Calibration and validation of the CONCEPTS model for predicting gully erosion and evaluating gully control measures in the sub-humid highlands of Ethiopia

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ABSTRACT

The objective of this study was to calibrate and validate the CONCEPTS model for simulating gully expansion and for evaluating the effects of protection measures on gullies in the sub-humid Debre Mawi watershed near Lake Tana, Ethiopia. The watershed drains an area of 608 ha, and its elevation ranges from 2194 to 2362 m above sea level, receiving annual average total rainfall of 1240 mm. We collected data on boundary material stratigraphy (four layers) and its associated grain-size distributions, bulk density, and shear strength. The model was calibrated and validated against the observed changes in width and bed elevation of a 389 m long, 23 m wide, and 4.7 m deep gully during the 2013 (calibration-period) and 2014 (validation-period) rainy seasons. The average values for calibrated erosion-resistance parameters for the four layers were: cohesion 12.6 kPa, which is about half of that of the measured; internal friction angle 20.8°, which increased by 30% from that of the measured; soil critical shear stress 0.67 Pa; soil erodibility $1.22\text{x}10^{-7}$ $m^3(N\cdot s)^{-1}$; and suction angle 10°. The simulation results showed that the model predicted the sidewall erosion more accurately (R^2 = 0.99, NSE = 0.99) and fairly predicted the change in bed elevation (R^2 = 0.88, NSE = 0.98). Based on the calibrated values, we used the model to evaluate the effect of gully erosion control measures. Considering the bank on one of the 35 cross sections of the gully, reshaping the sidewall slope to a slope of 45° reduced the bed erosion by 25% and sediment yield by 33%. Targeted bed and bank toe protection reduced sediment yield by 90% and sidewall erosion by 100%. When the groundwater table is lowered from 0.1 m to 0.7 m below the ground surface, the sidewall erosion reduced by 83%. that the results suggest that CONCEPTS can successfully simulate gully erosion based on the calibrated values, which fall within the typical range expected for the soils surrounding the gully.

Keywords: Bank failure, Blue Nile, conservation, shear strength

INTRODUCTION

Gully erosion is one of the most damaging forms of soil erosion, which can be expressed in has major benefits in designing cost effective erosion control measures (Langendoen et al. 2014).

The physically-based computer model CONCEPTS is used to simulate the evolution of incised or incising streams and to evaluate the long-term impact of rehabilitation measures to stabilize stream systems and reduce sediment yield (Langendoen & Simon 2008; Langendoen et al 2009). The model simulates the three main processes that shape incised streams: hydraulics, sediment transport and bed adjustment, and streambank erosion, which, in turn, comprises the two processes responsible for the retreat of cohesive streambanks: hydraulic erosion and gravitational mass failure (Langendoen and Alonso 2008). The validation studies against laboratory and field experiments demonstrated that CONCEPTS is able to simulate the long-term retreat of stream banks (Langendoen & Simon 2008). Stream bank failure occurs when gravitational forces that tend to move soil downslope exceed the forces of friction and cohesion that resist movement. Banks may fail by four distinct types of failure mechanisms: (1) planar failures; (2) rotational failures; (3) cantilever failures; and (4) piping and sapping failures of which CONCEPTS performs stability analyses of planar and cantilever failures (Langendoen and Alonso 2008), which are most widely observed in the Ethiopian highlands (Zegeye et al. 2016). Bank material may be cohesive or non-cohesive and may comprise numerous soil layers. The detachment of cohesive soils is calculated following an excess shear-stress approach. An average shear stress on each soil layer is computed. If the critical shear stress of the material is exceeded, entrainment occurs. CONCEPTS is able to simulate the development of overhanging banks. The risk of stream bank failure in CONCEPTS model can be expressed by a factor of safety (F_s) representing the ratio of resisting-to-driving forces or moments based on Equation 1.

$$F_s = \frac{\sec\beta \sum_j (c'_j L_j + [N_j - U_j] tan\, \varnothing'_j\ )}{\tan\beta\ \sum_j W_j - F_w} \qquad (Equation\ 1)$$

where is index of a vertical slice in a failure block, is normal force acting on the base of a slice, is horizontal component of the hydrostatic pressure acting on the bank face, ′ is effective cohesion, is length of a slice base along the failure plane, is soil weight, β is failure-plane angle, is pore-water force, and $\varnothing'$ is angle of internal friction.

