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

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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

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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 hydro-meteorological 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

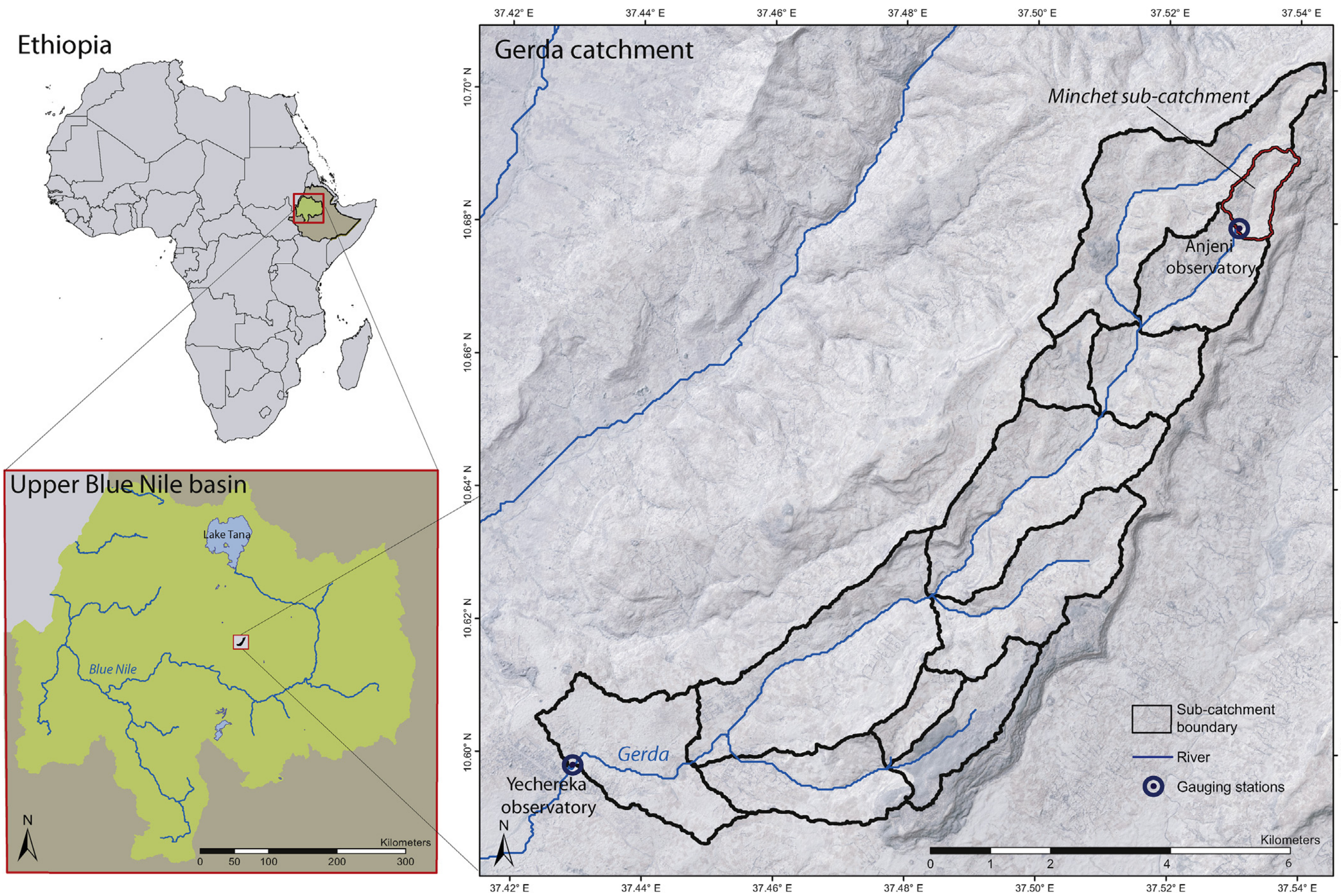

Fig. 1. The Gerda catchment and Minchet sub-catchment in the upper Blue Nile basin in Ethiopia.

Table 1
Information on the study area.

	Gerda catchment	Minchet sub-catchment
Location of gauging station	9.815°N, 37.711°E	10.678°N, 37.530°E
Area of hydrological catchment	4818.7 ha	113.4 ha[a]
Area as calculated with SWAT	4609.9 ha	101.9 ha
Altitude range	1975–2590 m asl	2417–2512 m asl
Average slope	14.5%	19.0%
Rainfall pattern	Unimodal	Unimodal

[a] Bosshart (1997).

authorities were replaced by acting local authorities, the farmers partially ploughed under the graded structures on their fields (Bosshart, 1997). This led to an above-average amount of sediment yield. Since then, the SWC measures have partly been re-established; today, almost all crop fields in the sub-catchment are conserved, although the distance between some terraces is larger than before 1990.

For the sake of simplicity, this study focused on the construction of *fanya juu* terraces rather than a broader array of SWC measures. Depending on land use management practice, slope, and maintenance, the development of a *fanya juu* terrace takes 7–20 years (Bosshart, 1997; Herweg & Ludi, 1999; Hudson, 1988) (Fig. 2). For this study, we assumed that the development of a new terrace takes 10–13 years.

To analyse the temporal development of SWC technologies in the whole Gerda catchment, we used high-resolution satellite images from Google Earth, from March 2005 and 2013. On the satellite images, *fanya juu* terraces can be identified as linear elements (Fig. 3), and it can clearly be distinguished if a structure was built before 2005 or 2013. Because the exact age of the terraces could not be precisely determined using the Google Earth satellite images, we assumed that the visible terraces had been implemented on average over the previous 7–10 years. To establish a clear classification of the age of the SWC measures with only a few overlapping years, the implementation period of terraces visible on the Google Earth satellite image from 2005 was defined as from 1998 to 2008; and the implementation period of terraces visible on the Google Earth satellite image from 2013 was defined as from 2006 to 2014.

In a ground-truthing survey, we verified fields with no visible terraces on the satellite image and classified them as fields with no SWC measures.

With this information, we established for the land use categories maize, barley, teff, and bean four categories of *fanya juu* implementation; no implementation, implementation from 1986 to 1998, from 1998 to 2008, and from 2006 to 2014 (Table 3 and Fig. 4). With the terracing operation we incorporated these categories into SWAT and simulated for the reference model the presence of a terrace on a given HRU on the specified day (Arnold, Kiniry, et al., 2012a). Thus we adjusted the average slope length of a filed (TERR_SL) according to the slope category of the HRU (Haan, Barfield, & Hayes, 1994), set the USLE practice factor (TERR_P) to 0.6–0.4 (Haan et al., 1994; Hurni, 1985), and adjusted the curve number (TERR_CN) based on the soil hydrologic groups of the different soil types, to increase the infiltration rate (USDA SCS, 1986).

Table 2
Land use categories in the Gerda catchment and Minchet sub-catchment.

SWAT Land use type	WLRC[a] Land use classes	Gerda		Minchet	
		Area (ha)	% of total area	Area (ha)	% of total area
FRSE	Forest	450.36	9.77	12.33	12.14
RNGB	Bushland	373.46	8.10	1.43	1.40
AGRC	Homestead	381.35	8.27	4.23	4.17
PAST	Grassland	1174.73	25.48	14.02	13.81
CORN	Maize	513.12	11.13	12.74	12.55
BARL	Barley	696.82	15.12	28.01	27.58
TEFF	Teff	924.67	20.06	28.78	28.35
SOYB	Bean	74.92	1.63	–	–
BARR	Bare soil	20.55	0.45	–	–

[a] WLRC (2016).

