Modeling of soil erosion and sediment transport in the Blue Nile Basin using the Open Model Interface Approach

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Abstract

Rapid land use change due to intensive agricultural practices in the Ethiopian Highlands, results in increasing rates of soil erosion. This manifested in significant impacts downstream by reducing the storage capacity of reservoirs (e.g., Roseires, Sennar), and high desilting costs of irrigation canals. Therefore, this paper aims to provide a better understanding of the process at basin scale. The Soil and Water Assessment Tool (SWAT) was used to model soil erosion in the upper catchments of the Blue Nile over the Ethiopian Plateau. The SWAT output forms the input sediment load for SOBEK, a river morphology model. The two models integrated using the principles of the Open Model Interface (OpenMI) at the Ethiopia-Sudan border. The Nash-Sutcliffe coefficient was found to be 0.72 and 0.66 for results of SWAT daily sediment calibration and validation, respectively. The SOBEK results also show a good fit of the simulated river flows at Roseires and Sennar reservoirs, both for calibration and validation. The results of the integrated modeling system showed 86 million tonnes/year of sediment load from the Upper Blue Nile, while SOBEK computes on average 19 Mm^3/year of sediment deposition in the Roseires Reservoir. The spatial variability of soil erosion computed with SWAT showed more erosion over the northeastern part of the Upper Blue Nile, followed by the northern part. The overall exercise indicates that the integrated modeling is a promising approach to understand soil erosion, sediment transport, and sediment deposition in the Blue Nile Basin. This will improve the understanding of the upstream-downstream interdependencies, for better land and water management at basin scale.

Introduction

Sediment transport degrades soil productivity as well as water quality causing worldwide problems of reservoirs sedimentation, and alternation of river morphology. These problems are more distinct in the Blue Nile basin – the main tributary of the River Nile. Rapid population increase led to fast land-use change from forest to agricultural land, and as associated with steep terrain, these changes has resulted in severe soil erosion over the

Upper Blue Nile (Nyssen, et al., 2004). The soil erosion and sediment transport processes have affected the whole Blue Nile basin negatively even though it was nutrient-rich sediment source (Nixon, 2002). The upper Blue Nile is losing fertile topsoil, exacerbating impacts of dry spells and drought, a common incident in the area. While, the reservoirs and irrigation canal in the lower Blue Nile are seriously affected by sediment deposition, leading to significant reduction of reservoirs storage capacities, and excessive de-silting costs of irrigation canals. In general, there is very limited information on how much is the soil erosion, and its impact downstream. Therefore, this paper aims for better understanding of the process at basin scale.

Methodology

The SWAT model was used to compute the soil erosion from Upper Blue Nile, routed up to the outlet (El Diem), and then SOBEK-RE was used to compute the morphological change of the river and reservoirs from the border till the Blue Nile outlet (Khartoum) and the Open Modelling Interface (OpenMI) was used to link the two models at the border.

SWAT set up

The Soil and Water Assessment Tool (SWAT) is a physical process based model to simulate the process at catchment scale (Arnold, et al., 1998, Neitsch, et al., 2005). The catchment is divided into hydrological response unit (HRU) based on soil type, land use and management practice.
The Upper Blue Nile watershed was delineated using the Digital Elevation Model (DEM) approximately 90 m grid of SRTM (http://www2.jpl.nasa.gov/srtm/index.html). The USGS landuse map of 1 km resolution (http://edcsns17.cr.usgs.gov/glcc/glcc.html) and the FAO soil map of 10 km resolution (FAO, 1995) were overlaid to obtain a unique combination of landuse and soil, hydrologic response unit (HRU). The sensitivity analysis of the SWAT computation has been done by varying key parameters value and investigating reaction on model outputs. An automatic (SWAT) sensitivity analysis has been carried out and those parameters that influence the predicted outputs were used for model calibration.

SOBEK set up

SOBEK is a one-dimensional hydrodynamic numerical modelling system capable of solving the equations that describe unsteady water flow, sediment transport and morphology, and water quality. The flow module is described by the continuity and the momentum equations and the morphological module is described by sediment continuity equation (WL/Delft Hydraulics and RIZA, 1995).