Langendoen et al (2014) tested the BSTEM and CONCEPTS models in the Debre Mawi watershed for their ability to simulate gully-forming processes, and carried out preliminary simulations to develop effective gully stabilizing measures in Vertisols, which was the predominant soil type in the study area. According to the preliminary test results of the two models by Langendoen et al. (2014), BSTEM predicted stable bank slopes between 75 degrees for a bank height of 3 m to 47 degrees for a bank height of 6 m; and CONCEPTS predicted flow velocities up to 8 m s^{-1} and shear stresses as large as 400 Pa on the upstream end of the regraded gully head. However, both models were not calibrated and validated for Ethiopian climatic and hydrologic conditions. Model calibration and validation are necessary and critical steps in any model application (Love & Donigian 2002; Arnold et al. 2012). Love and Donigian (2002) also explained "For most watershed models, calibration is an iterative procedure of parameter evaluation and refinement, as a result of comparing simulated and observed values of interest". Model validation, an extension of the calibration process, is conducted to assure that the calibrated model properly assesses all the variables and conditions. Therefore, the objectives of our study were to calibrate and validate the CONCEPTS computer model, and to evaluate gully controlling techniques based on the validated model in (sub) humid Ethiopian conditions.

MATERIALS AND METHODS

Description of the Study Area

The study was conducted in the sub-humid Debre Mawi watershed, located about 30 km south of Lake Tana at 11°20'13" to 11°21'58" N and 37°24'07" to 37°25'55" E. The watershed drains an area of 608 ha, and its elevation ranges from 2194 to 2362 m above sea level. The slope in the watershed ranges from 1 to 2% for flat bottom lands and from 8 to 30% elsewhere. Rainfall is unimodal and its annual average is 1240 mm. More than 70% of the annual rainfall occurs during June, July, and August. The average maximum annual temperatures range from 22 to 29.4°C while the minimum range from 5.4 to 12.1°C.

The watershed is underlain by shallow, highly weathered and fractured basalt. In the watershed, the basalt is covered with a black clay layer becoming thicker down slope. The black clay is generally underlain by brown silt loam that can be highly compacted, followed by a saprolithic layer (Tebebu et al 2010). The soils consist mainly of Nitisols, Vertisols, and Regosols (Amare et al. 2014). Nitisols dominate the upper landscape positions of the watershed and are suitable for crop production, while Regosols occur on steep and highly degraded slopes. In foot slope positions, fine-textured soils are found with undifferentiated Vertisols and is suitable to cultivate Tef ( ), chickpea ( ) and grass pea ( ).

While the watershed is located in the most productive region of the country, the land is being devastated by networks of gullies (Figures 1 and 2) and to a lesser degree by sheet and rill erosion on the cultivated slopes (Zegeye et al. 2010; Langendoen et al. 2013; Amare et al. 2014; Langendoen et al. 2014). The gully networks are mainly found in the periodically saturated bottom lands (Tebebu et al 2010; Zegeye et al 2016) and in some upland areas where lava dykes in the watershed affect the hydrology, forcing subsurface flow to the surface and causing saturated source areas (Tebebu et al 2010).