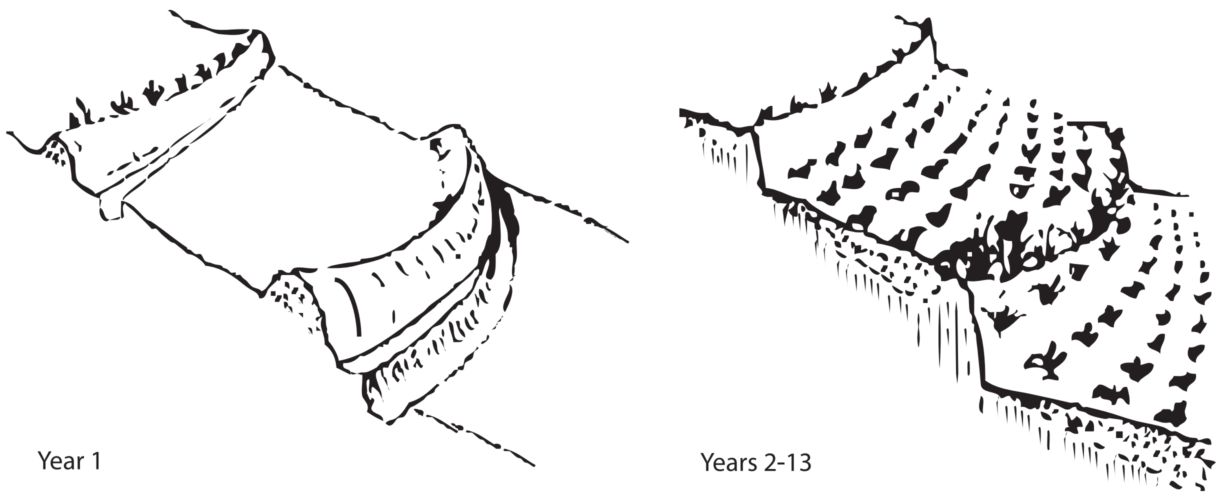

Fig. 2. Development of *fanya juu* terraces as simulated in SWAT. In year 1, newly constructed terraces reduce the average slope length (TERR_SL). In years 2–13, with the development of the new terraces, surface runoff decreases (TERR_CN) and cultivation practices change (TERR_P). Figure adapted from Hurni (1986).

2.3.3. Sediment, climate, and hydrological data

For the Minchet sub-catchment, sediment load, discharge, and weather data for 1984–2014, including maximum and minimum temperature, rainfall, and rainfall intensity, were available from the Water and Land Resources Information System (WLRC., 2016) with some gaps (Table 4). For the Gerda catchment, discharge and sediment yield data were available for 2013 and 2014 (the WLRC established a new observatory near Yechereka in 2012). Year-round flow observations were available (WLRC., 2016), while sediment load has only been measured during rainfall events, because the river is assumed to be relatively free of sediment during the dry season (WLRC., 2016).

Weather data derived from a global model, such as the Climate Forecast System Reanalysis (CFSR), were not used to fill gaps because of their unsatisfactory accuracy for catchments with the given climatic conditions (Roth & Lemann, 2016); Dile & Srinivasan, 2014). The data gaps for rainfall and temperature were therefore filled with the SWAT weather generator and potential evaporation was simulated with the Hargreaves method (Hargreaves, Hargreaves, & Riley, 1985).

2.3.4. Model setup

A drainage area of 100 ha was chosen as the threshold for the delineation of the catchment, as this approximately corresponds to the size of the Minchet sub-catchment. This resulted in 12 sub-catchments, of which the outlet of the Minchet sub-catchment was set manually in SWAT. In the whole catchment, 4011 HRUs were defined with a 0% threshold area, to get a detailed land cover map. The model simulated discharge and sediment load for every month in a 31 years period. A 2-year warm-up period allowed the model to initialize and stabilize reasonable starting values for the modelled parameters (Setegn, Srinivasan, Dargahi, & Melesse, 2009).

2.3.5. Sensitivity analysis and calibration setup

For sensitivity analysis, calibration, and validation of the modelled discharge and sediment load data, we used the SUFI-2 program (Abbaspour, 2015; Abbaspour et al., 2007, 2004). The calibration and validation period was chosen based on the discharge data available for the Gerda catchment and Minchet sub-catchment (Table 4). In a first step, a sensitivity analysis was performed to identify the key parameters for discharge and sediment load in the Minchet sub-catchment. The 18 most sensitive parameters were used to calibrate discharge and sediment load in the Minchet sub-catchment with four calibration iterations (1000 simulations each). In a second step, we validated the modelled discharge and sediment load with measured data from the Minchet sub-catchment (2010–2014). In a third step, we took the model with the calibrated and validated parameter band from the Minchet catchment and extrapolated it to the whole Gerda catchment, validating the simulated discharge and sediment load with measured data from the outlet of the Gerda catchment (2013–2014).

To quantify the goodness-of-fit of the calibration and validation, we used hydrographic observations and five model evaluation statistics—the widely used coefficient of determination (R^2) and

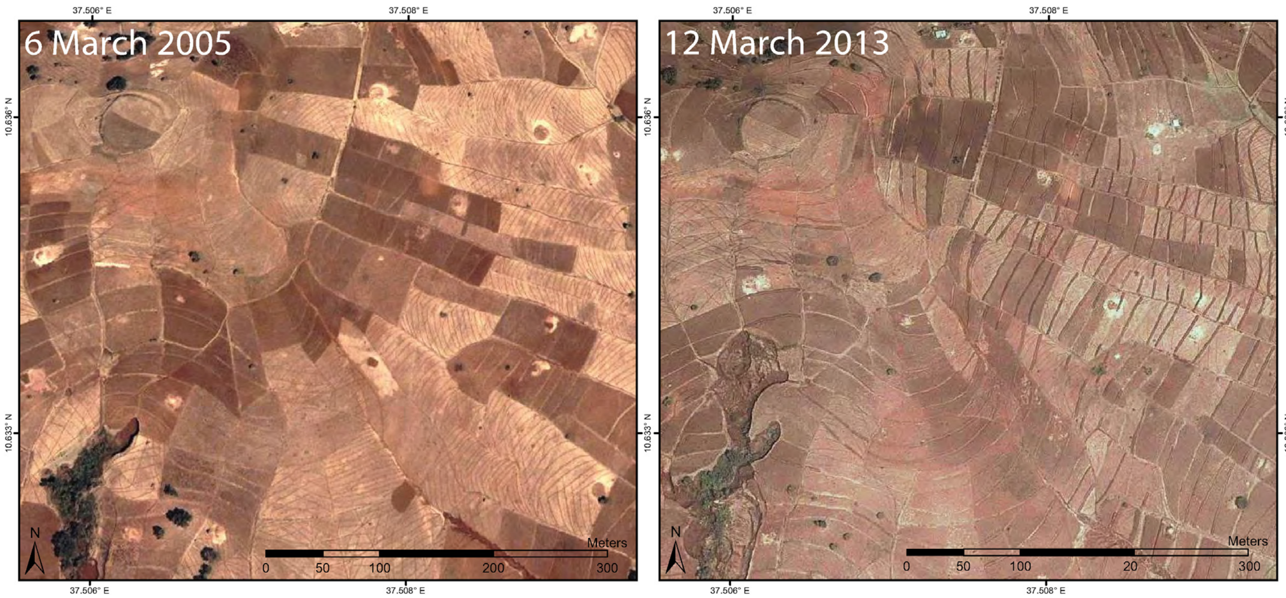

Fig. 3. Google Earth images from the years 2005 and 2013, showing new fanya juu terraces and an increasing gully (bottom left) in the Gerda catchment.

