Simulating discharge and sediment concentrations in the increasingly degrading Blue Nile basin

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Abstract **– Future discharge predictions seldom take into account the degrading landscape. The objective of this paper is to investigate based on past records of precipitation, discharge and sediment concentrations, the effect of a changing landscape on the hydrology and sediment transport in the Ethiopian Blue Nile Basin. We used the Parameter Efficient Distributed (PED) model to examine how the relationship between precipitation, discharge and sediment concentration changed in time. All input data to the PED model were kept constant except for a conversion of permeable hillside to degraded soil in time. Our results show that with a gradual increase of the degraded areas from 10 % in the 1960's to 22% in 2000's, the observed discharge pattern and sediment concentration could be simulated well. Simulated annual runoff increases by 10% over the 40 year periods as a result of the increase in degraded soils. Sediment loads appeared to be increased many times more, but this needs to be further validated due to limited data available. In general, the model results would indicate that rehabilitating the degraded and bare areas by planting permanent vegetation would be extremely effective in decreasing the sediment concentration in the rivers. Research should be undertaken to investigate the effectiveness of these plantings.**
Key words- **Saturation excess runoff, variable source hydrology, Ethiopian highlands**

I. INTRODUCTION

The Nile is the longest in the world and at the same time one the most water-limited basins. Without the Nile major portions of Sudan and Egypt would run out of water. Eighty five percent of water entering Lake Nasser is originating from the Ethiopian highlands [10]. Consequently, there is a growing anxiety about changes in discharge and sediment load due to planned dams, climate and landscape induced changes.

Several studies have employed past rainfall and discharge as an effective method [13,5,1], to study the effect of climate on hydrology. In one study by Tesemma et al. [11] past trends of precipitation and discharge in the in the Blue Nile basin were investigated. The results show that there was no significant trend at 5% significant level in the basin wide annual, dry season, short and long rainy season rainfall in the past 40 years. These results are in agreement with Conway [1].

Tesemma et al. [11] reported that despite the rainfall did not have a trend, the discharge for Bahir Dar and Kessie, representing the upper one third of Blue Nile Basin in Ethiopia and El Diem at the border between Sudan and Ethiopia changed significantly over the forty year period. Specifically, the annual discharge increased by about 25 % over the 40 year period for the upper Blue Nile while it remained the same for the whole Blue Nile basin at El Diem. The increase of discharge in the upper Blue Nile basin is surprising since annual rainfall remained the same and potential evaporation from year to year usually does not vary greatly. We would therefore have expected as was the case El Diem the annual discharge which is the difference between precipitation and evaporation should stay the same for a given annual rainfall amount. The reasons for the difference in discharge will be discussed later. In addition to the annual trends, all three stations show significant increasing discharge in the long wet season (June through September). As a percentage of the 40-year seasonal mean, these increments were 26% at Bahir Dar, 27% at Kessie and 10% at El Diem. In addition, the results show a significant increase for the short rainy season discharge (March to May) at Bahir Dar by 33% and Kessie, by 51% which was likely caused by the start of operation of the Chara Chara weir in 1996 at the outlet of Lake Tana that increased the flow during the dry season. No significant change was observed at El Diem over the short rainy season. During the dry season (October to February), both Bahir Dar and Kessie discharge did not change significantly but there was a significant decreasing trend at El Diem by 10%.

The long term erosion studies for which sediment concentration data are available for an extended period are only available for small Soil Research Conservation Practices watersheds in the upper reaches of the large basins. Nyssen et al. [7] found that historically erosion and sedimentation were directly related to rainfall amounts. When the climate was wet, gullies formed and the rivers incised. When rainfall amounts decline, the gullies filled up. Professors Ahmed and Bashir findings indicate that these historic trends apply to recent times as well, since the Rosieres dam at the border with Sudan filled up more during low flow years that during wet years as concentrations at the end of the rainy season were greater for the dry years than for the wet years [9].

Most studies on the future changes in hydrology employ future rainfall rates predicted with GCM models. The changing landscape is not included in these hydrological considerations. To assess whether landscape changes can be justified, we will investigate how in the past the landscape has affected the discharge and erosion rates. We will do this by using a mathematical model and apply it to a 40 year period from 1964 to 2003 Changes in best fit parameters with time are assumed to be indicative of changes in the landscape

II. RAINFALL-RUNOFF-EROSION SIMULATION

Rainfall-runoff-erosion models can establish if the relationship between rainfall discharge and sediment concentration has changed in time [6] and what are the undelaying landscape parameters for this change. This is different from statistical tests that examine trends in rainfall and discharge which are 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. [8], Tesemma et al. [11] and Tilahun et al. [12] 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 saturate, 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, 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 outlet within the time step. The percolation is calculated as any excess rainfall above field capacity on the permeable hillside soil. Zero and first order reservoirs determine the amount of water reaching the outlet. Equations are given in Steenhuis et al. [8] and in Figure 1 [12].