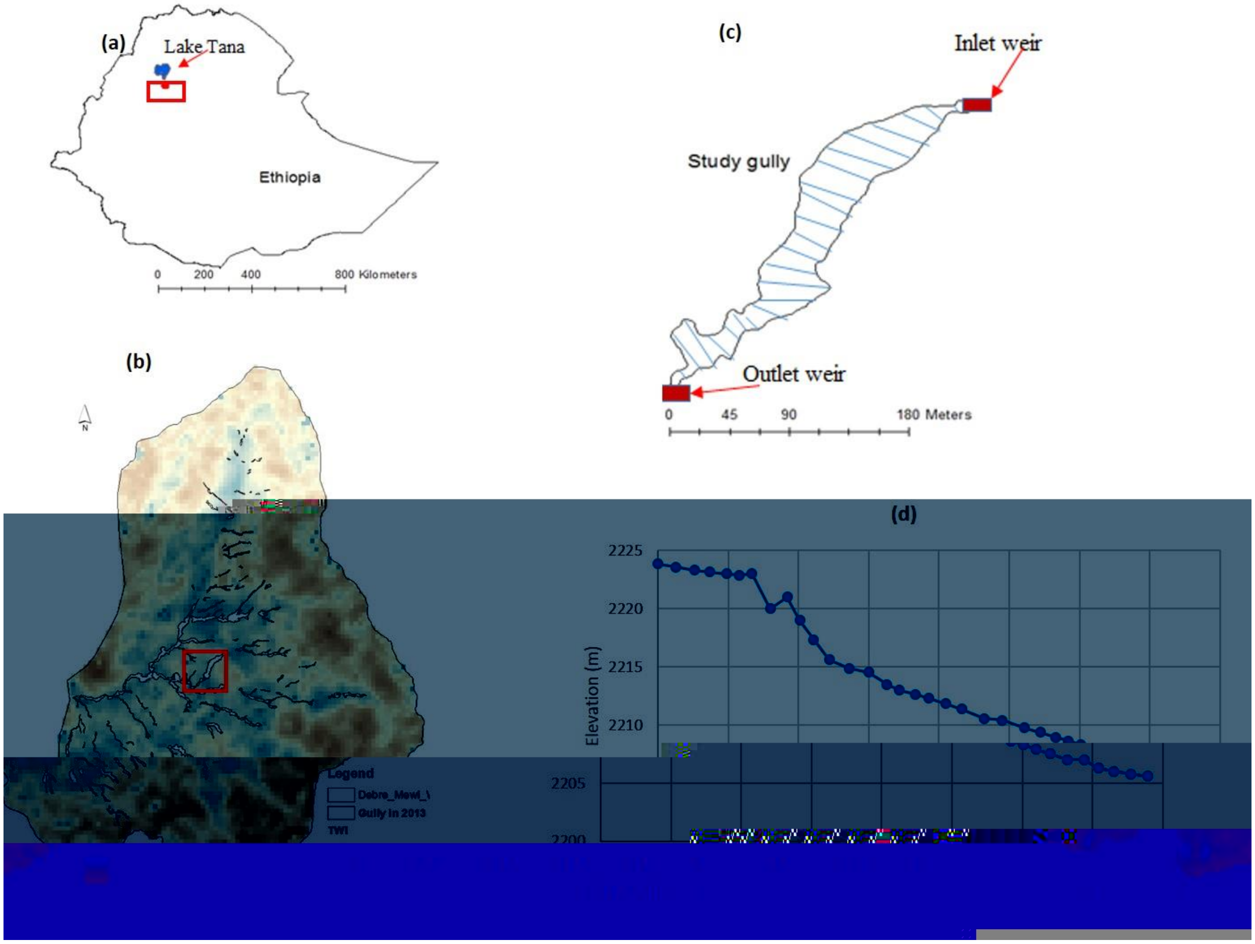

Figure 1. Gully networks digitized from aerial imagery in 2013 in the Debre Mawi watershed (Zegeye et al. 2016). (a) Location of Debre Mawi watershed. (b) Map illustrating the relationship between location of gully formation and change in topographic wetness index (TWI). (c) The cross-sectional lines drawn in the study gully indicate the approximate locations of a sub-set of cross sections, (d) Plot of bed elevation at all 35 cross-sectional points versus gully length.

Characteristics of the Test Gully

The CONCEPTS model was employed to simulate the evolution of one selected gully, hereafter called G6, located at the Vertisols areas of periodically saturated bottom lands of the watershed with elevation ranging from 2215 to 2227 m and a channel slope of 0.03 m m^{-1}. The upstream catchment of the gully is about 17.4 ha. The surface area of G6 at the start of the study (in 2013) was 9110 m^{2} and the average depth was about 5 m. The modeling study reach gully extends from cross section number 1 to 35 with a total length of 389 meter (Figure 1) and contains 35 surveyed cross sections. The gully had two rectangular weirs at its inlet and outlet to measure discharge and sediment concentration.

Figure 2. Pictures illustrating dominant types of bank failure observed in the Debre Mawi watershed; the left photo is of the study gully and the right photo is a headcut of a nearby gully located at a distance of 50 m.

Procedures of Calibration and Validation

We calibrated and validated a CONCEPTS model using input data collected in the field. We calibrated this model for two reasons: (1) CONCEPTS was primarily developed for stream systems in the mid-continental United States (US), whose climate, soil and hydrology are different from the (sub) humid Ethiopian highlands; and (2) because it is generally impossible to characterize all the variability of the model parameters throughout a study reach. The input parameters for the model are spatially and temporarily averaged values rather than point values obtained from field measurements. As a consequence of this discrepancy in scales, lack of data, and measurement errors, the model has to be calibrated.

The modeling process is comprised of three main phases. The first phase in this process includes data collection, model input preparation and a sensitivity analysis of the input parameters. Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs (parameters). It is necessary to identify key parameters and the parameter precision required for calibration and validation processes. This is the phase in which the model is evaluated to assess whether it can reasonably represent the gully erosion mechanics. The second phase is calibrating and validating the model based on the data determined in the first phase. Model validation is the next step after calibration process. This is the phase where the predicted value was compared with the observed data that were not used for calibration. We used the 2013 observed values for calibration; once the final parameter values were developed through calibration, simulation was performed for the period of 2014 observed values and goodness-of-fit between observed and simulated values was reassessed. The third phase includes the ultimate use of the model, as a decision support tool for gully management.

Model Setup

Cross section setup

A total of 35 cross sections were surveyed before and after the rainy seasons of 2013 and 2014 using a combination of total station and tape meter measurements. To determine the more optimal spacing between two consecutive cross-sections, the distance ratio between the two consecutive cross sections was calculated based on Equation 2 (Langendoen 2000).

$$0.65 < \frac{\Delta x_i}{\Delta x_{i+1}} < 1.5 \qquad (Equation\ 2)$$

where is the cross section index, and Δ is the distance between two consecutive cross sections

CONCEPTS supporting software provides a Microsoft Excel macro to interpolate a cross section to optimize spacing between cross sections. In our model the distance between consecutive cross sections ranged from 8 to12 m, and the distance ratio varied between 0.76 and 1.44, which is in the range of Equation 2. When the cross section spacing is outside this range, the model may not predict the gully morphology adequately, and could introduce numerical instabilities.