Table 3
Implementation of soil and water conservation measures on crop fields in the Gerda catchment. Crop fields cover roughly 48% of the total Gerda catchment.

Year of implementation[a]	Time span[b]	Crop area	Share of total Gerda crop area	Data source
1986	13 yrs.[c]	64 ha	2.9%	Bosshart, 1997, 1998; Herweg & Ludi, 1999
1998	11 yrs.	539 ha	24.4%	Google Earth (2005)
2006	11 yrs.	531 ha	24.1%	Google Earth (2013)
Crop fields with no SWC		1075 ha	48.6%	
Total crop area		2209 ha	100.0%	

[a] In SWAT: New terrace slope length (TERR_SL).
[b] In SWAT: Biennal decreasing surface runoff (TERR_CN) and USLE practice factor (TERR_P).
[c] Implementation was interrupted in 1990–1991.

Nash-Sutcliff efficiency (*NSE*), the *P-factor* and *R-factor*, and the objective function bR^2. The *P-factor* ranges between 0 and 1 and is the percentage of observed values inside the 95% prediction uncertainty band (95PPU), measured between the 2.5th and 97.5th percentiles. The *R-factor* is the thickness of the average 95PPU band divided by the standard deviation of the observed data (Abbaspour, 2015). A *P-factor* of 1 and *R-factor* of 0 is a simulation that exactly corresponds to measured data. In order to compare measured and simulated discharges, this study used the objective function bR^2 (Abbaspour et al., 2007) which makes it possible to account for discrepancies in the magnitude of two signals as well as their dynamics (Ficklin, Luo, & Zhang, 2013). It is a slightly modified version of the efficiency criterion defined by Krause, Boyle, and Bäse (2005):

$$bR^2 = \begin{cases} |b|R^2 & if|b| \leq 1 \\ |b|^{-1}R^2 & if|b| > 1 \end{cases}$$

where the coefficient of determination R^2 represents the discharge dynamics, and$b$ is the slope of the regression line between the observed and simulated runoff and ensures that overprediction and underprediction are properly reflected in the statistics. The minimum value of the objective function threshold was set to 0.6; according to Faramarzi et al. (2013a) and Schuol, Abbaspour, Srinivasan, Yang (2008a) and Schuol, Abbaspour, Yang, Srinivasan (2008b), bR^2 should be ≥ 0.6 to be sufficient.

According to Arnold, Kiniry, et al. (2012a) and Arnold, Moriasi, et al. (2012b), no absolute criteria for judging model performance have been firmly established in literature. Acceptable statistical measures are always project specific (Engel, Storm, White, Arnold, & Arabi, 2007). However, Moriasi et al. (2007) and Andersen, Refsgaard, and Jensen (2001) have proposed to judge a calibration and validation result as “very good” if $NSE > 0.75$ and $R^2 > 0.95$, “good” if $0.65 < NSE \leq 0.75$ and $0.85 < R^2 \leq 95$, and “satisfactory” if $NSE > 0.5$ and $R^2 > 0.7$. Satisfactory *P-* and *R-factors* depend on the quality of the measured data. If the measured data are of high quality, then the *P-factor* should be > 0.8 and *R-factor* < 1 (Abbaspour et al., 2007). But according to Schuol, Abbaspour, Srinivasan et al. (2008a) and Schuol, Abbaspour, Yang et al. (2008b), a *P-factor* > 0.5 and *R-factor* < 1.3 are still sufficient under less stringent model quality requirements. For sediment yield, a smaller *P-factor* value and larger *R-factor* value are also acceptable (Abbaspour, 2015).

2.3.6. Scenario modelling

To analyse the impact and the potential of SWC measures on blue and green water distribution and sediment yield in the Gerda catchment since 1986, two scenarios were simulated in SWAT, adapting the parameters TERR_CN, TERR_SL, and TERR_P. The scenarios were compared with the calibrated and validated reference model, which represents the SWC implementation identified using Google Earth satellite images and field reports (Bosshart, 1997, 1998; Herweg & Ludi, 1999).

Under the first scenario, SWC measures were implemented on every crop field in the Gerda catchment to observe simulated discharge and sediment loss if sufficient terraces were

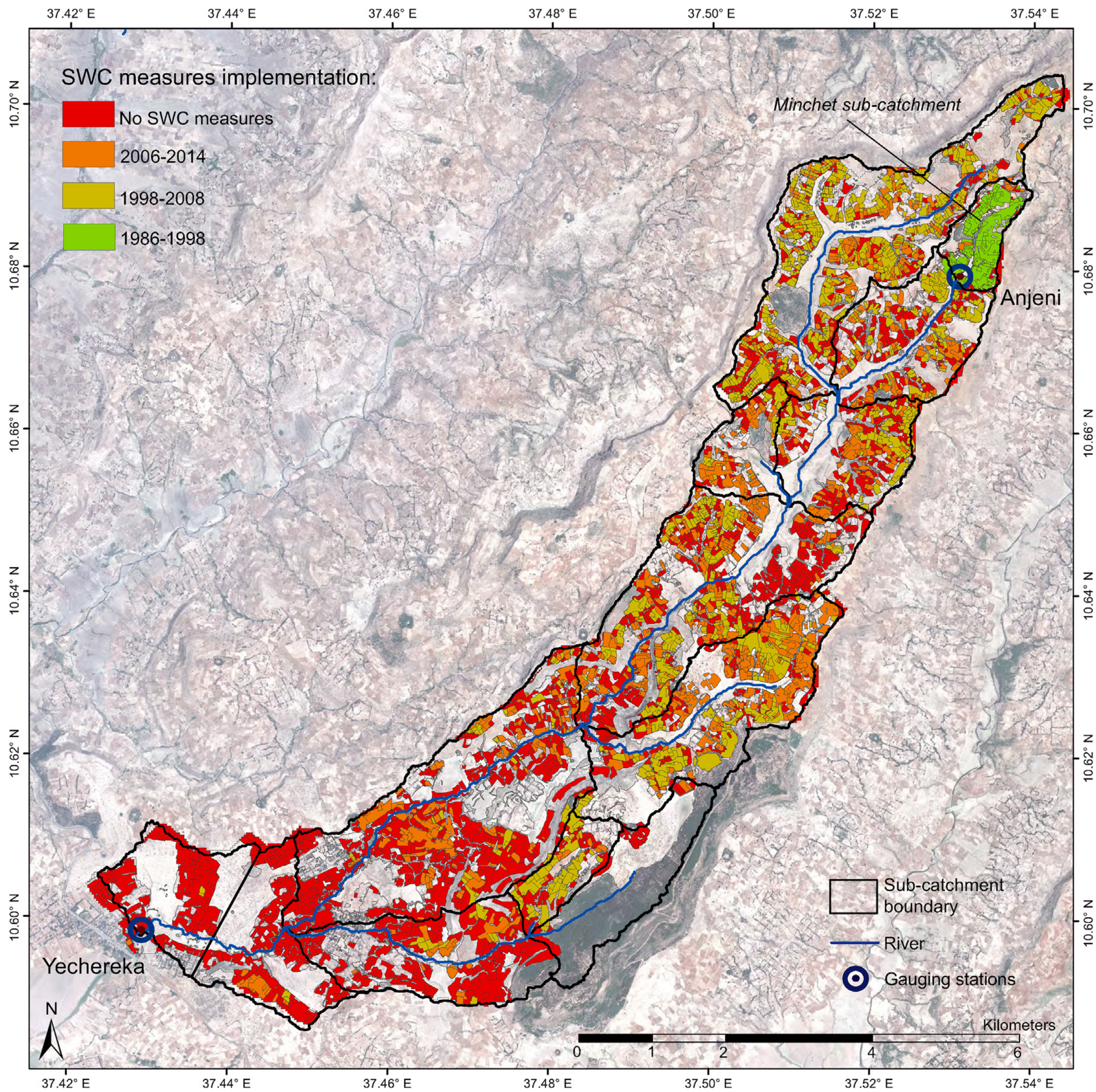

Fig. 4. Spatial and temporal implementation of soil and water conservation measures on crop fields in the Gerda catchment.