Sediment concentrations are obtained as a function of the surface runoff per unit area and a coefficient that decreases linear from the transport limit at the start of the rainy monsoon phase to the source limit after about 500 mm rainfall. Tilahun et al. [12] based on the work of Hairsine and Rose [4] and Ciesiolka et al.[2] expressed the sediment concentration, C_r (g L^{-1}) in runoff from runoff source areas as:

$$C_r = [a_s + H(a_t - a_s)]{q_r}^n \qquad (1)$$

a_t is variable derived from stream power and relates to the sediment concentration in the water when there is equilibrium between the deposition and entrainment of sediment, a_s related to the sediment concentration in the stream when entrainment of soil from the source area is limiting H, defined as the fraction of the runoff producing area with active rill formation. Assuming that the interflow and baseflow are sediment free, the sediment load per unit watershed area, Y (g m^{-2}day^{-1}), from both the saturated and degraded runoff source areas can be obtained as the relative area and the flux per unit area, e.g.

$$Y = A_1 q_{r_1}\left[a_{s_1} + H\left(a_{t_1} - a_{s_1}\right)\right]{q_{r_1}}^n + \\ + A_2 q_{r_2}\left[a_{s_2} + H\left(a_{t_2} - a_{s_2}\right)\right]{q_{r_2}}^n \qquad (2)$$

Where q_{r_1} and q_{r_2} are the runoff rates expressed in depth units for-contributing area A_1 (fractional