Bank toe setup

Failed bank material is deposited at the toe of a bank, and consequently removed by fluvial erosion. Simulated flow depths in the gully were typically fairly small, and insufficiently submerged the failed material to initiate its removal by the flowing water. We therefore lowered the elevation of the toe that is flattened the gully bed in a cross section, so that the toe is submerged and the flow can erode any failed material depending on erosion-resistance of the bed and the failed material. The tension crack depth was measured in the field and used as input in the model.

Base flow setup

The measured base flow was as low as 0.0005 m^3 s^{-1}. Such low value created numerically flow instability at all cross sections in the reach. By increasing the base flow by an order of magnitude, it reduced the numerical instability along the reach. This adjustment produced a reasonably better simulation result, and was still small enough to not erode the gully boundary materials.

Calibration approach

Conventionally, calibration is performed manually and consists of changing model input parameter values to produce simulated values that are within a certain range of the measured data (Tague et al. 2004; McMichael et al 2006). For this study, an iterative approach was used for manual calibration based on expert judgment and other guidance within reasonable parameter value range, and the process was repeated until it was determined that the best results were obtained. The 2013 and 2014 measured discharge data were used for calibration and validation, respectively.

Input Parameters Determined from Field and Laboratory Testing

Hydraulic data

The groundwater table depth was measured along both banks of the gully using piezometers at 8 and 15 locations during the 2013 and 2014 rainy seasons, respectively (Zegeye et al. 2014; Zegeye et al. 2016). The piezometer data was interpolated to each of the 35 cross section to obtain a time series for both left and right bank. The measured flow discharge during the 2013 and 2014 rainy seasons was specified at the upstream end of the gully (inlet). A boundary condition at the model outlet is optional, however, we imposed the measured rating curve relation between discharge and flow depth to ensure proper flow depth which was simulated for a given discharge. Details of the discharge measurement procedure are given by (Zegeye et al. 2014; 2016).

Sediment and geotechnical data

If bed material is highly erodible, the extent of incision will be limited by bed rock. Five representative pits were excavated along the gully channel up to 4 m depth when the presence of groundwater prevented further excavation. Therefore, we assigned this depth as the bed rock elevation in the model. The gully bank erosion calculations require the specification of bank material stratigraphy, with its associated grain-size distributions, bulk density, resistance to erosion (critical shear stress and erodibility coefficient) values, and shear-strength (cohesion and friction angle) values. Most properties were measured by collecting samples from four layers of gully bank and bed.

After the soil samples were collected from each layer of right and left gully banks using cylindrical core sampler (98 cm^3), the soil bulk density (BD) was calculated by dividing the mass of the oven-dried soil (soil dried to a constant weight at 110°C) by the volume of the cylindrical core. The average BD (1.21 g cm^{-3}) was used for the input model. Soil porosity in its natural state is defined as the percentage of the total volume which is occupied by air space between the soil particles, and was calculated using the measured BD as indicated in equation 3:

$$\text{Porosity}(\%) = 100\left(1 - \frac{BD}{PD}\right) \qquad (Equation\ 3)$$

where particle density (PD) is 2.45 g cm^{-3} for mineral soils.

The soil texture and the grain size distribution for each bank layer (including stream bed), and suspended sediment samples collected at the gully inlet during 33 rainfall events in 2013, were analyzed using sieve analysis (2 mm sieve only) and the hydrometer method (Day 1965). For the hydrometer analysis, 50 g of soil passing the 2-mm sieve was mixed with water and dispersing agent to form a 1000 ml solution in a cylindrical jar (Day 1965).

Soil shear strength is a combination of cohesive forces between soil particles and the frictional resistance between particles, which are forced to slide over one another or moved out of interlocked positions (Léonard and Richard 2004). To determine shear strength of the gully bank materials, four undisturbed soil samples were collected from four layers of the right and left gully banks. A direct shear box was used in the laboratory to evaluate effective cohesion, ', and the effective angle of internal friction, Ø. The test equipment consisted of a metal box in which the soil specimen was placed. The box was split horizontally into two halves. The samples were placed in the split box and subjected to a vertical force (normal stress), and then shear forces of 60, 120 and 240 kPa were applied by moving one half of the box relative to the other to cause failure in the soil specimen. Values of effective normal stress and shear stress were then plotted to determine the cohesion and friction angle (Table 1). To reduce the influence of negative pore-water pressure, that is air, which increases the total or apparent cohesion, the laboratory experiments were applied on saturated soil samples so that the pore-water pressure equaled zero and hence effective cohesion was measured.

Calibrated Parameters

Cohesion and internal friction angle

The calibrated parameters that gave us optimal simulated values are presented in Table 1. The measured cohesion and friction angle values were too large to produce bank failures. Though several bank failures occurred during survey, the model was unable to predict based on these values. Therefore, we calibrated these parameters after several iterations. Finally, 50% of the measured cohesion and 130% of the measured friction angle values gave us the optimal simulated value. The suction angle used for all bank layers was 10^{o}.