Table 4
Availability of weather and discharge data and calibration/validation periods.

	Minchet	Gerda
Precipitation and temperature	1984–2002, 2004–2014	2013–2014
Discharge	1984–1998, 2010, 2012–2014	2013–2014
Suspended sediment load	1984–1998, 2010, 2012–2014	2013–2014
Calibration period	1986–1998	
Validation period	2010–2014	2013–2014

Notes: A few data are missing for Gerda for 2013 and for Minchet for 1984 and 2008. The calibration period had a two-year warm-up period.

implemented in the study region. Under the second scenario, all SWC structures in the model were removed, to observe the biophysical situation if the terraces were not implemented at all.

Because the result is a data range and not a single value, the simulated monthly and annual discharge and sediment yield values are given as a 95% prediction uncertainty band (95PPU). In addition, we used the 50th percentile (M95PPU) to compare the values and to calculate the rainfall–runoff ratio (Faramarzi et al., 2013).

3. Results and discussion

3.1. Calibration and validation – uncertainty analysis

Discharge and sediment load were calibrated for the Minchet sub-catchment from 1986 to 2000 and validated from 2010 to 2014. The two parameters were also validated for the Gerda catchment, within which the Minchet sub-catchment is located (Fig. 1).

Sensitivity analysis with SUFI-2 – carried out by keeping the chosen parameters constant, while varying one parameter in a realistic range – showed that the most sensitive parameters for prediction of discharge were GW_DELAY (groundwater delay), RCHRG_DP (deep aquifer percolation fraction), and CN2 (runoff curve number). For prediction of sediment load, the most sensitive parameters were CN2 and all parameters used in the USLE, such as HRU_SLP (average slope steepness), USLE_K (soil erodibility factor), USLE_C (cover management factor), and USLE_P (support practice factor). It must be taken into account that these sensitivities not only depend on the interaction of the parameters, but also on the range that is assigned to the parameters, the fixed parameter, and

Table 5
Final calibration and validation statistics for the Minchet sub-catchment and the Gerda catchment.

	P-factor		R-factor		R^2		NSE		bR2	
	Cal	Val	Cal	Val	Cal	Val	Cal	Val	Cal	Val
Discharge										
Minchet	0.88	0.75	0.53	0.46	0.94	0.92	0.93	0.92	0.93	0.92
Gerda	–	0.68	–	0.84	–	0.94	–	0.92	–	0.94
Sediment										
Minchet	0.33	0.47	0.46	0.61	0.71	0.86	0.53	0.84	0.7	0.85
Gerda	–	0.63	–	1.48	–	0.79	–	0.70	–	0.78

Note: Cal = calibration, Val = Validation.

the chosen objective function (Abbaspour et al., 2007).

We selected 18 parameters (Table 6) for the calibration of discharge and sediment load. For USLE_C, we used different parameter ranges for the different land use systems. The ranges of the different parameters were reduced after each iteration until the calibration result was satisfying.

The overall goodness-of-fit for discharge calibration was "very good" for the Minchet sub-catchment with $NSE = 0.93$, $R^2 = 0.94$, and $bR^2 = 0.93$. The relative width of the 95PPU band was less than 1 (*R-factor* = 0.53), and it enclosed more than 80% of the measured data (*P-factor* = 0.88) (Table 5). Other studies on discharge modelling within the Minchet sub-catchment with other spatial data and shorter time series attained similar statistical results (Easton et al., 2010; Setegn et al., 2010). These good results can be explained by the constant hydrological response of the catchment, which makes modelling more straightforward; within the last 29 years, no big changes in the rainfall–runoff ratio have been observed (Fig. 7).

Sediment yield modelling is in general more sophisticated because of different accumulation and erosion processes, such as gullies (Fig. 3) and riverbank erosion, and the "second storm" effect, which can hardly be modelled (Abbaspour, 2015; Abbaspour et al., 2007; Arnold, Moriasi, et al., 2012b). Another challenge is that considerable uncertainty can be expected in measured sediment load data and that the SWAT model uses simulated sediment loads in small rainfall events, where no measured data are available. These might be a reason that only 33% of the observed data were bracketed by the 95PPU band (*R-factor* = 0.33) (Fig. 5). Another reason is the narrow 95PPU band (*P-factor* = 0.46) due to the implemented terraces in our model. On fields with terraces, the parameters USLE_P, SLSUBBSN (average slope length) and CN2 were not changed during calibration because these parameters are defined using terracing operation parameters (TERR_SL, TERR_P, TERR_CN), that were not used for calibration and validation. Fig. 4 shows that particularly in the Minchet Catchment almost every field has been conserved with terraces. Nonetheless, the statistics of the calibration of sediment yield are "satisfactory" with $R^2 = 0.71$, $NSE = 0.53$, and $bR^2 = 0.70$ (Table 5).

The validation period for the Minchet sub-catchment shows results similar to those of the calibration period. The statistics for discharge validation were "very good" with $NSE = 0.92$, $R^2 = 0.92$, and $bR^2 = 0.92$ and the *P-factor* and *R-factor* were in a good range, at 0.75 and 0.46, respectively.

Even with remarkably low measured sediment yield in 2013, compared with the high amount of precipitation and discharge (Fig. 6), validation of sediment yield in the Minchet sub-catchment resulted in better statistics than calibration ($R^2 = 0.86$, $NSE = 0.84$, and $bR^2 = 0.95$). But more observed data were also bracketed by the 95PPU band (*P-factor* = 0.47) with an *R-factor* of 0.61 (Table 5).

Subsequently, the model was extrapolated with the same parameter ranges to the whole Gerda catchment and validated by means of discharge and sediment load data from the outlet of the Gerda catchment. Because the discharge and sediment load data set covered less than two years, no prior calibration was executed. The two measured rainy seasons were very different and therefore challenging for modelling, because soil erosion processes are especially sensitive to fluctuation in precipitation level (Setegn et al., 2010). In 2013, annual precipitation at the Anjeni observatory was 2145 mm, the highest ever measured at that location, with a peak in July (539 mm) and August (480 mm). In contrast, in 2014, rainfall was only 1670 mm and distributed over the whole year, but with the highest ever measured monthly rainfall in March (138 mm) and May (257 mm).

Table 6
Description of input parameters selected for calibration, and final parameter ranges after calibration of discharge and sediment load.