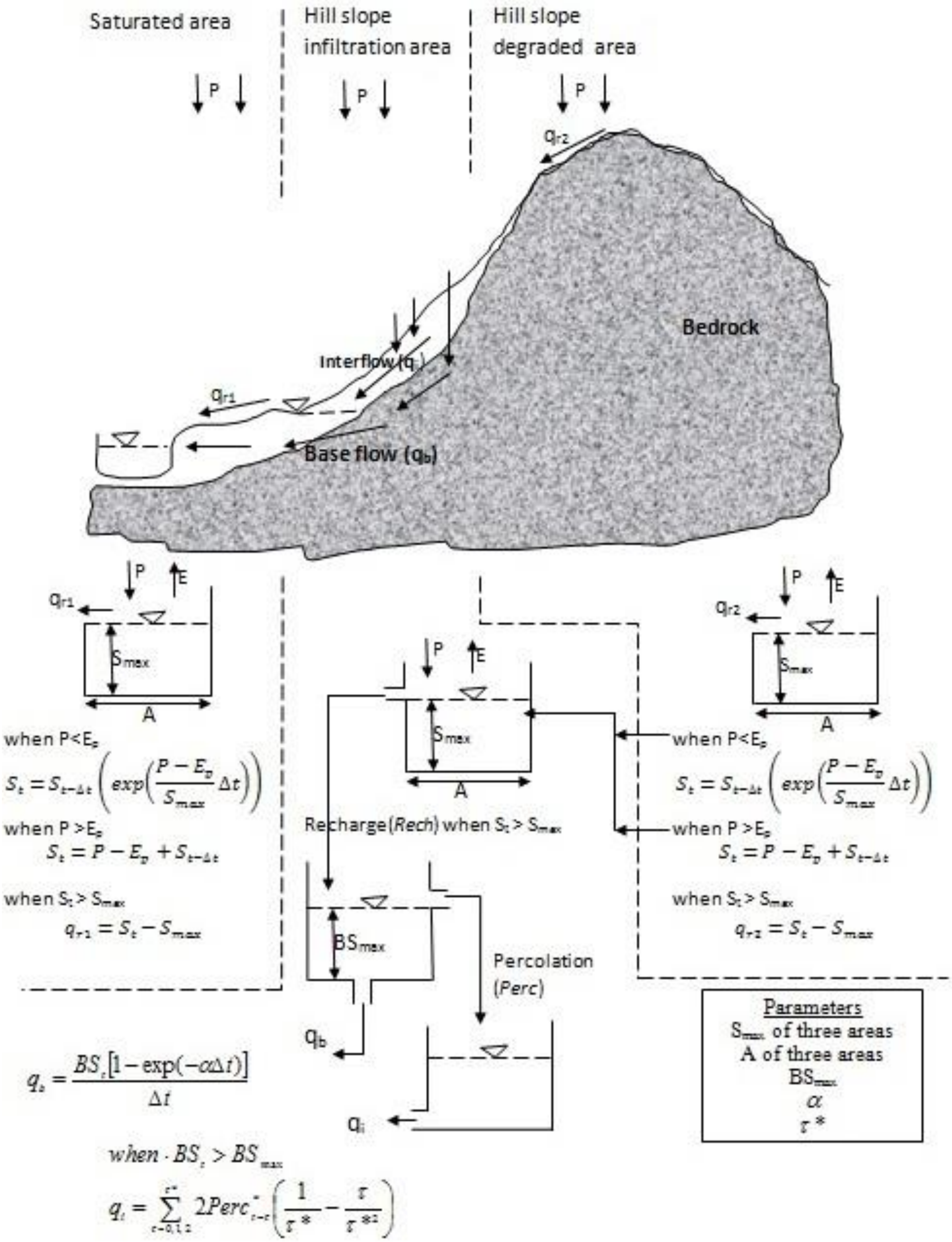


Figure 1: Schematic of the hydrology model (P is precipitation; Ep is potential evaporation; A is area fraction for zones of 1-saturated area, 2-degarded area and 3-infiltration areas; S_{max} is maximum water storage capacity of the three areas; BS_{max} is maximum base flow storage of linear reservoir; $t_{½}$ (=0.69/α) is the time it takes in days to reduce the volume of the base flow reservoir by a factor of two under no recharge condition and ; τ* is the duration of the period after a single rainstorm until interflow ceases [12]

Table 1: Model input parameters fixed in time for surface flow components, base flow and interflow parameters

Parameters		Input values	Units
A_s	Fractional area, saturated bottom lands	0.15	
$S_{max,s}$	Maximum water content saturated lands	200	mm
$S_{max,d}$	Maximum water content, degraded soils	10	mm
$S_{max,h}$	Maximum water content. permeable hillsides	250	mm
t^*	Duration of interflow after rain event	200	days
$t_{½}$	Half-life base flow aquifer	40	days
BS_{max}	Maximum water content aquifer	80	mm
$a_{t,s}$	Transport limit erosion saturated lands	3	$(g\ L^{-1})(mm\ d^{-1})^{-0.4}$
$a_{t,d}$	Transport limit erosion degraded area	6.5	$(g\ L^{-1})(mm\ d^{-1})^{-0.4}$
a_s	Source limit erosion	3	$(g\ L^{-1})(mm\ d^{-1})^{-0.4}$

saturated area) and A_2 (fractional degraded area), respectively. Theoretically, for both turbulent flow and a wide field n is equal 0.4 (12,4,14). Then, the concentration of sediment in the stream can be obtained by dividing the sediment load Y (eq. 2) by the total watershed discharge

$$C = \frac{(A_1 q_{r_1}{}^{1.4}[a_{s1} + H(a_{t1} - a_{s1})] + A_2 q_{r_2}{}^{1.4}[a_{s2} + H(a_{t2} - a_{s2})])}{A_1 q_{r_1} + A_2 q_{r_2} + A_3(q_b + q_i)} \quad (3)$$

where q_b (mm day^{-1}) is the base flow and q_i (mm day^{-1}) is the interflow per unit area of the non-degraded hillside, A_3 where the water is being recharged to the subsurface (baseflow) reservoir.

A. Input data

Two types of input data are needed: climate and landscape. Climate input data consisted of 10-day rainfall amounts that were obtained by averaging the 10-daily rainfall of the selected 10 rainfall gauging stations using the Thiessen polygon method [5]. The potential evaporation was set according to Steenhuis et al. [8] at values of 3.5 mm/day for the long rainy season (June to September) and 5 mm/day for the dry season (October to May). These values were selected based on the long-term average of available potential evaporation data over the basin. As landscape input parameters for the model, the relative areas of the three regions are needed as well as the amount of water (available for evaporation) in the root zone between wilting point and the threshold moisture content. For the two areas that produce runoff, the threshold value is set to the saturated moisture contents. Any rainfall in excess of saturation becomes runoff. For the permeable hillside the threshold value is field capacity and excess rainfall becomes recharge filling up the ground water reservoir and when that is full, the interflow reservoir. This in addition to the six "surface parameters" there three base flow parameters. These are a first order baseflow reservoir constant, a zero order interflow rate constant that indicates the duration of the linearly decreasing interflow and the maximum water content of the baseflow reservoir. The landscape parameter values cannot be determined a priori and need to be obtained by calibration. For the sediment input parameters we choose the H function similar to Tilahun et al [12], with the exception that we assumed that during the latter part of the rainy monsoon phase, some sediment in the streams would be picked up from the banks (Figure 2).

Since the flow at Bahir Dar and Kessie is most affected by the Chara-Chara weir, we used the gauge at El Diem at the Ethiopian Sudan border to establish the relationship between precipitation and discharge and between sediment concentrations and the predicted surface runoff and subsurface flow.

Available data at Kessie for this study were ten day precipitation for the period from 1964 - 1969; 1993; 1998- 1993. Ten day discharge measurements were available for 1964 -1969, 1993 and 2003. Monthly discharge was available for the period 1998 to 2003. Erosion measurements were available only for two years 1993 and 2003.

