff source areas consist of shallow soils over a dense hardpan or areas where the water table is close to surface. Saturated areas are also prone to gullying. Simulation of watershed evaluations indicate that most erosion occurs from degraded areas, from temporarily saturated agricultural land and from gullies in the saturated bottomlands near the river. In addition, we found that the annual runoff and sediment concentrations increased significantly in the Blue Nile basin at the border with Sudan. The model results would indicate that rehabilitating the degraded and bare areas by planting permanent vegetation and preventing further incision by gullies would be extremely effective in decreasing the sediment concentrations. Reduced tillage would likely result in less sediment transport but would increase use of pesticides and the cattle cannot graze freely anymore. Tentatively, we conclude that decreasing upland erosion might decrease sediment concentration downstream, since there is relatively little sediment storage in the main rivers of the Blue Nile basin.

Introduction

The Nile is the longest river in the world. Without the Nile, major portions of Sudan and Egypt would run out of water. Eighty five per cent of the roughly 85 km³ (on the average of 25 mm over the whole Nile basin) entering Lake Nasser originates from the Ethiopian highlands.
The highlands are becoming more populated and in an attempt to increase prosperity (and thereby assure food security), the Ethiopian Government is both encouraging management practices for increased rain water productivity and increasing irrigated agriculture. Consequently, there is a growing anxiety downstream in Sudan and Egypt about climate, landscape and human induced changes in discharge and sediment load especially with respect to the newly built Grand Ethiopian Renaissance Dam and other planned dams on the Blue Nile.

Several researchers have utilized past rainfall and discharge records as an effective method to study the effect of climate on hydrology (Yilma and Demarce 1995; Conway 2000; Tekleab et al. 2010). Conway, (2000) and Tesemma et al. (2010) indicated that there was no significant trend in the basin wide annual, dry season, short and long rainy season rainfall in the past 40 years. However using statistical tests by Tesemma et al. (2010) and Gebremicael et al. (2013) researchers, found that the discharge during the rainy phase of the monsoon for the Blue Nile at the Sudanese border have increased during the last 50 years. In addition Gebremicael et al. (2013) reported a significant increase in sediment concentration in the past 30 years.

Since it appears that sediment concentration are increasing in time, the objective of this paper is to examine the cause of this increasing trend in the Blue Nile basin and propose effective management practices to reverse this trend. In order to understand erosion at different scales, three watersheds with vastly different areas were investigated: Anjeni (113 ha), Gumara (1500 km²) and the Ethiopian Blue Nile (18,000 km²).

**Study areas**

The **Anjeni** watershed covers 113.4 ha with a mean annual rainfall of 1690 mm with a low variability of 10%. Agriculture is the dominant land use activity. Starting in 1986 and continuing in 1987, graded Fanya-Juu (throw uphill) bunds were installed to terrace the hillslopes. Rainfall, discharge and sediment concentration were made available by ARARI for the period of 1 June 1984 to 31 December 1993.

The **Gumara watershed** is located east of Lake Tana. Its drainage area is about 1500 km². Discharge and precipitation data are available for the period of 1981 through 2005. Rainfall was on the average 1400 mm/year and varied between 1100 mm/year in 1983, 1984, 2002 and 2004 and 1700 mm/year in 1994 and 1997. Twenty seven sediment samples were taken for the period of 1982 to 2005 to determine the relationship between sediment load and discharge.

The **18,000 km² Blue Nile River** emanates from Lake Tana and flows nearly 850 km to the Sudan-Ethiopian border, with a fall of 1300 m. From approximately 30 km downstream of Lake Tana and into Sudan, the river flows through deep rock-cut gorge. Annual average precipitation varies from nearly 1400 mm north of Lake Tana to over 1800 mm on the higher elevations.

**Rainfall-runoff-and erosion simulation**

Parameter changes in time in mathematical constructs (i.e. models) relating rainfall, runoff and sediment concentrations can show whether the landscape is changing affecting these parameters. This is different from statistical tests in which rainfall and discharge are considered independent of each other.