Parameter name	Description	Min	Max
a__CN2.mgt	SCS runoff curve number for moisture condition II	−10	12
v__ALPHA_BF.gw	Baseflow alpha factor	0.7	0.95
v__GW_DELAY.gw	Groundwater delay (days)	10	150
v__GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	20	100
v__ESCO.hru	Soil evaporation compensation factor	0.4	0.75
v__GW_REVAP.gw	Groundwater "revap" coefficient	0.05	0.2
v__REVAPMN.gw	Threshold depth of water in the shallow aquifer required for "revap" to occur (mm)	10	200
v__CH_N2.rt	Manning's "n" value for the main channel	0.01	0.17
v__SURLAG.bsn	Surface runoff lag coefficient	4	5
v__RCHRG_DP.gw	Deep aquifer percolation fraction	0.05	0.7
r__OV_N.hru	Manning's "n" value for overland flow	−0.2	0.05
r__SLSUBBSN.hru	Average slope length	−0.1	0.17
r__HRU_slp.hru	Average slope steepness	−0.05	0.3
v__SPCON.bsn	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing	0.0001	0.00015
v__USLE_P.mgt	USLE support practice factor	0.55	0.7
r__USLE_K.sol	USLE soil erodibility factor	0	0.25
r__USLE_C.plant.dat	Minimum value of USLE cover-management factor applicable to the land cover/plant		
AGRC	*Homestead*	−0.05	0.15
FRSE	*Forest*	−0.05	0
PAST	*Grassland*	−0.1	0
RNGB	*Bushland*	−0.15	0
Other	*Maize, barley, teff, bean, bare soil*	0	0.25
r__SOL_AWC.sol	Available water capacity of the soil layer	−0.05	0.2

Note: In the parameter names, a__ means the given value is added to the existing parameter value; r__ means the existing parameter value is multiplied by (1 + a given value); v__ means the existing parameter value is to be replaced by the given value (Abbaspour, 2015).

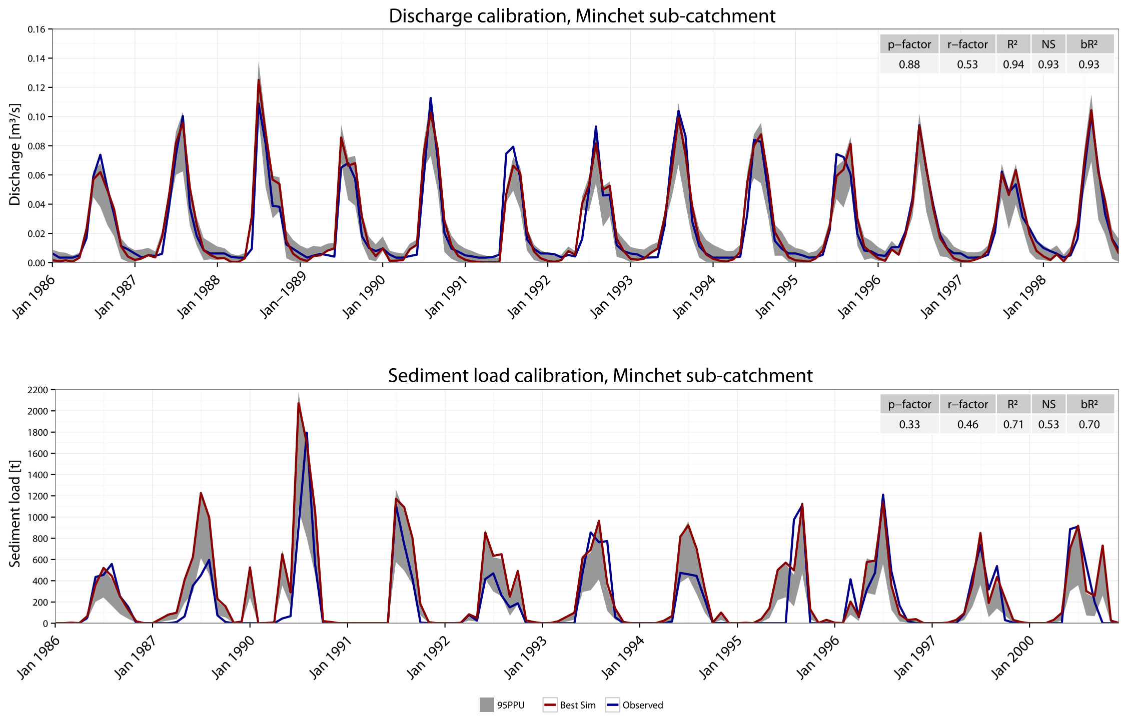

Fig. 5. Model calibration results: Observed discharge and sediment load with 95% model uncertainty (95PPU), and best estimation (Best Sim) at Anjeni (Minchet sub-catchment) gauging stations.

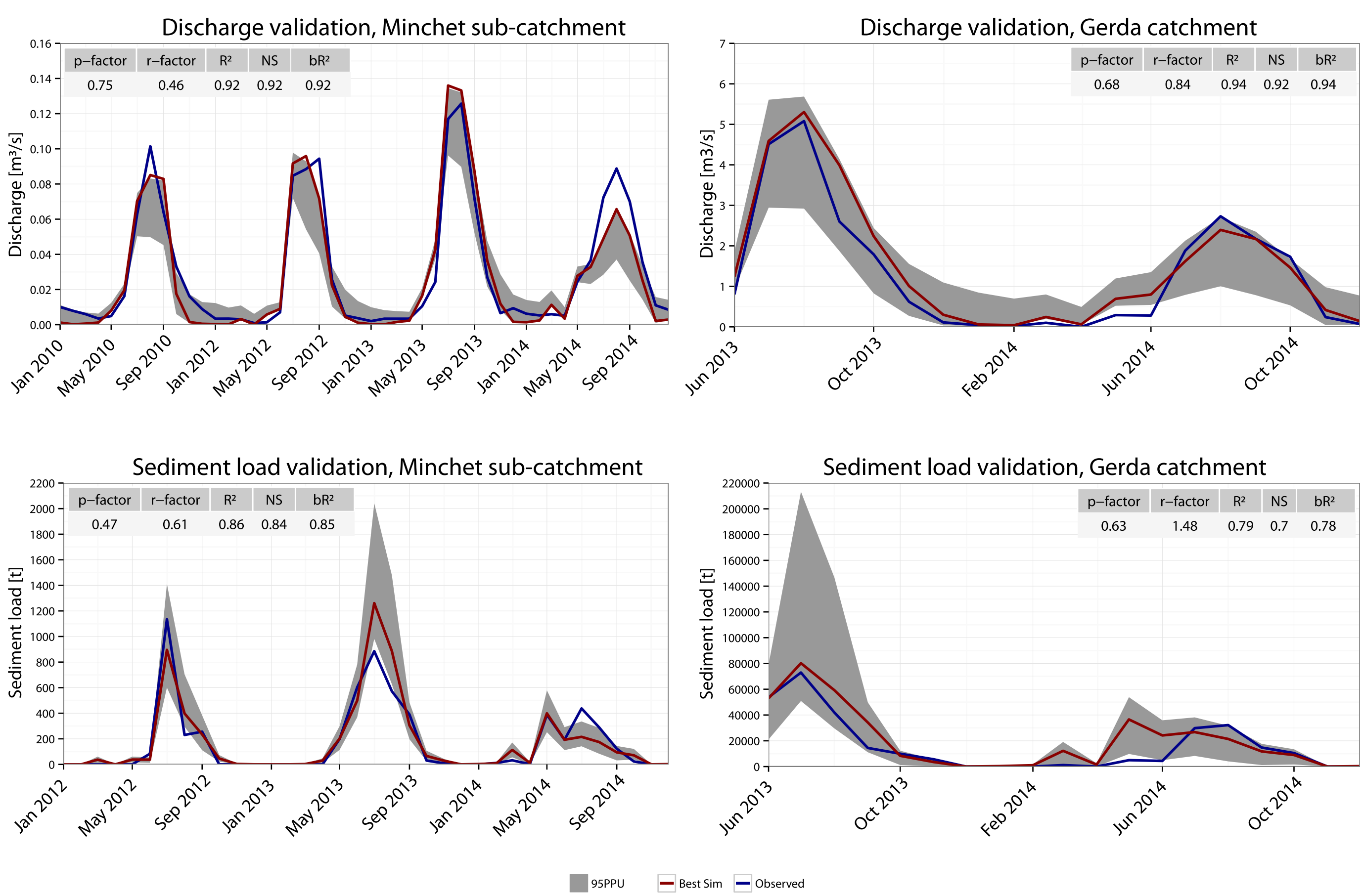

Fig. 6. Model validation results: Observed discharge and sediment load with 95% model uncertainty (95PPU), and best estimation (Best Sim) at Anjeni (Minchet sub-catchment) and Yechereka (Gerda catchment) gauging stations.