III. RESULTS

Calibration of the model parameters (Tables 1 and 2) was based on the assumption the subsurface flow parameters (interflow and baseflow) remained the same over time, as well as the storage of the landscape components. We assumed that over the 40 year time span only those parameters would change that were affected by erosion. Since erosion makes the soil shallower, the fraction of the degraded soils that produce surface runoff was increased from the 1960s and to 2000's.

For estimating sediment concentration we assumes that the erosivity (both transport and source limit remained the same in time). Thus the variations in concentration were contributed to increase in degraded areas over the simulation period.

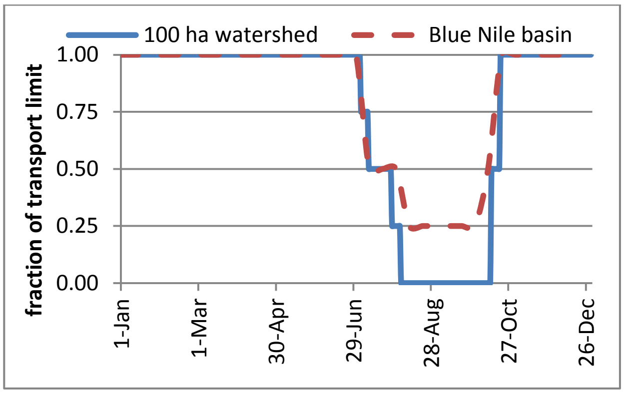


Figure 2: Fraction of transport limit used in PED model

The calibrated parameter values that are fixed throughout the rainy phase for the model are shown in Table 1. In accordance with earlier findings [8,3, 12] for small watersheds, we assumed that a total of 15% of the Blue Nile basin produced surface runoff when the area became saturated around the middle to end of July. Since the Blue Nile basin intercepts interflow that is missing in the water balance from the smaller basin the interflow last approximately 5 months (Table 1) and is much longer than from the smaller basins. Half-life of the aquifer was 40 days and is in range that is found for the smaller basins. The calibrated transport limiting and source limiting coefficients are in the range found earlier as well.

As we noted above only the fraction of the degraded hillsides was adjusted so that the predicted discharge would fit better to observed 10-day discharge values for the periods 1964-1969 and the years 1993 and 2003. Since the fractions of the three fractions should add up to 1, an increase in degraded land resulted in a decrease in permeable hillsides (Table 2).

A. Discharge

In the 1964-1969 period the observed and predicted discharge values corresponded most closely when the hillside (recharging the interflow and groundwater) made up 75% of the landscape with a soil water storage of 250 mm (between wilting point and field capacity). Surface runoff was produced from the exposed surface or bedrock making up 10% of the landscape and saturated areas comprising 15% of the area (Tables 1 and 2, Figure 3, solid line). After the dry season, the exposed bedrock needed to fill up storage of 10 mm before it became hydrologically active, whereas the saturated areas required 200 mm (Table 1) which were invariant in time. The Nash Sutcliffe Efficiency was a respectable 0.88 for discharge over a 10-day period (Table 3).

Table 2: Model input parameters variable in time for fractional areas of degraded hillsides and permeable hillsides.

Period	Fractional areas of hill sides	
	Degraded	Permeable
1964-1969	0.10	0.75
1993	0.18	0.67
2003	0.22	0.63

Table 3: Nash Sutcliffe (NS) values and root mean square error (RM) in mm/day for discharge at El Diem. The last three rows indicate the goodness of fit when the degraded areas in the second row are used in the PED model for the years specified in the first column. Bolded numbers are the best fit.

	1964-1969		1993		2003	
Degraded area	0.12		0.18		0.22	
Period	NS	RM	NS	RM	NS	RM
64-69	**0.87**	**3.3**	0.87	3.4	0.84	3.7
1993	0.92	2.7	**0.94**	**2.4**	0.92	2.7
2003	0.95	3.1	0.97	1.7	**0.98**	**1.2**

In 1993 it was assumed that the fraction of degraded area in the basin was increases to 18% (Table 2) with otherwise the same input parameters. The predicted discharge fitted the observed 10-day values with a Nash Sutcliffe efficiency of 0.94. Note that the average precipitation for 1993 came from a difference source than Tesemma and we used a constant potential evaporation of 4 mm/day to obtain a mass balance. The best fit was obtained for 2003 by increasing exposed bedrock coverage to 22% (from the 10% in the 1964-1967 period) and decreasing the hillslopes by 12% to 63% (Table 2) while all other parameters were kept the same (Table 1, Figure 4b). The Nash-Sutcliffe model efficiency of 0.98 was again remarkably high for this PED model with nine imput varibales (Table 3). Similarly, small Root Mean Square Errors were obtained (Table 3). The high runoff Nash-Sutcliffe efficiencies are an indication that although simple, the model effectively captured the hydrological processes in which various portions of the watershed become hydrologically active after the dry season.