The river (1D) model constitute a length of 730 km. River cross data (surveyed in 1990) of the Ministry of Irrigation, Sudan was used. Compound structure was made from General structures and Weir to model the two dams Roseries and Sennar. A SOBEK time controller has been used to represent reservoir level simulating the operation program of the reservoir for a given year. A Chezy coefficeint of 50 both for positive and negative flow has been used. Time series discharge hydrograph has been used as upstream boundary conditions at El Deem and water level at Khartoum as downstream boundary conditions. For morphology computation, time series sediment inflow of was used us an upstream boundary conditions at El Deem and bed level of 368 m at Khartoum for downstream conditions. Time step of 4 hours and distance step of 1000m was used. The SOBEK-RE model covers the Blue Nile channel from El Deim to Khartoum, has been run for the period between 2000 and 2003. The operation of the two dams (Roseires and Sennar) has been simulated (within SOBEK) using a time controller that assimilates the observed reservoir water levels. The dam releases used as calibration variables.

Models integration

The Open Modelling Interface (OpenMI) standard is a software component interface definition for the computational core (the engine) of the hydrological and hydraulic models (Gregersen et al., 2007). The OpenMI was developed by EU co-financed HarmonIT project to address easy model linking of existing and new models. The SWAT model has been migrated into OpenMI compliant model. The detail of model development can be seen Betrie et al., 2009.

SWAT model results and discussion

The SWAT model (hydrology part) has been calibrated using daily flow hydrograph of El Deim (Ethiopia/Sudan border) station from 1981 to 1986, and validated with data from 1987 to 1996. The computed model performance using Nash-Sutcliff coefficient for the calibration and validation found to be 0.92, and 0.82, respectively. Since, the main emphasis of this paper is to compute soil erosion from upper Blue Nile and route the sediment all the way up to the confluence with White Nile at Khartoum, the detailed description of the Rainfall-Runoff model calibration and validation is given in Betrie et al., 2008.

The sediment hydrograph at El Deim used for calibration has been generated using sediment concentrations that were generated using sediment rating curve (flow sediment relations derived from historical data). SWAT sediment out flow calibrated for the period 1981 to 1986, while 1980 was used for warming the model. The calibration results show good agreement with observed sediment load, (Figure 1a). The model could simulate low flow erosion and sediment transport though this assumed zero relative to the peak period erosion in the observed data. The Nash-Sutcliffe efficiency computed to be 0.72 for the calibration period (1981to 1986), which is generally satisfactory results for soil erosion modelling (Arnold, et al., 1999,and Zeleke, 1999).

The validation of sediment modelling (1990 to 1996) is given in Figure 1b. The model was able to simulate the peak sediment for most of the years, except for 1993 and 1994, in particular when there is a sharp rise of silt content. Similar to calibration period the model could simulate sediment transport during dry period and beginning of wet period flow which is assumed zero in the observation data. The model performance NS equal to 0.66, assumed reasonable for such computation.

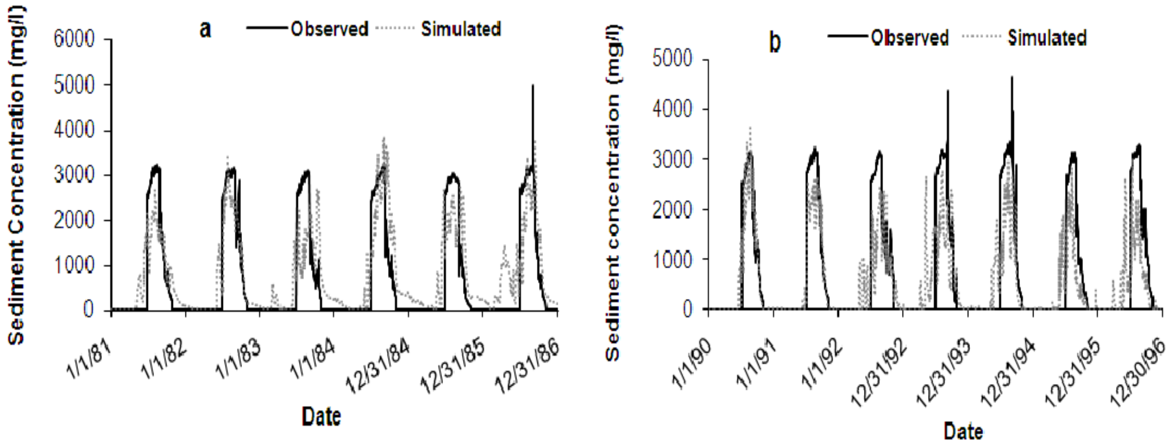

Figure 1: Observed and Simulated sediment concentration comparison during calibration (a) and validation (b) period at El Deem station.