The runoff and erosion model used here is the Parameter Efficient Distributed (PED) model that was validated by Steenhuis et al. (2009), Tesemma et al. (2010) and Tilahun et al. (2013a, b) for the Blue Nile Basin. In the PED model, various portions of the watershed become hydrologically active when threshold moisture content is exceeded. The three regions distinguished in the model are the **bottom lands** that potentially can get saturated, **degraded hillslopes** and **permeable hillslopes**. Each of the regions is the lumped average of all such areas in the watershed. In the model, the permeable hillslopes contribute rapid subsurface flow (called interflow) and base flow. For each of the three regions,
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A Thornthwaite Mather-type water balance is calculated. Surface runoff and erosion are generated when the soil is saturated and assumed to be at the watershed outlet within the time step. The percolation is calculated as any excess rainfall above field capacity on the permeable hillslopes. Zero and first order reservoirs determine the timing when the percolate reaches the outlet. Based on the work of Hairsine and Rose (1992) and Ciesiolka et al. (1995), sediment concentrations are obtained as a function of the surface runoff per unit area and a coefficient that decreases linearly from the transport limit at the start of the rainy monsoon phase to the source limit after about 500 mm rainfall. Subsurface flow is sediment free except for the Gumara. Equations are given in Tilahun et al. (2013a, b).

Results

In order to fit the PED model, we varied only the fractional areas of the degraded and permeable hillsides. The remaining landscape and erosion parameters were kept constant (Table 1). The input parameters (Table 1) were fitted to a portion of the rainfall, discharge and sediment concentration record.

Anjeni: In the 113 ha Anjeni watershed, Fanya-Juu bunds were installed during starting at the end of 1985. We divided up the record in four periods: I) prior to Fanya-Juu bunds installation in 1984–1985; II) during installation in 1986–1987; III) immediately after Fanya-Juu installation was completed in 1988 and 1989 and terraces were likely being formed and IV) post installation from 1990 through the end of 1993. Cumulative discharge and sediment load for each of the periods is depicted as the red line in Figures 1a and 1b, respectively, clearly showing that sediment losses were small only from July 1986 through the end 1989 shortly after the graded Fanya-Juu were constructed.

The first step in the application of the PED model was fitting the landscape parameters that were kept constant (Table 1). We took arbitrarily the period of 1984 through 1985 for calibration and found as expected almost the same values as Tilahun et al. (2013 a, b) for the same watershed.

The fractions of the degraded and permeable hillsides were fitted with the PED model for three of the four periods omitting period II when the bunds were being constructed in 1986 and 1987. Depending for what period the hillslope parameters were calibrated, various line colours were used for the predicted discharge (Figure 1a) and sediment cumulative load (Figure 1b).

Period I (1984–1985) prior to Fanya-Juu installation: Using the hillslope parameters in Table 2 where 15% of the area is degraded and, 50% of the area contributed to the interflow and baseflow (second column Table 2), the observed cumulative discharge (Figure 1a) and the sediment load (Figure 1b) in 1984 and 1985 were simulated well with a Nash Sutcliffe value of 0.86 for daily discharges for 1984–1986 period. Consequently, the total area that contributed water to the gage is 67% (consisting of 65% hillside, Table 2 and 2% saturated area, Table 1). The rain falling on remaining 33% of the area is leaving the watershed either by evaporation or deep percolation. Applying the two hillslope fraction of 15 and 50% to the remaining periods, the PED model over-predicted the soil loss greatly especially for the period 1988–1989 after the graded Fanya-Juu were installed and terraces were being formed (purple line in Figure 1b). The daily discharge was marginally over-predicted (purple line Figure 1a) but consistently with decreased Nash Sutcliffe values of 0.68 and 0.79. In other words, sediment load was reduced by the installation of the Fanya-Juu and only for a few years after installation.

Period III (1988 and 1989) immediate after installation of Fanya-Juu: Construction of the bunds (Figure 2a) began in 1986 and it took some time before they were all installed as indicated by the high sediment concentrations early in 1986. In 1988 these bunds were effective. Accordingly, in order to fit the cumulative discharge and soil loss data for 1988–1989, we assumed that the Fanya-Juu became quite effective as all water was infiltrating and sediments was deposited behind the Fanya-Juu bunds. Decreasing the fraction of degraded area to zero (Table 2) and increasing the permeable hillsides to 56% (Table 2) in the discharge in a good fit (Figures 1a) with Nash Sutcliffe value of 0.91 for the period 1988–1989 This parameter set fitted the observed cumulative load (black line in Figure 1b) amazingly well without changing any of the sediment transport properties in Table 1. This hillslope parameter set for any other period reduced the Nash Sutcliffe
values for daily discharge to 0.79. By comparing black line (indicating what the loss would have been in the case that the Fanya-Juu practices would have remained effective) and red lines in Figure 1 we find that the Fanya-Juu and the terraces that formed behind them reduced the discharge marginally and sediment load in the watershed significantly.