Table 1. Measured and calibrated soil erosion-resistance parameters in Debre Mawi watershed, northern Ethiopia.

Gully bank layers	% clay	Porosity (%)	Mean particle size (mm)	Soil erosion-resistance parameters					
				Effective cohesion (kPa)		Friction angle (°)		Critical shear stress (τ , Pa)	Erodibility cm^3 (Ns)$^{-1}$
				Measured	Calibrated	Measured	Calibrated		
1	64	57	0.0114	24	12	16	20.8	0.668	0.122
2	62	61	0.0110	20	10	18	23.4	0.675	0.122
3	74	59	0.0117	33	16.5	11	14.3	0.659	0.123
4	72	56	0.0118	24	12	19	24.7	0.658	0.123

Estimating soil critical shear stress and soil erodibility

The critical shear stress (τ) is defined as the stress at which soil detachment begins or the condition that initiates soil detachment (Terzaghi 1936; Bradford et al 1973; Noor et al 2008). When the shear stress exerted by the flowing water exceeds τ , the erosion rate is proportional to an erodibility coefficient . If the critical stress is higher than the exerted stress, the erosion rate is considered zero (Noor et al 2008). Theoretically, keeping the channel boundary shear stress below τ is a requirement for streambank stability (Clark and Wynn 2007). Therefore, determination of τ is required to correctly model and understand streambank retreat (Owoputi and Stolte 1995). Smerdon and Beasley (1961) conducted a flume study on 11 cohesive Missouri soils to relate basic soil properties (plasticity index, dispersion ratio, mean particle size, and percent clay) to the critical shear stress. In this study, we used the relation with mean particle size, which resulted in better predicted bank erosion in the model compared to other relations.

$$\tau_c = 3.54 * 10^{-26.1D_{50}} \qquad (Equation\ 5)$$

where $_{50}$ is the median particle size (m).

Once the critical shear stress is determined, we used the Equation 6 to calculate the erodibility coefficient K in m^3 (Ns)$^{-1}$ (Langendoen, 2000):

$$K = 10^{-7}\tau_c{}^{-0.5}\,, \qquad \text{for}\tau_c > 0 \qquad\qquad (Equation\ 6)$$

Boundary resistance

Flow resistance is parameterized using the Manning friction factor. The

RESULTS AND DISCUSSION

Calibration and Validation Results of Gully Geometry

Model calibration (2013 rainy season) and validation (2014 rainy season) were conducted by comparing observed and simulated changes in gully width and depth. Figure 3 presents both the calibration (left) and validation (right) of gully top width and depth. Model efficiency (e.g., R^2) criteria for validation are of the same level of accuracy as the calibration results for top width, whereas the validation for depth is more accurate than the calibration. The NSE and PBIAS values of top width during calibration were 0.97 and -1.13% and during validation were 0.98 and 0.98% respectively. Similarly, the corresponding NSE and PBIAS values for bed adjustments during calibration were 0.33 and 24%, and during validation were -0.92 and 47%, which contradicts with the coefficient of determination as shown in Figure3. Zegeye et al (2016) reported that assessing the quality of fits between gully expansion parameters cannot solely be done based on R^2, and that good fits also require other measures like NSE and PBIAS to be in the acceptable range. The analysis also demonstrated that further calibration is needed until the depth prediction better fits with the observed change in depth.