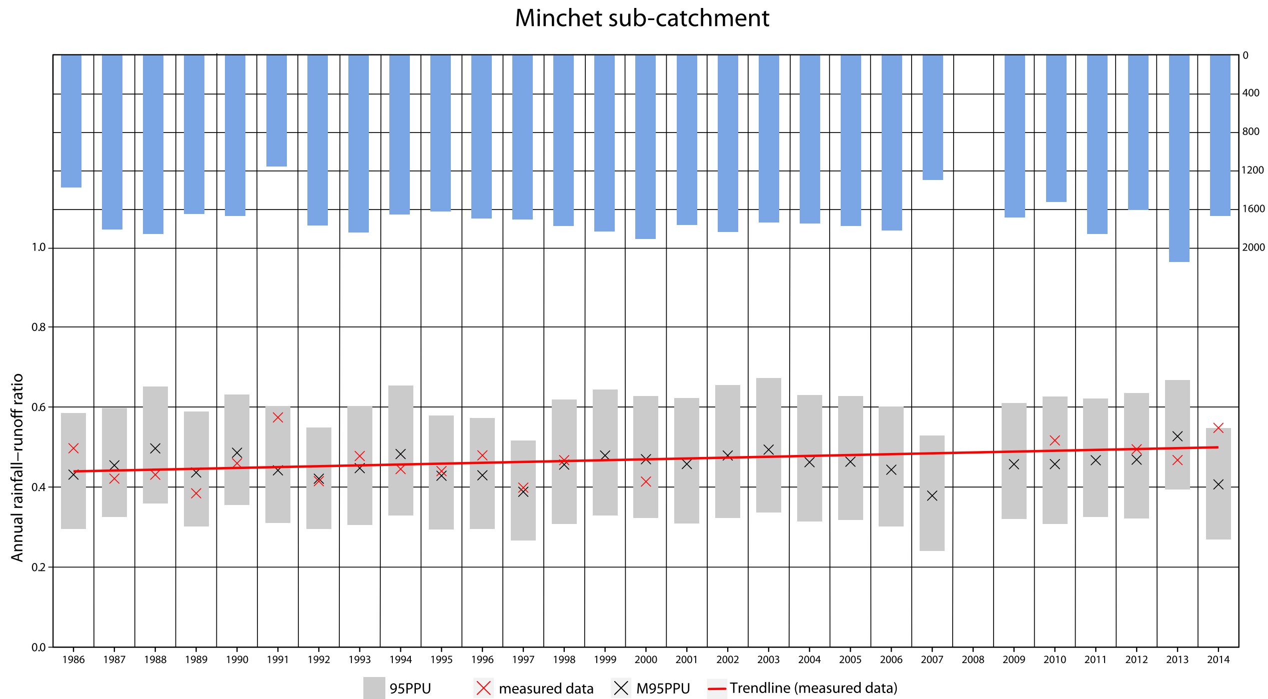

Fig. 7. Annual precipitation and the trend of the rainfall-runoff ratio in the Minchet sub-catchment over 29 years: Measured data, 95% model uncertainty (95PPU), and 50th percentile out of 1000 simulations (M95PPU).

Table 7
Comparison of modelled and measured sediment yield, sediment load, and rainfall – runoff ratio in the Gerda catchment and Minchet sub-catchment for the two scenarios and the reference model.

	Gerda				Minchet			
	Scenario 1[c]	Scenario 2[c]	Reference[a,c]	Measured	Scenario 1[c]	Scenario 2[c]	Reference[a,c]	Measured
Average annual sediment yield (t/ha), 1986–2014	17.7	37.8	33.5	–	13.8	44.3	19.3	21.8[b]
Average annual sediment load (t), 1986–2014	85,291	182,146	161,426	–	1565	5024	2189	2,472[b]
Annual sediment yield (t/ha), 2014	14.0	32.6	23.4	21.2	11.6	40.8	12.7	14.7
Annual sediment load (t), 2014	67,462	157,090	112,758	102,156	1315	4627	1440	1667
Average annual rainfall – runoff ratio, 1986–2014[d]	0.351	0.359	0.355	–	0.449	0.468	0.454	0.465[b]

[a] In the reference model, sediment load was modelled based on observed SWC measures.
[b] Numbers represent average values for 1986–1998, 2010, and 2012–2014.
[c] The 50th percentile out of 1000 simulations (M95PPU).
[d] Without 2008.

The overall goodness-of-fit for discharge validation was “very good” with $NSE = 0.92$, $R^2 = 0.94$, and $bR^2 = 0.94$ and sufficient *P-* and *R-factors* of 0.68 and 0.84, respectively. The statistics for sediment yield were also “satisfactory” to “good” ($R^2 = 0.79$, $NSE = 0.7$, and $bR^2 = 0.78$), even though the fluctuations of the measured sediment yield during the extreme rainfall periods could not be reproduced properly (Fig. 6). This resulted in a greater degree of uncertainty with a larger *R- factor* (1.48) and a *P-factor* of 0.63 (Table 5).

These validation results show that for SWAT a parameter transfer is indeed applicable in the larger Gerda catchment.

3.2. Impact of SWC measures on discharge

The parameters pertaining to SWC were predefined using SWAT’s terracing operation. For the reference model, these parameters (TERR_SL, TERR_P, TERR_CN) were adjusted for the different HRUs according to their soil, land use, and slope, and adjusted over 10–13 years, the time required to implement a terrace (Bosshart, 1997; Herweg & Ludi, 1999; Hudson, 1988). The time frames for implementation were categorised, based on Google Earth images (Fig. 3) and observations (Herweg & Ludi, 1999), to 1986–1998, 1998–2008, and 2004–2014.

Looking at the annual drainage ratio from 1984 to 2014 in the Minchet sub-catchment, where SWC measures have been implemented on almost every crop field, it can be seen that the percentage of rainfall drained through the river increased slightly (Fig. 7). The increase of available blue water for downstream stakeholders can be explained by an increase in the annual amount of rainfall and not by a decrease in green water. Under the present hydro-climatic conditions, the rainfall–runoff ratio is increasing with more precipitation, due to saturation-excess processes (Lemann et al., 2016; Liu et al., 2008).