To further confirm that the model parameters predicting discharge actually changed between the mid 1960s to the 2000's we interchanged the calibrated model parameters between the three periods. The results (Table 3) show that the accuracy of simulation decreased when the degraded areas were inputted for the other periods. This was most distinct for the discharge simulations for 2003. The 10% degraded area resulted in a Nash Sutcliffe efficiency of 0.92 and a root mean square error of 3.1 mm/10-day (Table 3). This improved to 0.97 and 1.7 mm/10-day respectively for the 18% degraded fractional area and for the optimum 22% degraded area the Nash Sutcliffe was 0.98 and the root mean square error was 1.2 mm/10-day (Table 3 bottom row). Moreover, by comparing observed versus predicted discharge in Figure 3, it becomes obvious that the peaks are over predicted by using the 22% degraded area (instead of the optimum 10%) and the peak is under predicted in Figure 4b for the 10% degraded area instead of the 22%. The increased runoff with increasing degraded areas is also confirmed by calculating the average discharge for the years of 1963-1969, 1993 and 1997-2003 which is 290 mm/year for a 10% degrades area and 317 mm/year for 22% degrade area. Thus runoff increases by almost 10%. The results in Figure 4a are not as conclusive for the peak flows but show that initial amounts of runoff increase when the degraded areas increase, which is better simulated by the optimum solution. Finally, the simulations (Figures 3 and 4) show that the base and interflow are decreasing when the degraded areas are increasing, because there is are smaller portions in the watershed that fill up the reservoirs.

Although this model is based on a conceptual framework, it can be seen as an arithmetical relationship that relates the spatially averaged ten-day rainfall to the ten-day watershed discharge. This relationship between rainfall and watershed discharge clearly changes over the 40 year period (Figures 3 and 4), indicating that the runoff mechanisms are shifting due to landscape characteristics since the precipitation did not vary. .

The discharge model results in the following explanation: soil erosion during the period from the early 1960s to 2000. The hillsides that were eroded in this period no longer stored rainfall produced runoff in 2003 while they were a source of interflow in 1963. This in turn caused a greater portion of the watershed to become hydrologically active at an earlier stage, releasing more of the rainfall sooner and resulting in earlier flows and greater peak flow

These simulation results are in line with the statistical result at the El Diem site which shows increasing trends of runoff during long or short rainy seasons but decreasing dry season runoff, while annual flow has no significant change at Eldiem likely due the large forest tracks in the south but significant increase in wet season flow in the upper Blue Nile as was found by Tesemma et al [11] in the statistical analysis.

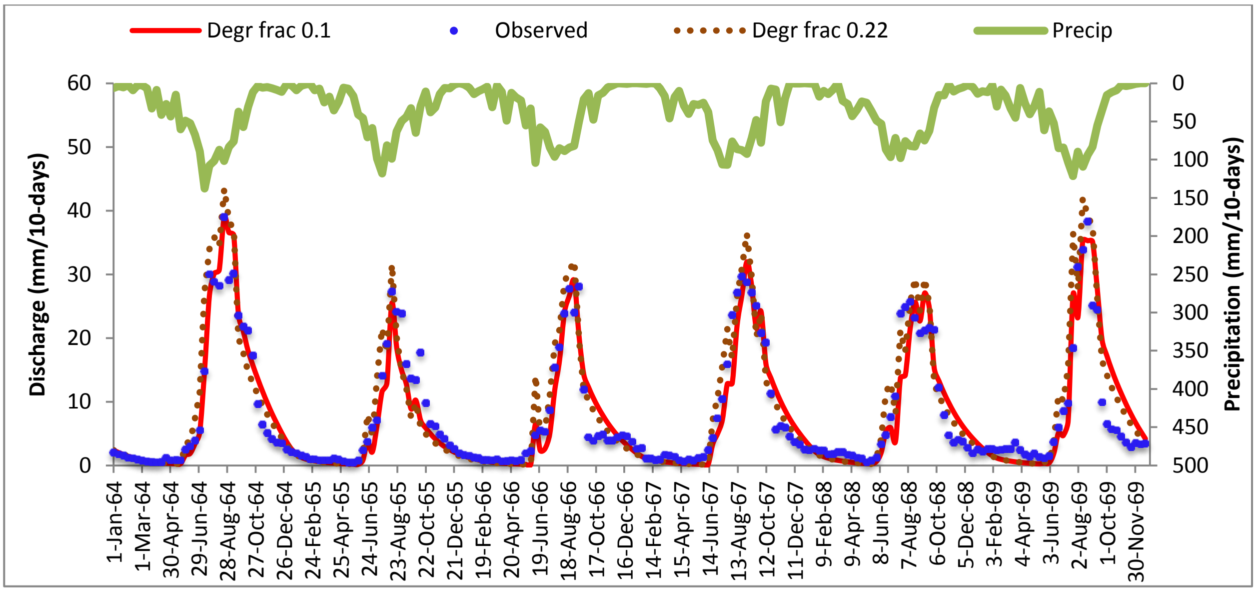


Figure 3: Observed (closed spheres) and predicted (solid line, with 10% of the watershed consist of degraded hillslopes) discharge for the Blue Nile at El Diem at the Ethiopian Sudan border for the period of 1963 to 1969. The dotted line is the discharge assuming that the degraded areas constitute 22% of the landscape.