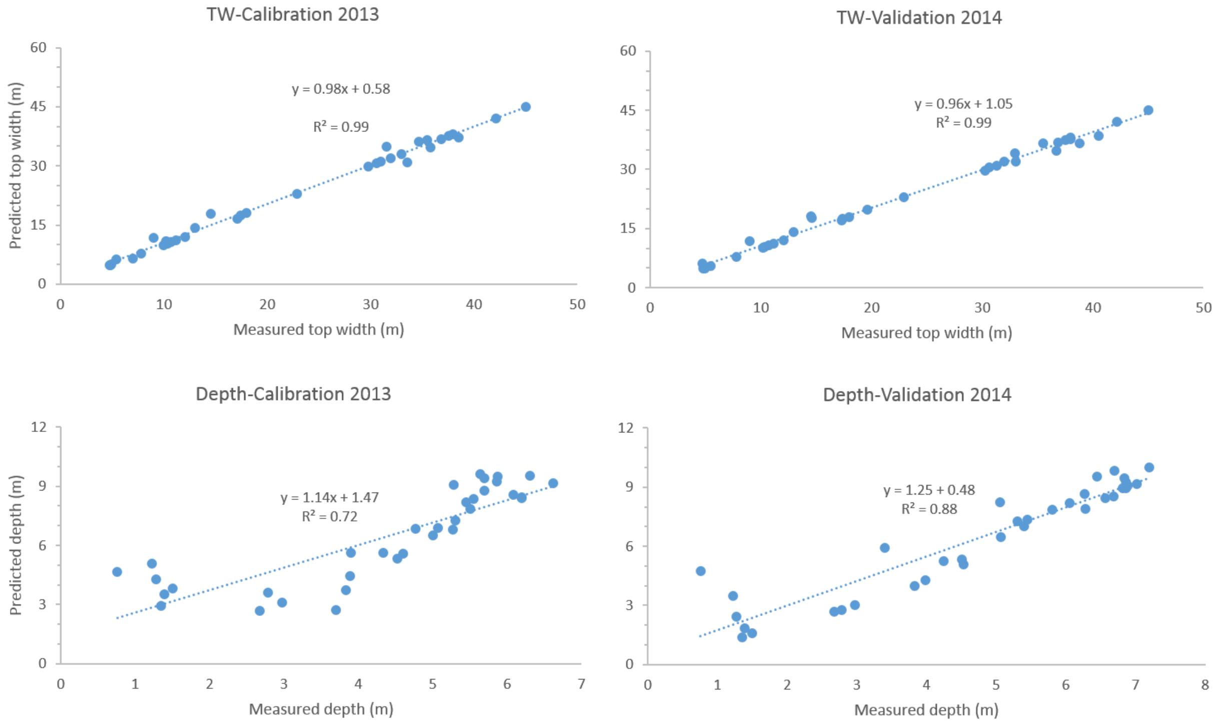

Figure 3. Calibrated and validated channel top width (TW) and depth values simulated by the CONCEPTS model against measured values during calibration period (2013) and validation period (2014).

Most bank failures were observed and predicted immediately downslope of the gully headcut between 70 to 120 m downstream from the inlet weir (cross-sections XS-8 to XS-12 in Fig. 4). In both years (2013 and 2014), the model over predicted a top width change at XS-28 and XS-29 which is located around 300 m downstream of the inlet (Figure 4). Possible reasons could be: (1) The model assumes a straight channel (Langendoen 2000), which may over or underestimate boundary forces when there are abrupt cross-sectional changes. For example, the top widths of cross-sections XS-28 and XS-29, respectively 14 m and 9 m, were smaller than those of the surrounding cross-sections XS-27 and XS-30, respectively 37 m and 17 m, which increased the friction slope and boundary shear stress at sections XS-28 and XS-29. (2) Gully bank materials in each layer or horizon are assumed in the model to be similar along the 389 m gully reach, which is not likely.

Cantilever-Planar Failure Relationships

Two bank-failure conditions (planar and cantilever) were simulated by the CONCEPTS model. Cantilever failures are formed when the flow preferentially erodes deeper, more erodible layers. The dashed line in Figure 5(a) shows the failure block weight produced by the cantilever failure, which in turn produced the planar failure (bold line). This indicates that the two failure processes occur successively. The planar failure at this cross-section was triggered after a total of 190 kN m^{-1} in bank soil was removed by cantilever failures as shown in Figure 5(a). Similar findings by Langendoen et al (2014) show that “both tension crack depth and groundwater table can significantly affect factor of safety. During runoff events the free over fall over the brink of the gully head will scour the toe of the head cut and form an undercut. These undercuts can significantly reduce factor of safety.”