The spatial variability of soil erosion results computed by SWAT is very useful information to assess areas of high/low sediment sources. As given by Figure 2 the highest soil erosion occurs at sub-basin 10 (16 ton ha-1yr-1). Medium soil erosion occurs in sub-basins 11 (9 ton ha-1yr-1), and 1 8 ton ha-1yr-1and low erosion occurs in the remains subbasins. Comparable result was reported by BCEOM (1998) when analyzing several years of observed data.

The total amount of soil erosion computed by SWAT at the outlet (El Deim was found to be 491 t km-2 year-1. This result was found to be within the range previous estimate such as 480 t km-2 year-1 Blue Nile catchment above El Diem (Ahmed A.S., 2006), 200- 400 t km-2 year-1 for upper Blue Nile and Tekeze basins (Mc Dougal, 1975) and 100-1000 t km-2 year-1 from Ethiopian highlands (Walling,1984). The biophysical process is that after soil erosion processes there is deposition of sediment in river channel within the Upper Blue Nile, which account 24 Million ton per year. The amount of sediment yield delivered out of the upper Blue Nile estimated to be 62 Million ton per year at Ethiopia-Sudanese boarder.

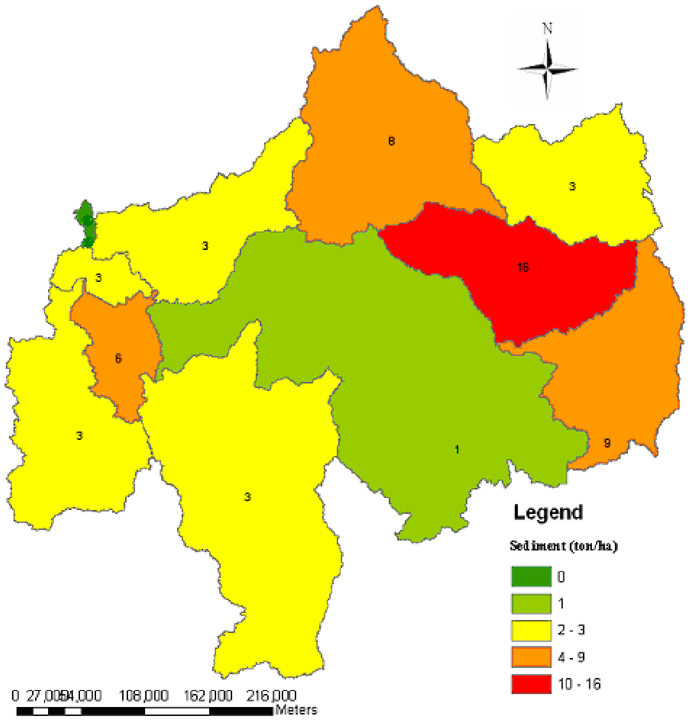

Figure 2: Simulated soil erosion in upper Blue Nile subbasins

SOBEK model results

The SOBEK model could accurately simulate the flow regime of the Blue Nile. Calibration result for the flow downstream Roseires dam is given in Figure 3a. While, the flood peak was not captured accurately, its propagation and values for the rest of the year seems very reasonable, in particular the rising and falling limb of the hydrograph. No clear reason for the mismatch of September 2000. Though likely it could be attributed to ungauged inflow from the catchment between El Deim and Roseires. Another reason could be a questionable accuracy of the dam equation while computing releases during rapidly rising flood.