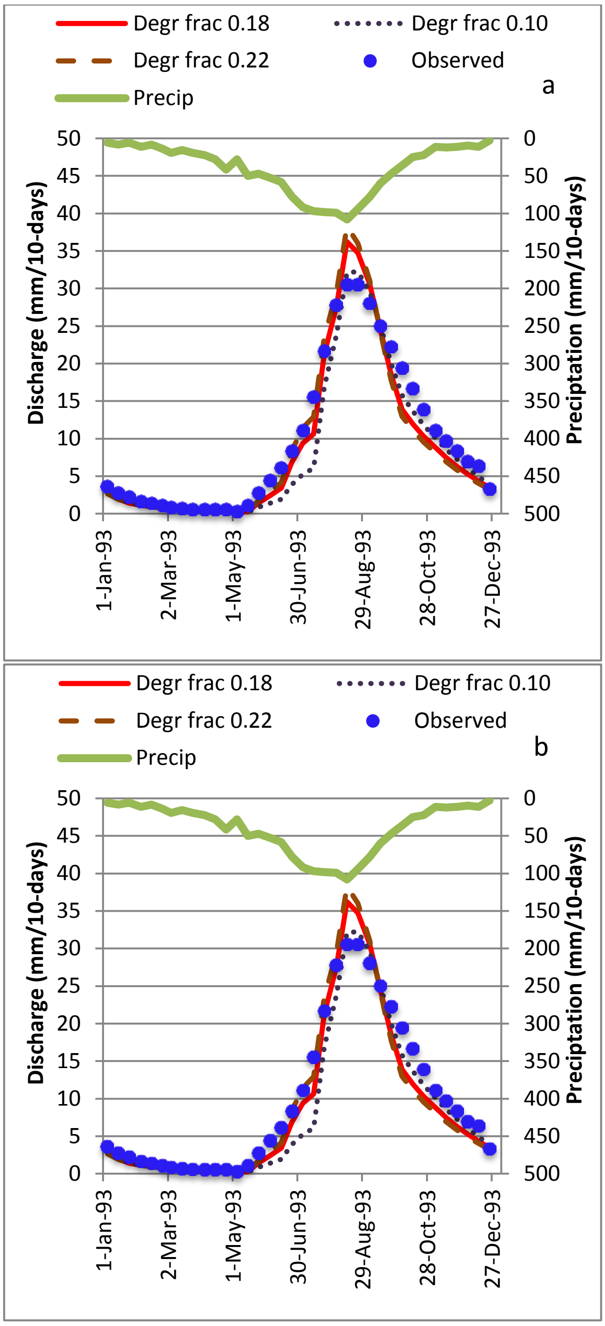


Figure 4: Observed (closed spheres) and predicted discharge (solid line) for 1993 for the Blue Nile at El Diem at the Ethiopian Sudan border where 18% of the watershed consist of degraded hillsides (top figure, a) and lower figure b for 2003 where the solid line represents 22% of the watershed is degraded. The dotted line represents the discharge when the watershed has 10% degraded area and the dashed line the 22% degraded area in a) and 18% b).

B: Sediment concentrations

Sediment concentrations were simulated using Eqs 1-3. Input data consisted of the surface runoff and base and interflow calculated with the hydrology model (Figure 1), the H function (Figure 2) and the transport and source limit (Table 1). Consequently, we did not change any erosion related parameters for 1993 and 2003. In this case we obtained the best fit for predicted and observed sediment concentrations for 1993 and used the same parameters (with only the increased surface runoff due the increased degraded hillsides obtained by the the hydrology model) for estimating the sediment concentration in the Blue Nile at the El Diem for the year 2003.

Table 4: Nash Sutcliff (NS) values and root mean square error (RM) values for sediment concentration in g/l during the rainy monsoon phase at El Diem. The last two rows indicate the goodness of fit when the degraded areas in the second row are used in the PED model for the years specified in the first column. Bolded numbers are the best fit.