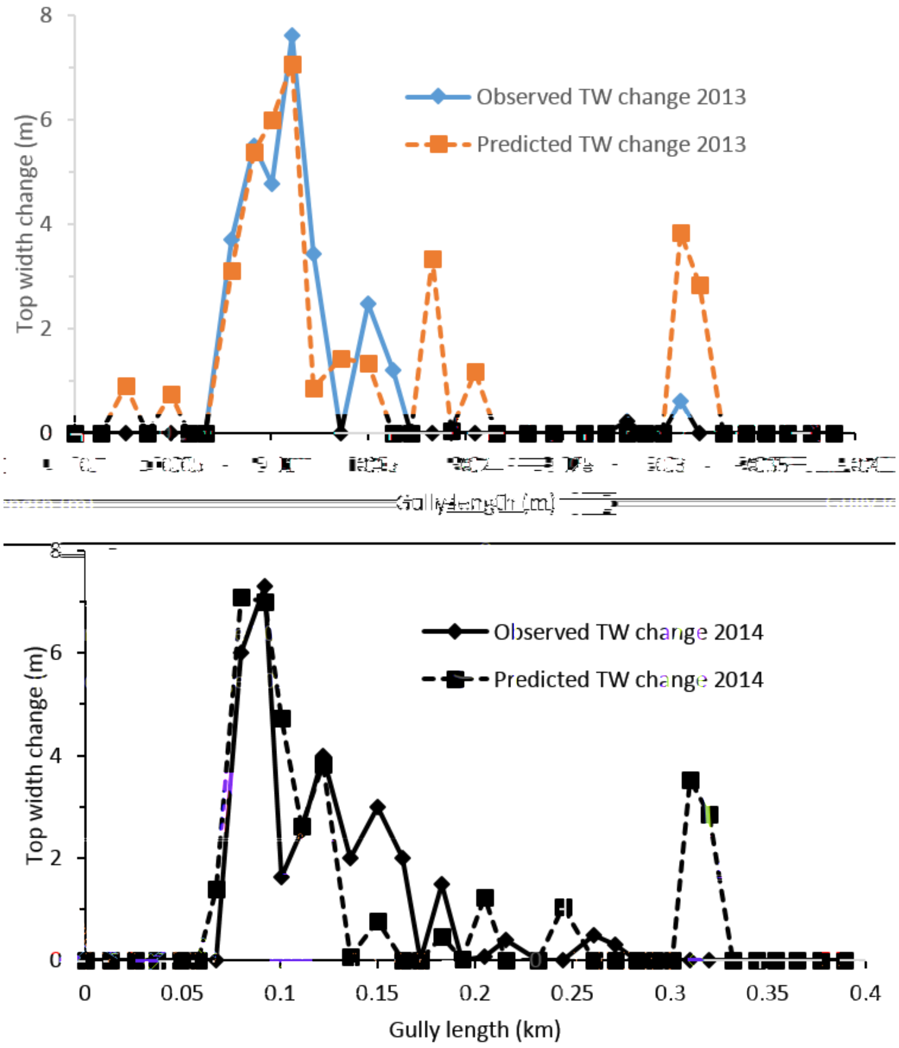

Figure 4. Comparison of observed versus predicted changes in top width (TW) during 2013 (top) and 2014 (bottom) rainy seasons.

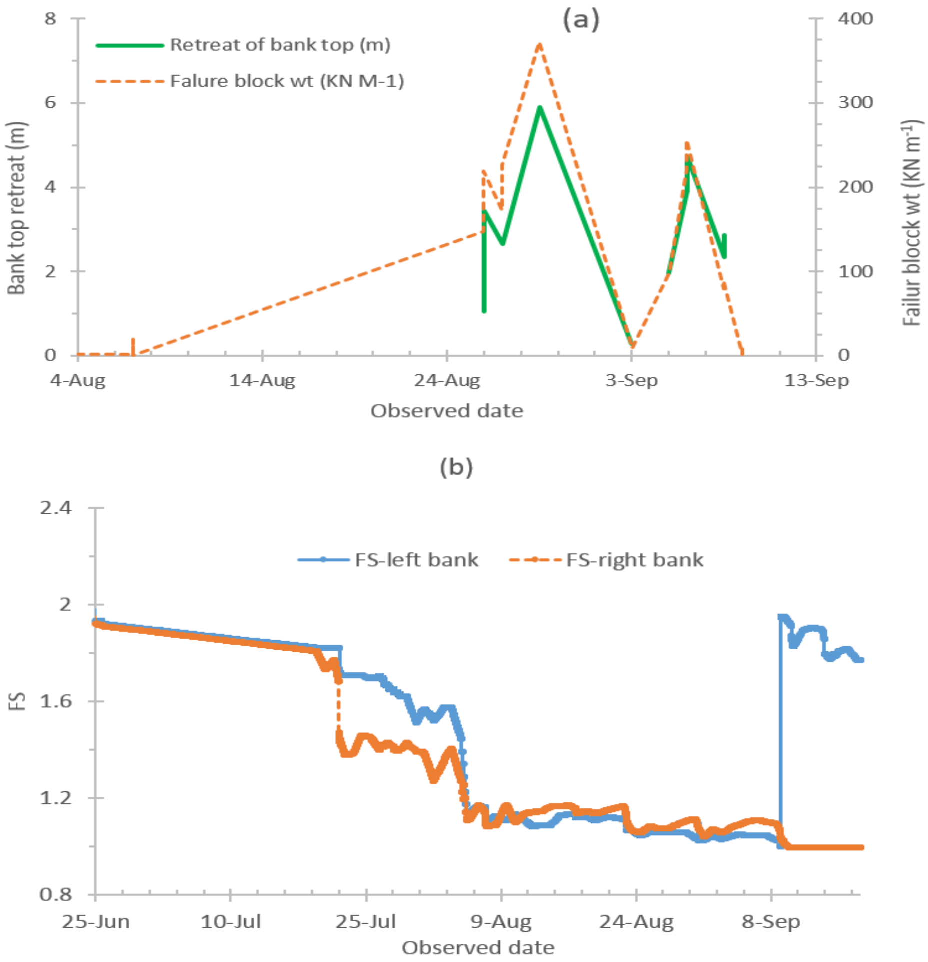

Figure 5. Simulated bank failures at cross-section 8 (XS-8) during the 2014 rainy season. (a) A failure of block weight by cantilever failure (dashed line) followed by planar failure (solid line); (b) Evolution of Factor of safety (FS) in 2014 at which planar failures occur when FS falls below one.