For the two simulated scenarios, trends calculated based on the average annual M95PPU revealed almost no differences in discharge. The simulated average annual discharge under scenario 1 was only 2.8% lower over the last 29 years than that of scenario 2 (Table 7). In the reference model, which is the observed situation, with 51.4% of all crop fields conserved (Table 2), the average annual amount of discharge was only 1.2% lower than in scenario 2 (Table 7

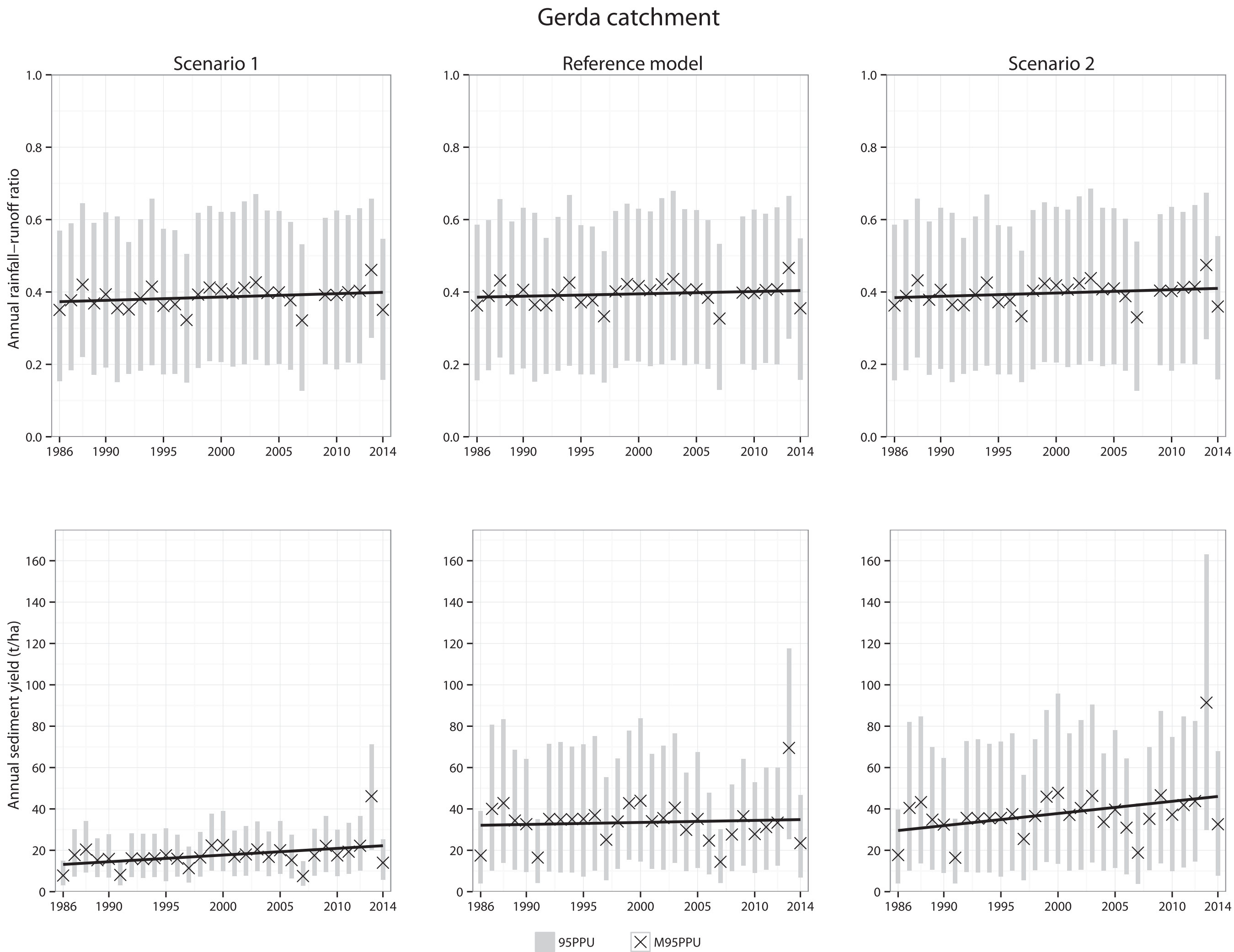

Fig. 8. Comparison of the 95% model uncertainty (95PPU) and the 50th percentile out of 1000 simulations (M95PPU) of the annual rainfall–runoff ratio and sediment load of the reference model and two scenarios for the Gerda catchment.

and Fig. 8).

This means that the amount of blue water for downstream users is unlikely to decrease noticeably with the implementation of additional SWC measures in this high-rainfall agro-climatic zone, even if the whole watershed is conserved with terraces. Similar catchment-level results have been observed in the Duhe Basin in China (Brandsma, van den Eertwegh, Droogers, Bai, & Zhang, 2013), where implemented bench terraces on agricultural land caused only a slight decrease in available blue water (4.5%) over an area with a mean annual precipitation of 973 mm.

Contradicting results in other studies (Adimassu et al., 2012; Amare et al., 2014; Herweg & Ludi, 1999) occurred because the study site was in a different agro-climatic zone, featuring much less rainfall, or because the study adopted a different approach in which only experimental plots were considered and therefore lateral flows were excluded. Hurni et al. (2005) stated that the water conservation effect on fields with implemented SWC measures can be explained as the measures resulting in enhanced base flow and a slightly increased groundwater portion of the catchment runoff. In this agro-climatic zone with annual rainfall amounts upwards of 1700 mm, groundwater storage will be filled during the rainy season and new SWC measures will thus primarily increase lateral flows, and not influence the groundwater proportion. Further, in the modelled results it can be observed that there are only negligible differences in annual actual evapotranspiration between scenarios 1 and 2. Even without SWC, the actual evapotranspiration is increasing during the rainy season to almost 100% of the potential evapotranspiration; the possibility of increasing actual evapotranspiration is therefore rather small. The amount of green water over a year is thus more or less stable, and surplus rainfall is leaving the catchment through the river. But there is still a need to increase water productivity (crop yield per unit of water) and minimizing non-productive green water (Falkenmark & Rockström, 2006). With additional SWC measures upstream, stakeholders can increase their agricultural yields without reducing the amount of blue water available to downstream stakeholders.

3.3. Impact of SWC measures on sediment yield

Over the last 29 years, the sediment yield of the Gerda catchment as a whole did not show a striking trend, although there were wide variations between years (Fig. 8). The picture is different for the sediment yield of the Minchet sub-catchment (Fig. 9). Here, on average almost half as much annual sediment yield can be expected as in the whole Gerda catchment and it has been decreasing over the last 29 years. But the 95PPU of the Gerda catchment is also