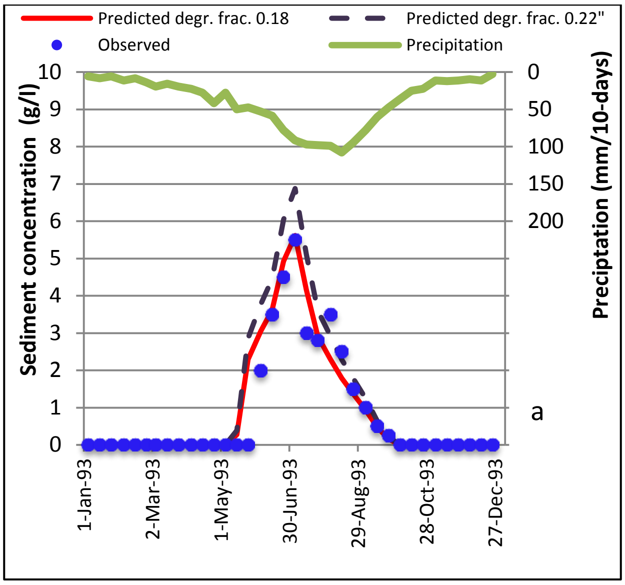
Period	1993		2003	
Degraded	0.18		0.22	
Year	NS	RM	NS	RM
1993	**0.97**	**0.9**	0.94	1.4
2003	0.90	1.3	**0.94**	**1.0**

The simulation results are shown in Figure 5 and the statistics in Table 4. The Nash Sutcliffe efficiencies are amazingly close to 1 for the averaged 10 day concentrations. For both years interchanging the hydrology output of the PED model resulted in a poorer fit. For example using the degraded area of 18% for simulating 2003 the sediment concentration had a Nash Sutcliffe efficiency of 0.90 while using the correct 22% degraded area increased the Nash Sutcliffe efficiency to 0.94 (last line Table 4) The root mean errors were also significantly improved.

While the total discharges were only minimally affected for the 1993 and 2003 as can be seen in Figure 4 where the dashed line can hardly be distinguished from the solid lines, the erosion concentrations were significantly more affected. The peak concentration in 1993 of 5 g/l in Figure 5a was well simulated by 18% degraded area (solid line) but by using the 22% degraded area in the hydrology model over resulted in a peak concentration of almost 7 g/l which overestimated the observed peak concentration by 2 g/l . In Figure 5b the peak concentration of 7 mg/l was well simulated by using predicted surface runoff and subsurface flows for the 22% degraded area. The 18% degraded area under predicted the peak

IV DISCUSSION

In all cases the PED model could simulate the discharge and sediment concentrations well. This allowed us to optimize the model parameters so that the effect of increasingly degrading landscape could be detected in the output signal (both discharge and sediment concentration) of the watershed It is obvious from our results that the changing landscape characteristics should be included in any future discharge prediction and the amount of water available in Sudan and Egypt. The 10 % increase in discharge in 40 years is in the same order as the evaporation from Lake Nasser!



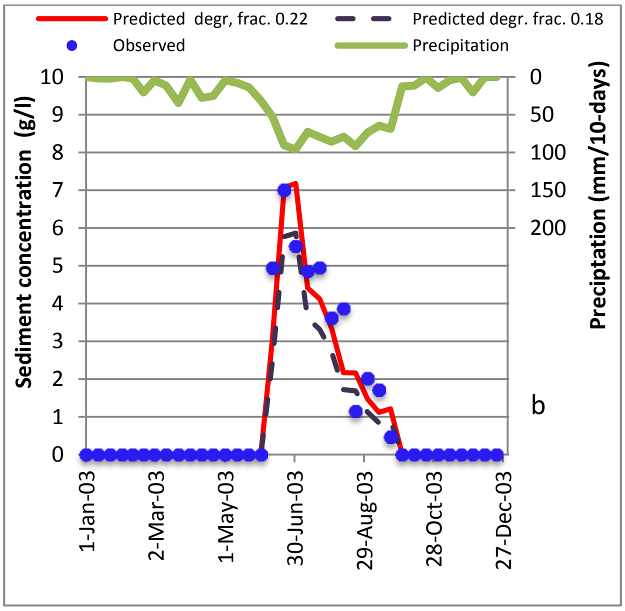


Figure 5: Observed (closed spheres) and predicted sediment concentrations (solid line) for 1993 for the Blue Nile at El Diem at the Ethiopian Sudan border where 18% of the watershed consist of degraded hillsides (top figure, a) and lower figure b for 2003 where the degraded area is 22%. The dashed line represents the sediment concentrations when the degraded areas are interchanged in simulating the flows with the PED model.

The effect on sediment concentration (Figure 5) by increasingly degrading landscape is significant. However its effect on sediment loads should be more significant since both surface runoff and concentration are increasing. As an example we calculated the cumulative sediment load for the period of 1998 to 2003 assuming that land had not degraded since the 1960's with 10% degraded areas, was intermediately degraded (the 1993 situation with 18% degraded) and the land and severely eroded with 22% of the land degraded. We assumed that there were no conservation measures carried out which is unrealistic. It is however of interest to see what the "pure" effect is the degraded areas.