**Period IV (1990 to 1993) post installation of Fanya-Juu** We are not sure why in 1990 the discharge increased slightly compared to the period before and sediment concentrations became much higher (compare the black and green line in Figure 1. The increase in runoff could be simulated by assuming that a greater portion (10%, Table 2) of the watershed started to contribute to surface runoff. This increase in degraded area could also simulate the increase erosion (Figure 1b, green line). There are two likely scenarios why this might have been the case. The sediment that was not in the runoff 200 ton/ha (obtained by adding the difference is soil loss between the observed soil loss (red line) and what the soil loss would have been if no intervention would have taken place (the purple line) for periods II and III in Figure 1b) or 13 cm of soil over the whole watershed in 4 years (1986–1989) filled up some of the storage behind the bunds. Figure 2b shows the terraces as they are today in the watershed. A second scenario is that the extra water that infiltrated and increased the water table and saturated the soil in the bottom part of the watershed (as shown by Tebebu et al. 2010 and 2013) can result in gully formation and results in soil loss. This is corroborated by the local informants who indicated that the gully started around this time. Now in 2013, this gully has greatly expanded (Figure 2c, note the size of the people)!

**Gumara:** For the 1500 km² Gumara watershed, similar to the Anjeni watershed, we divided the rainfall and discharge data into several consecutive periods, kept the landscape parameters constant (Table 1), increased the portion of degraded land area and decreased the permeable hillsides by comparable amounts (Table 3). The periods considered are 1981–1985, 1987–1992, 1994–1999 and 2000–2005.

The watershed parameters in Table 1 for the Gumara were in general the same as for the Anjeni watershed with the exception of a much shorter half-life of the first order linear reservoir than for Anjeni and in the same order as other watersheds in the region. In addition, the sediment transport capacity of the degraded areas was much higher and might have been caused by the sandy nature of some of the sediments in the river which were suspended during high flow. The degraded area was increased from 5% in 1980’s to 15% in the 2000s (Table 3). The daily discharge values had Nash Sutcliffe values varied between 0.52–0.73 and are equivalent with those obtained with SWAT (Setegn et al. 2009). Monthly values Nash Sutcliffe were above 0.80. The predicted and observed sediment losses for the two periods are reasonably close (1981 to 1992, Figure 3a, red line) and (1993–2005, Figure 3b, red line) with good R² values and a slope close to 1. As for Anjeni, we did not change the sediment transport properties to obtain these results. By using the hillslope parameters of last period (2000 to 2005) for predicting the discharge in the two first periods, the Nash Sutcliffe values are either larger or remain the same (last row, Table 5) and the sediment concentration are greatly over predicted (blue line in Figure 3a) and similarly by using the calibration for the early period with 5% degraded area, the sediment concentration are severely under predicted (blue line Figure 3b)

**Blue Nile at the Sudan Border.** We have reported the predicted recharge and sediment concentration for the Blue Nile at the Ethiopia Sudanese border before (Tesemma et al. 2010; Steenhuis et al. 2013; Tilahun et al. 2013a b) and only a short summary is presented. Similar to the Gumara watershed, we found that the best fit between predicted and observed discharge amounts was obtained by increasing the fraction of degraded area in the watershed from 10% in 1964 to 18% in 1993 to 22% 10 years ago in 2003 (Steenhuis et al. 2013). In addition, similar to the results above, the PED model predictions provided a good fit for the 10 day averaged sediment concentrations (solid green line in figure 4a for 1993 and solid black line for 2003 in Figure 4b) with Nash Sutcliff values greater than 0.94 (Steenhuis et al. 2013). Sediment concentrations are increasing because by interchanging the calibrated degraded areas (i.e. using the 22% degraded area for 1993), the observed sediment concentration are over-predicted in 1993 (black line, Figure 4a) and under predicted in 2003 (green line, Figure 4b).
Discusses and concludes

It is obvious from the results that the discharge and soil loss are increasing with time throughout the Nile basin (Figures 1, 3 and 4). This is consistent with the findings of Gebremicael et al. (2013) who had access to the 1972 and 2003 daily sediment concentration data at the Egyptian Sudan border in which the concentrations in the beginning of the rainy season are 2 to 3 times greater in 2003 than in 1972.