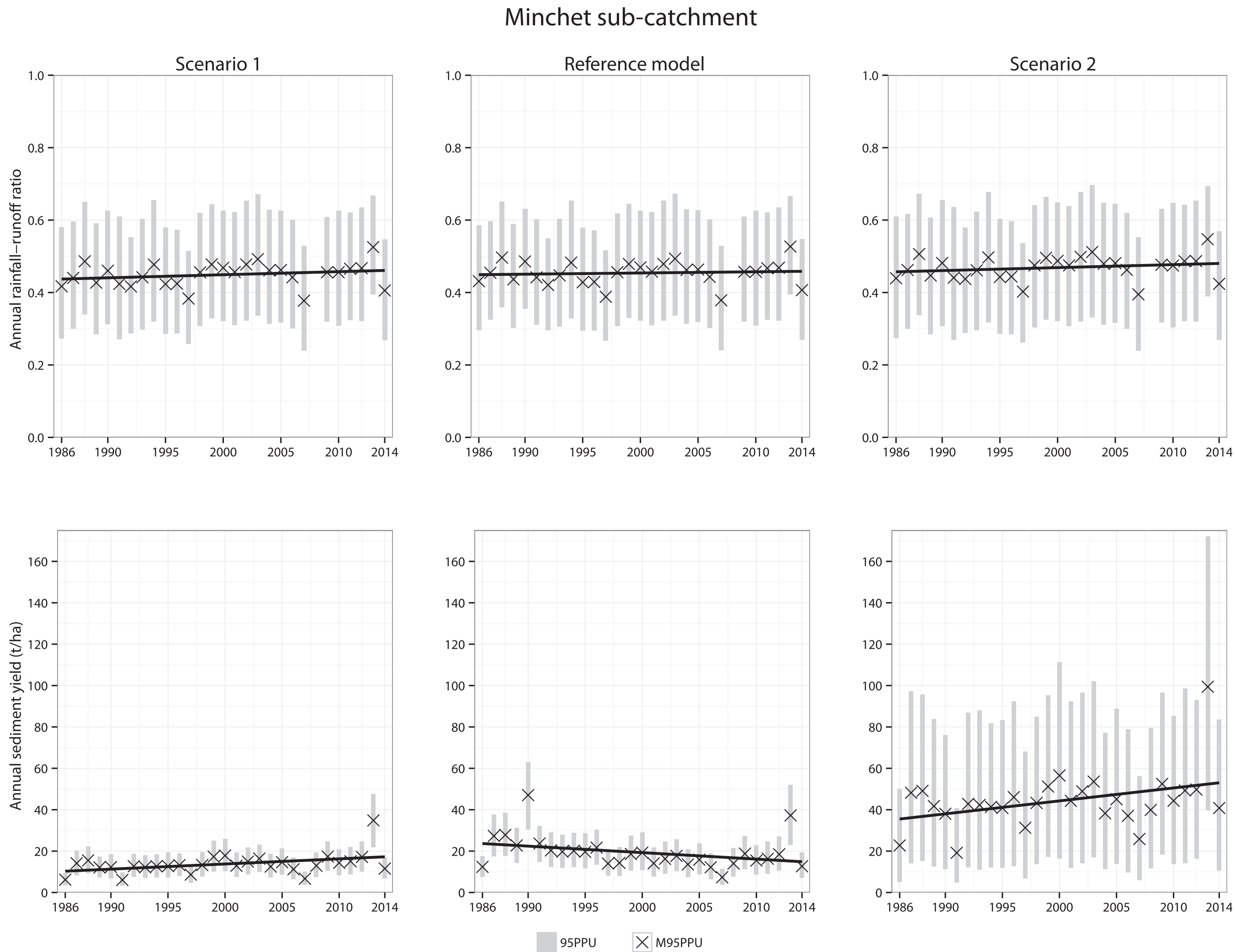

Fig. 9. Comparison of the 95% model uncertainty (95PPU) and the 50th percentile out of 1000 simulations (M95PPU) of the annual rainfall–runoff ratio and sediment load of the reference model and two scenarios for the Minchet sub-catchment.

larger than of the Minchet sub-catchment. These differences can be explained by the presence of more conserved fields in the Minchet sub-catchment. While SWC reduces soil erosion, parameters used to model SWC measures in SWAT have a single value and not a range and thereby reduce the 95PPU band. This is also the reason for the different widths of the 95PPU band for scenarios 1 and 2.

Being aware of the uncertainty of the results, which depend on the width of the 95PPU, we quantified the annual sediment load with the M95PPU to give an idea of the extent to which sediment can be retained using SWC measures. We modelled an average annual sediment yield of 33.5 t/ha for the Gerda catchment and 19.3 t/ha for the Minchet sub-catchment over the last 29 years. The annual average measured sediment yield for the 14 measured years in the Minchet sub-catchment is 21.8 t/ha (Table 7).

To show the influence of the implemented SWC measures in the Gerda catchment over the last 29 years, Figs. 8 and 9 compare the 95PPU band of the annual sediment load of the reference model with scenarios 1 (full SWC) and 2 (no SWC) for the Gerda catchment and Minchet sub-catchment. In contrast to the reference model, both scenarios show an increasing trend, but at different levels. In the Gerda catchment, comparison of the two scenarios indicates that SWC can reduce the average annual sediment yield by more than 20 t/ha or keep back, on average, more than 96,000 t of sediment per year.

From 1986 to 1998, when mainly the Minchet sub-catchment was conserved with *fanya juu* terraces, the reference model of the Gerda catchment was similar to scenario 2. With the implementation of more terraces, the 95PPU band of the reference model approximated scenario 1 (Fig. 8). This explains why sediment yield did not increase in the reference model over the last 29 years. Unlike in scenarios 1 and 2, new terraces have been implemented over time and surface runoff and erosion have been reduced, while precipitation and discharge have increased.

Comparing the sediment yield of the reference model with scenario 2 in the Gerda catchment it can be seen that, with the SWC measures implemented over the last 29 years, on average 4.3 t/ha per year could be retained. This is equal to an average annual sediment load of more than 20,000 t. Considering only the sediment yield data for 2014, when all the current SWC measures in the Gerda catchment have been implemented, and comparing the reference model with scenario 2, a reduction of 30% (or 44,332 t) sediment loss can be observed. But there is additional potential: if in 2014 SWC measures would have been implemented on every crop field (scenario 1), another 45,300 t of sediment could have been retained in the Gerda catchment. Also Brandsma et al. (2013) modelled SWC management scenarios on catchment level with a sediment loss reduction of up to 50% on agricultural land in the Duhe Basin in China. Similar or even higher reduction of sediment loss with implemented SWC measures could be measured by Amare et al. (2014) and Herweg and Ludi (1999) on experimental plots in the same agro-climatic zone. But when comparing results from plot and catchment level, it has to be taken into account that on catchment level not every field is cultivated and e.g. forest and grassland generate in general less soil loss than cultivated fields, with or without SWC measures.

4. Conclusion

In this study, we assessed the impact of SWC measures on the availability of blue water for downstream stakeholders, availability of green water for rainfed agriculture, and amounts of sediment leaving a catchment in the upper Blue Nile basin. To do so, we compared different Google Earth satellite images and reports to determine spatial and temporal implementation of SWC measures in a small-scale, and a meso-scale catchment. SWAT was used to simulate hydrological and sedimentological processes, and SUFI-2 was used to calibrate and validate the simulation against measured river discharge and suspended sediment load. Based on the calibrated parameter ranges, we simulated two scenarios for the last 29 years: one with no SWC measures and one in which SWC measures were implemented on every crop field.

Comparisons of the different scenarios showed that new SWC measures are not influencing discharge significantly in these hydro-climatic conditions, even if surface runoff is decreasing. Without reducing blue water for downstream stakeholders, upstream farmers can increase water productivity and minimize non-productive green water. At the same time, enhanced infiltration and lateral flow decreased erosion of fertile soil and suspended sediment load in the river. This can lead to more sustainable agriculture in the headwater catchments and less sedimentation in the dams along the Nile River. Until recently, SWC measures have been implemented on 50% of all crop fields in the study area, and sediment has been reduced by almost 30%. But there is still the potential to reduce sediment yield by another 30%.

These results do not apply to the whole upper Blue Nile basin, due to variation in rainfall patterns and amounts. In drier regions, SWC measures may lead to less discharge due to higher evapotranspiration and groundwater depletion rates. But this study shows the potential of SWC measures in the Wet Wenya Dega agro-climatic zone to reduce sediment yield and increase green water productivity without decreasing blue water availability for downstream stakeholders.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apgeog.2016.06.008.

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