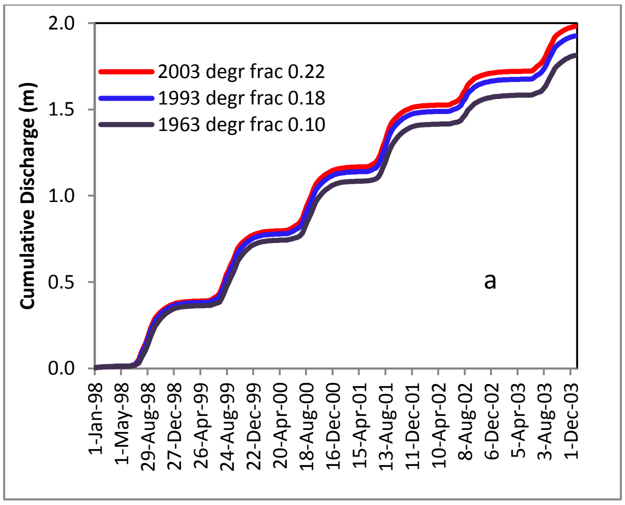
The results of the cumulative discharge over the six year period from 1998 to 2003 (Figure 6a) show that a doubling of degraded areas from 10% to 22% increase the annual discharge at El Diem from approximately from 30 cm to 33 cm per year . Thus a similar 10% increase as for the 13 year record.

Figure 6b shows that the cumulative sediment loads are increased by a factor of 3 from approximately 2 ton/ha/year for the 10% degraded area to 6 ton/ha/year for the 22% degraded area. The 5-6 ton is equal to what is the same as the reported sediment loss at El Diem [9], but the 2 ton/ha/year in the 1960's at El Diem (assuming the same rainfall as in the 1990) is likely not realistic. Many soil and water conservation practices have been installed during the last 50 years and that would have lowered the present-day erosivity. This implies that the erosivity in the 1960's would have been greater resulting in more soil loss at that time.

Moreover, unlike the conclusion on discharge, our findings on the sediment concentrations are clearly limited by the restricted access to the sediment data at El Diem. In our case we had only two years of sediment data available and that were only 10 years apart . The two years sediment data indicated a significant increase in the sediment concentrations over a 10 year period which was well simulated by assuming that the degraded areas increased. However extrapolating this over a larger period as was done in Figure 6b is interesting but likely not justified. Thus more research needs to be done before our sediment load results representing the 1960's can be accepted.

V Concluding Remarks

The Blue Nile in Ethiopia that drops from Lake Tana more than 1300 m to the Ethiopian Sudan border in approximately 800 km has more than enough stream power to carry all of the sediment delivered from the agricultural land to the outlet. Although there may be sediment deposition before the runoff reaches the stream, we hypothesize that once the sediment in the stream, it is carried downstream across the Ethiopian border (if that would not be the case the Blue Nile Gorge would be filling up). This has positive and negative implications. When sediment delivery from the agricultural land is decreased, the concentration in the river is decreased as well and less sediment will deposit in the reservoirs. On the other hand if more sediment is delivered when the landscape degrades more or forests are being converted to agricultural lands, this additional sediment can be delivered downstream as well and fill up the planned reservoirs at a more rapid rate once constructed.



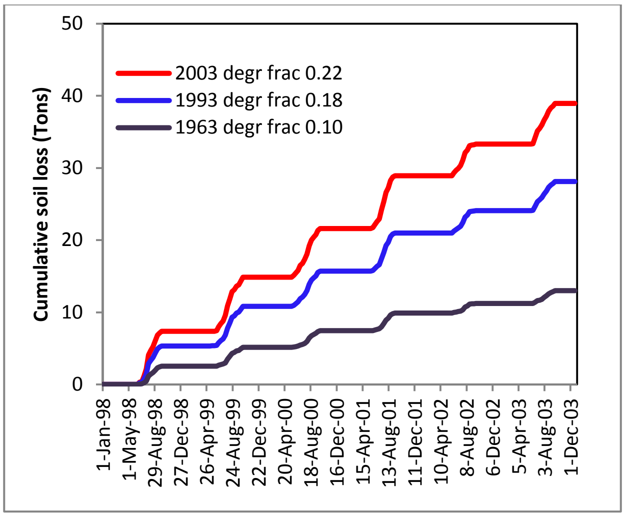


Figure 6: Cumulative runoff (a) and sediment losses (b) for the Blue Nile at the border with Sudan for the period 1998-1993 assuming an increasing fraction of the land scape becoming degraded

Our results indicate that erosion control on the degraded areas, would be highly effective in reducing overall sediment concentrations and loads carried by the Blue Nile. Covering these areas with trees or grasses that would keep the soil in place would likely be very desirable to reduce sediment transport. However the PED model as presented in this paper is a simplified mental construct that need to be confirmed, before any recommendation can be based on the simulation results. We recommend therefore experimenting with the suggested conservation methods in an experimental watershed.

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