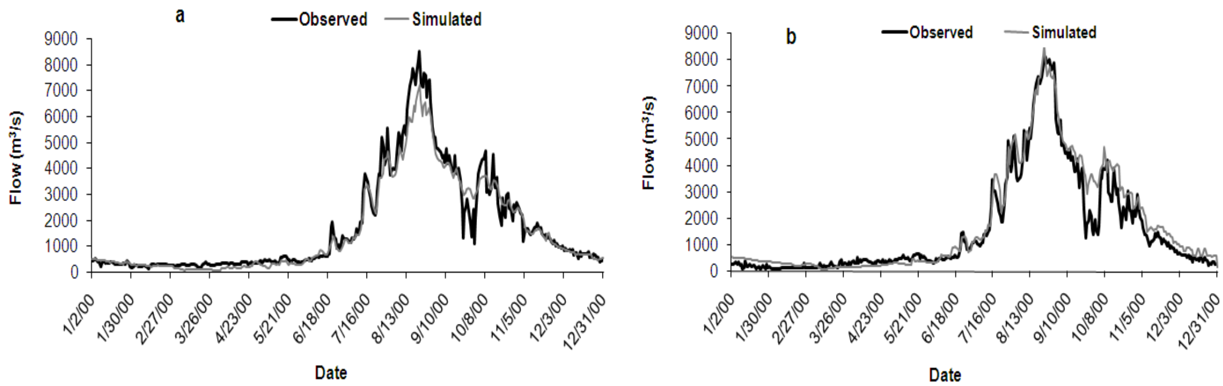

Figure 3: Observed and Simulated discharge calibration year 2000 at Roseries (a) and Sennar (b) reservoirs

The calibration result at Sennar dam (Figure 3b) shows a good fit. Unlike Roseires, peak flow has been simulated accurately. The model could not simulate sudden lowering of gate to flush sediment at the last week of September 2000. In addition, the model overestimated the falling limb, which could be due to abstraction for irrigation along the reach Roseires-Sennar.

The SOBEK model validation has been done for year 2003 at Roseries and Sennar dams. Figure 4 depicts good fit between simulated and observed discharge at Roseries and Sennar reservoirs. The rising limb and the peak flow were well captured by the model. The model did not catch the peak in the beginning of September in which the reservoir starts to be filled if the discharge is at El Deim drops to 350 M m3/day. This is attributed to the fact that during the calibration period the flow at El Deim satisfied the reservoir filling condition so the model was not trained to lower the weir in a case the flow does not drop to 350 M m3/day; in fact the flow at El Deim for the validation period was 432 M m3/day. Similar to the calibration period the model could not simulate the sudden opening of the weir to flush the sediment at both Roseries and Sennar.

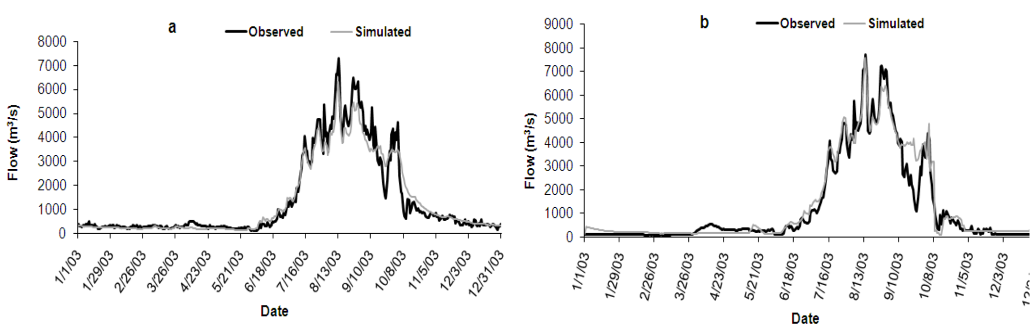

Figure 4: Observed and Simulated discharge validation year 2003 at Roseries (a) and Sennar (b) reservoirs

Since the morphological changes feedback to the hydrodynamics and the close relations between resistance and sediment transport, the calibration and verification of the hydrodynamic and sediment transport modules are closely inter-linked. Thus, after good calibration of the hydrodynamic part, the model was run in morphological mode to compute the bed level change. The sediment transport module was not calibrated along the river reach because of the data limitation on different grain size. However, the sediment transport verification result showed good fit between observed and simulated sediment concentration at Wad Elias station (Figure 5).