Given that the degrading areas are responsible for large amount of the soil loss, we will define new management practices that can be employed to reduce soil loss. According to the analysis of Gebremicael et al. (2013), 1% of the Blue Nile basin is bare and these are obvious the very hotspots that should be treated first. These hotspots likely include gullies and hillsides where all top soil is removed. Tebebu et al. (2013a, this proceeding) lists measures that can be tried to halt gully expansion. The bare land area where the top soil is removed is a likely candidate for planting trees that can in time improve the soil. However, these bare areas cover only 1% of the land while the amount of degraded land in the PED model varied between 5–20%. So where do the other degraded areas occur in the landscape producing runoff and soil loss?

It is likely that the agricultural land that have a hardpan at very shallow depth surface and farmers have installed the local graded furrows to carry off the excess water are likely an additional source of erosion. Since there is more rain than evaporation during the rainy season, the only way to prevent saturation of the top soil is to open the old flow paths through the soil as proposed by Tebebu et al. (2013b, this proceeding) or potentially by adding charcoal and growing deep rooted crops as proposed by Bayabil et al. (2013, this proceeding). It is obvious that terraces are not effective in humid climates when they are not drained.

Reduced tillage or 'no-till' might reduce soil loss since the transport of the soil will remain at the lower source limit. However, this practice is unlikely to be popular given the importance of crop residues for fodder and fuel, in addition to the inherent increase in pests associated with no-till and the implications for pest management.

This indicates why sediment concentrations have been increasing over time despite the investment of millions and perhaps billions of Ethiopian birr in soil and water conservation practices. The structural Fanya-Juu practice tested here in the Anjeni watershed was effective for less than four years; thereafter it contributed only slightly less sediment than before (Figure 3). Fanya-Juu terraces may in fact be more successful than other structural practices installed in Ethiopia, because as Haile et al. (2006) reported, 40% of all erosion is caused by practices installed incorrectly.

By understanding the cause of the increase in sediment concentrations, we can devise measures to reduce the load (Merrey and Gebreselassie 2011). The above analysis finds that the increase in degraded lands is related to the increase sediment loads. On the other hand, Gebremicael et al. (2013) and many others correlate land use change seen in satellite imagery to an increase in sediment load. These findings may be mutually reinforcing, because as shown by Bayabil et al. (2010) land use is directly related to the watershed hydrology. For example lands that become degraded and cannot support crop growth become grass land (Hanson et al. 2004). Findings of Balthazar et al. (2013) in the Ethiopian highlands support our hypothesis that degraded land are an important driver of soil loss: ‘Statistical analyses have shown that 41% of the observed variation in SSY (area-specific sediment yield) can be explained by surface vegetation cover (expressed as a percentage of poorly vegetated areas)….’ Gebremicael et al. (2013) also noted that the degraded areas increased during their 40 year period of observation. Finally, our findings are in agreement with Garzanti et al. (2006) that write based on their findings and that of Nyssen et al. (2004):

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Finally, in many river basins reducing the upland sediment load has no effect on the siltation of reservoirs, because the eroded sediment from the upland areas that remains in the river channels, is still prone to transport during storm flow. The Blue Nile in Ethiopia is exceptional in terms of the large volume of sediment transported. This is due
largely to high gradients which carry all its sediment downstream, as soon as sufficient rainfall in the rainy monsoon phase transforms the almost dry river channels to flood conditions. As our results show, this results in sediment concentration peaks before the peak of the discharge in all of the three basins, of greatly different scales, that we modelled. If sediment was not limiting in the river channel, sediment concentration and peak concentration would have coincided for the Gumara and the Blue Nile at the Sudan border.

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