Applied Geography 73 (2016) 89–101

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Modelling the effect of soil and water conservation on discharge and sediment yield in the upper Blue Nile basin, Ethiopia

Tatenda Lemann [a, b, *], Gete Zeleke [a, c], Caroline Amsler [b], Luciano Giovanoli [b], Hannes Suter [b], Vincent Roth [a, b]

[a] *Centre for Development and Environment (CDE), University of Bern, Hallerstrasse 10, CH-3012 Bern, Switzerland*
[b] *Institute of Geography, University of Bern, Hallerstrasse 12, CH-3012 Bern, Switzerland*
[c] *Water and Land Resource Centre (WLRC), Diaspora Square, Megenagna, PO Box 3880, ET-Addis Ababa, Ethiopia*

ARTICLE INFO

Article history:
Received 16 December 2015
Received in revised form
23 May 2016
Accepted 21 June 2016
Available online 1 July 2016

Keywords:
Hydrologic modelling
SWAT
Soil and water conservation
Blue and green water
Sediment yield
Upper Blue Nile basin

ABSTRACT

Soil and water conservation (SWC) can influence the amount of sediment yield leaving a catchment and the availability of water for up- and downstream stakeholders. The extent of this influence depends heavily on hydro-climatic conditions in the upstream catchments. This study investigated the changes in blue and green water distribution and sediment yield in a meso-scale catchment in the Wet Wenya Dega agro-climatic zone in the upper Blue Nile basin, where the implementation of SWC measures has been documented for the last 29 years. We implemented the temporal and spatial variability of SWC in the form of terracing into the Soil and Water Assessment Tool (SWAT) and modelled its influence on discharge and sediment load. Using the Sequential Uncertainty Fitting program (SUFI-2), we calibrated and validated discharge and sediment load with a 31-year data set from a sub-catchment (113 ha) and validated the model for the entire catchment (4818 ha) with a two-year data set. Modelling showed that discharge at the catchment level, and thus water availability for downstream stakeholders, did not change significantly with the implementation of new SWC measures, but SWC could substantially reduce sediment yield. Two modelled SWC scenarios showed that with the implementation of SWC measures the average annual sediment yield of the study area could be reduced from 37 t/ha to 17 t/ha.

1. Introduction

Driving forces such as population growth and economic development are increasing the demand for blue water along the Nile River. More water is used for irrigation, energy production, industry, domestic purposes, and other ecosystem services. Downstream countries with limited precipitation are highly dependent on blue water coming from the Ethiopian Highlands, where until recently more than 95% of all agriculture was rainfed, thus using almost exclusively green water (Hagos, Makombe, Namara, & Awulachew, 2009; Rockström, Lannerstad, & Falkenmark, 2007). Green water can be described as in situ vapour flow (from soil moisture) or evapotranspiration. By contrast, blue water is accessible surface and subsurface flow of water in rivers, lakes, and groundwater (Rockström, Barron, & Fox, 2003).

New dams and intensification of agriculture are changing the temporal and spatial distribution and availability of blue and green water in the headwaters of the Nile River. At the same time, there is a need to reduce sediment yield to retain fertile soil on the fields in the headwaters and to prevent siltation of new dams along the river. Integrated soil and water management approaches are focusing on improved rainfall infiltration, direct runoff reduction, and rainfall harvesting schemes in general to improve yields and reduce soil loss. But the expansion of soil and water conservation (SWC) measures has raised questions concerning hydrological responses and water availability for up- and downstream stakeholders.

Recent studies focused on the effect of these SWC measures on surface runoff and sediment loss in “twinned” catchments (Bosshart, 1998; Huang, Zhang, & Gallichand, 2003), with model simulations (Abouabdillah et al., 2014; Betrie, Mohamed, van

---

* Corresponding author. Centre for Development and Environment (CDE), University of Bern, Hallerstrasse 10, CH-3012 Bern, Switzerland.

E-mail addresses: tatenda.lemann@cde.unibe.ch (T. Lemann), gete.z@wlrc-eth.org (G. Zeleke), cn.amsler@gmail.com (C. Amsler), luciano.giovanoli@gmail.com (L. Giovanoli), suter.hannes@gmx.net (H. Suter), vincent.roth@cde.unibe.ch (V. Roth).

http://dx.doi.org/10.1016/j.apgeog.2016.06.008
0143-6228/© 2016 Elsevier Ltd. All rights reserved.

Griensven, & Srinivasan, 2011; Memarian et al., 2014; Yang et al., 2009), experimental plots (Adimassu, Mekonnen, Yirga, & Kessler, 2012; Amare et al., 2014; Herweg & Ludi, 1999; Teshome, Rolker, & de Graaff, 2013), and process monitoring before and after the implementation of new SWC measures (Huang & Zhang, 2004; Huang et al., 2003; Lacombe, Cappelaere, & Leduc, 2008; Nyssen et al., 2010). They generally found reduced sediment yields and reduced discharge after the implementation of new SWC measures. But the amount of decrease varies substantially between the different studies and study sites. Studies on experimental plots show larger decreases than studies at the catchment level. In addition, rainfall–runoff ratios in the Ethiopian Highlands are highly variable and depend not only on SWC but also on hydrometeorological conditions (Lemann, Roth & Zeleke, 2016) and the scale of the catchment (Nyssen et al., 2010). Lemann et al. (2016) even showed an increase in the annual rainfall–runoff ratio over the last 30 years in three catchments where SWC measures were implemented 20–30 years ago.