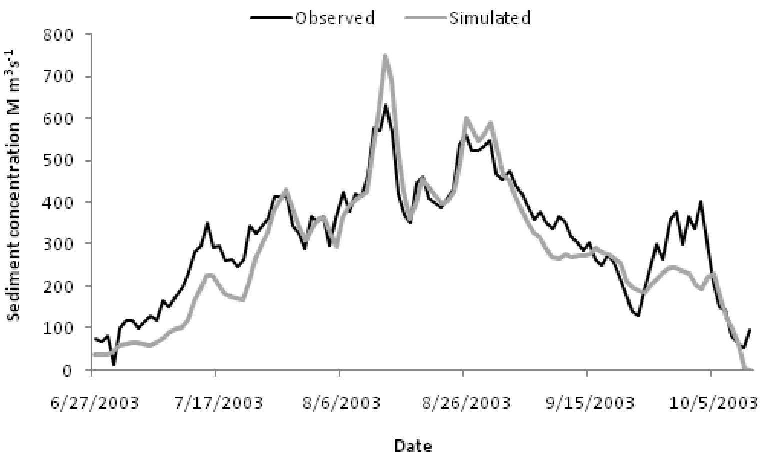

Figure 5: Sediment transport verification at Wad Elias station

The longitudinal profile of the SOBEK results showed a deposition of the suspended sediment that transported from upper Blue Nile has occurred at 35 km before Roseries dam. This is expected as to the effect of the backwater curve (Figure 6), i.e., typically development of reservoir delta. This result well agrees to the principle of reservoir sedimentation of Tarbel Resevoir, Pakistan in Sloff (1999). Close to El Deim, the beginning of the reach the model shows clear bed erosion. This is because the sediment boundary condition at upstream was consisted of only suspended sediment due to lack of measured bed load information. However, the Van Rijn sediment transport model needs bed load since it computes bed load and suspended sediment transport separately. Thus, it erodes the bed to satisfy its transport need. After Roseries dam there is severe bed erosion, could be due to increased sediment transport capacity because of the deposition suspended sediment upstream the dam. Although in reality there is erosion after the dam, it should not erode the bed that much because there is wash load which is not deposited upstream of the dam. The excessive erosion happened due to the fact the model does not solve the advection-dispersion equation which consider the wash load otherwise the effect might have been reduced. Thus, the substantial erosion just downstream the dams may not be accurate as other models that are more suitable for non-cohesive sediment transport. Nevertheless, this result could give qualitative information on river morphology behavior. Downstream of Sennar dam there is no excessive bed erosion unlike the Roseries since the sediment transport capacity is lowered due to enough eroded sediment. After Sennar to Khartoum there is local erosion and deposition as shown in Figure 6.The volume of sediment deposition at Roseries was estimated by integrating the area differences along the distance between El Diem, the mouth of the Reservoir and

Roseries dam. Annual average sediment deposition of 19 M m3 was obtained for the simulation period, which is comparable to literature values, e.g., 20 M m3/yr reported by (NBCBN-RM, 2005).

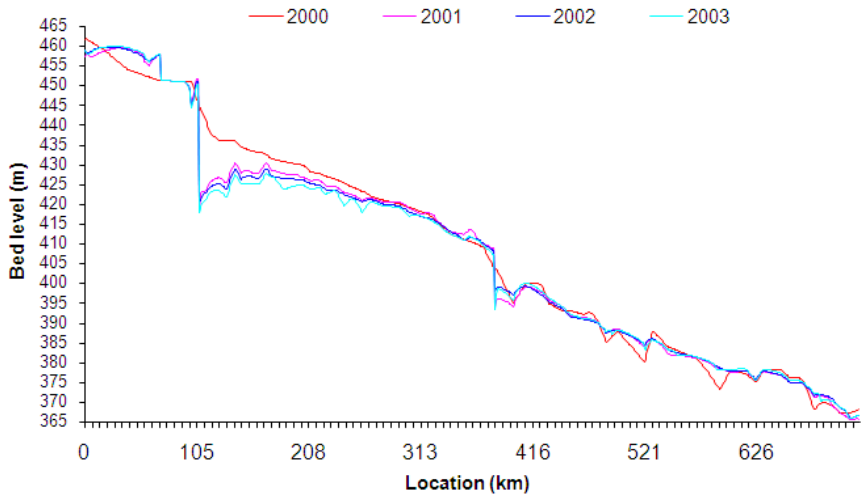

Figure 6: Erosion and deposition of Blue Nile river bed

Conclusions

The paper showed an integration of SWAT hydrological model to a SOBEK 1D hydrodynamic model using OpenMI interface. Useful information has been obtained on spatial distribution of soil erosion on Upper catchment, as well as to the total yield at outlet. The sensitive area to erosion and deposition were found to be the North and North East of Upper Blue Nile subbasins and Rosaries dam, respectively. The integrated soil erosion - sediment transport modelling showed that 86 ton per year of soil is eroded from Upper Blue Nile (at the border), 24 million ton per year deposited in the channel and 62 million ton per year transported to Lower Blue Nile at Eldiem. About 19 M m3year-1 year deposited at Roseries reservoir and the remaining transported downstream. The integrated modelling proved to be useful to study upstream-downstream interdependencies, e.g., to analyze the effect of different management practices upstream (e.g., forestation), and assess implications on flow and sediment hydrographs further downstream. These are essential information for effective basin scale water management.

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