The understanding of the effects of SWC measures and other parameters on the hydrological response and suspended sediment load at different catchment levels in the upper Blue Nile basin is important to improve SWC in the headwaters without reducing blue water availability for downstream regions. Accordingly, the key objectives of this study were (1) to simulate discharge and sediment load in a catchment where SWC measures have been implemented over the last 29 years, (2) to extrapolate the calibrated model from a small-scale (113 ha) to a meso-scale catchment (4818 ha) which is an enlargement of the smaller catchment, and (3) to quantify the influence of SWC measures on sediment yield and discharge under different scenarios.

Therefore, we identified the changes over time in SWC implementation based on Google Earth satellite images and field reports (Bosshart, 1997, 1998; Herweg & Ludi, 1999) and input the SWC data into the Soil and Water Assessment Tool (SWAT) (Arnold, Srinivasan, Muttiah, & Williams, 1998). Next, we calibrated and validated our model with the Sequential Uncertainty Fitting program (SUFI-2) (Abbaspour et al., 2007; Abbaspour, Johnson, & van Genuchten, 2004) for the Minchet sub-catchment and extrapolated and validated the model for the entire Gerda catchment. Finally, we simulated discharge and sediment load under two scenarios, one with no SWC and one with SWC on every crop field.

The results provide important information on the influence of SWC on sediment yield and blue and green water availability for up- and downstream stakeholders in the Blue Nile basin.

2. Materials and methodology

2.1. Study area

The Gerda catchment is situated in the north-western Ethiopian Highlands in the upper Blue Nile basin. It is typical for the high-potential ox-plough cereal belt (Bosshart, 1997) in one of the country's most productive agricultural areas (Liu et al., 2008). It has a unimodal rainfall regime with a prolonged rainy season from May to October (Hurni, 1998) and an average annual rainfall of almost 1700 mm. The Gerda catchment covers 4818 ha and includes the Minchet sub-catchment (113 ha) (Fig. 1), where the Water and Land Resource Centre (WLRC), formerly the Soil Conservation Research Project, has collected hydro-meteorological data since 1984 (Table 1).

2.2. Hydrological model

The SWAT allows different physical processes, such as discharge and sediment yield, to be simulated in watersheds with different scales (Neitsch, Arnold, Kiniry, & Williams, 2011). We used SWAT to model the discharge and sediment yield in the small and meso-scale catchments described above. The model requires information on soils, land use, land management, topography, and climate (Arnold, Moriasi, et al., 2012b). It is designed to calculate runoff and sediments for individual drainage units, called hydrologic response units (HRUs), in generated sub-catchments and routes modelled discharge and sediment load towards the outlet of the catchment (Stehr, Debels, Arumi, Romero, & Alcayaga, 2009). SWAT has been widely used in the past. More detailed description of the model is given in reviews of its performance and parameterization in Ethiopia and other regions (Betrie et al., 2011; Castillo, Güneralp, & Güneralp, 2014; Gessesse, Bewket, & Bräuning, 2014; Koch & Cherie, 2013; Lin et al., 2010; Schuol & Abbaspour, 2007; Setegn, Dargahi, Srinivasan, & Melesse, 2010; Stehr, Debels, Romero, & Alcayaga, 2008; Tan et al., 2015; Tibebe & Bewket, 2011).

2.3. Model input and setup

2.3.1. Spatial data

This study used land use data, soil data, and a digital elevation model of 5 m resolution from the Advanced Land Observing Satellite-2 (ALOS-2, "DAICHI-2") operated by the Japan Aerospace Exploration Agency (JAXA). The soil map and data on physical and chemical soil characteristics were adapted from a soil survey carried out by the WLRC (Belay, 2014). The soil map contains 19 soil types belonging to soil hydrologic group A, B, or C. The initial soil erodibility factor (USLE_K) used for the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) to calculate soil erosion with SWAT was derived from a study by Hurni (1985) showing a relation between soil colour and erodibility.

The land use data were adapted from a land use map with a field-scale resolution and nine land use categories (WLRC., 2016) (Table 2). The planting dates were adapted to the cropping calendar by Ludi (2002). To simulate crop growth, we used the auto-fertilization and auto-irrigation options of SWAT due to lack of fertilization and irrigation data, and the growing duration of the different crop types was scheduled by pre-defined heat units. Tillage was adapted to the use of the traditional Ethiopian *maresha* plough with a 150 mm depth of mixing (DEPTIL), a mixing efficiency of 0.3 (EFTMIX) (Dile & Srinivasan, 2014; Temesgen, Rockström, Savenije, Hoogmoed, & Alemu, 2008), and a random roughness (RRNS) of 25 mm. The initial value of the cover-management factor (USLE_C) was adjusted for Ethiopia according to Hurni (1985). For each land use type, the initial maximum canopy storage (CANMX), and the Manning n-value for overland flow (OV_N), were adapted from Strauch et al. (2012) and Engman (1986), respectively. To simulate excess rainfall we used the soil conservation service curve number (SCS-CN) method.

2.3.2. Soil and water conservation measures

The most common SWC technology in the study area is the traditional drainage ditch. These seasonal furrows are ploughed into the topsoil diagonally to drain excess surface water. But depending on the gradient of the structures, they can cause waterlogging, overflow, and rill erosion (Haile, Herweg, & Stillhardt, 2006). To reduce overland flow and soil erosion, other SWC structures, such as *fanya juu* terraces (Fig. 2), have been implemented in the study area since 1986. In the Minchet sub-catchment, SWC conservation measures have been observed and documented since 1986 (Amare et al., 2014; Bosshart, 1997; Herweg & Ludi, 1999; Hurni, Tato, & Zeleke, 2005). Most of the agricultural fields in this sub-catchment were treated with *fanya juu* in 1986 following the technical guidelines on soil conservations by Hurni (1986). In 1990, during civil war, when socially accepted