Effect of Groundwater Table Elevation on Gully Erosion

Most bank retreat occurred in August when the elevated groundwater table destabilized the banks. Zegeye et al (2016) observed that the water table rose above the gully bottom for the study gully during the rain phase, which resulted in increased pore-water pressure indicating mostly saturated gully head and bank soils. This gully condition was strongly linked with high linear retreat and volumetric expansion of the gully (Tebebu et al 2010; Zegeye et al. 2016). Increased pore-water pressures reduced soil shear strength and therefore the factor of safety of the gully bank, as shown in Figure 5(b). The for the left and right banks of XS-8 continuously decreased throughout the rainy season. Around 10 Sep 2014, the left bank dropped below one thereby triggering a 5 m deep failure (Figure 5(a)), which resulted in temporal stability of the bank and a sharp increase in . Many authors have reported the role of groundwater elevation (GWE) in the formation and expansion of gullies in the study area (Tebebu et al 2010; Zegeye et al 2016). For example, Figure 6 shows the effect of groundwater table depth on the simulated cross-sectional adjustment of XS-8 of the studied gully. The CONCEPTS model predicted an increase in sidewall retreat from 2 m to 6 m when the water table was elevated by 0.20 m, and predicted an increase to 19 m when the water table was near the ground surface (Figure 6). Similarly, the bed elevation at this cross-section was lowered by about 4 m due to the increase in GWE by 40 cm. The result demonstrated that lowering or draining the subsurface water can significantly reduce gully erosion and hence sediment yield.

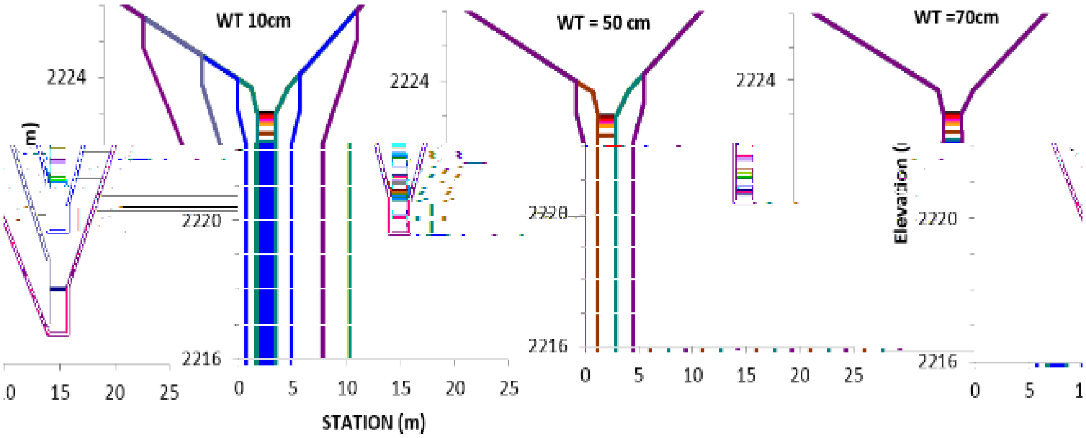

Figure 6. Effect of groundwater table on simulated gully geometry (XS-8). The groundwater elevation increases from 0.7 to 0.1 m below the surface (from right plot to left plot) resulted in increased side wall and bed erosion.

To evaluate effect of bank regrading and bed protection on gully erosion, two gully erosion control measures were evaluated: (1) regrading the banks of six cross sections to a 45-degree slope over a length of 55 m (XS-7 to XS-12); and (2) placing bed and bank toe protection at 5 cross sections over a length of 42 m (XS-8 to XS-12). As shown in Figure 7, the thalweg of the gully throughout the reach is impacted by both measures. Without any protection measures, the gully bed eroded a cross-sectional area of about 800 m^2 throughout the gully reach with an average change in bed elevation of 2 m. No sidewall erosion was simulated for either of the two control measures, which were applied to only a few cross-sections as shown in Figure 8(a).

One important observation was that protecting one cross-section could positively impact the neighboring cross-sections. For example, bed erosion at non-protected XS-7 was reduced by 1 m because of the regrading at XS-8. Similarly, bed erosion at XS-13 was reduced by more than 1 m (Figures 7 and 8). In general, targeted bed and bank toe protection or regrading the banks reduced the average bed erosion by more than 60%. Implementing either of the two control measures, could save a total of 400 m^{2}land under risk of gully erosion by reducing the sidewall retreat by an average width of 1 m throughout the reach length. To better understand the effects of regrading the banks on bed erosion, the sidewall of cross section 9 (XS-9) was regraded to a slope of various degrees, as shown in Figure 8(b). The result demonstrated that regrading the bank to a slope of 45° reduced bed erosion only by 25%, indicating that regrading only does not prevent gully erosion. Therefore, regrading the bank should be in combination with bed and bank toe protection measures.

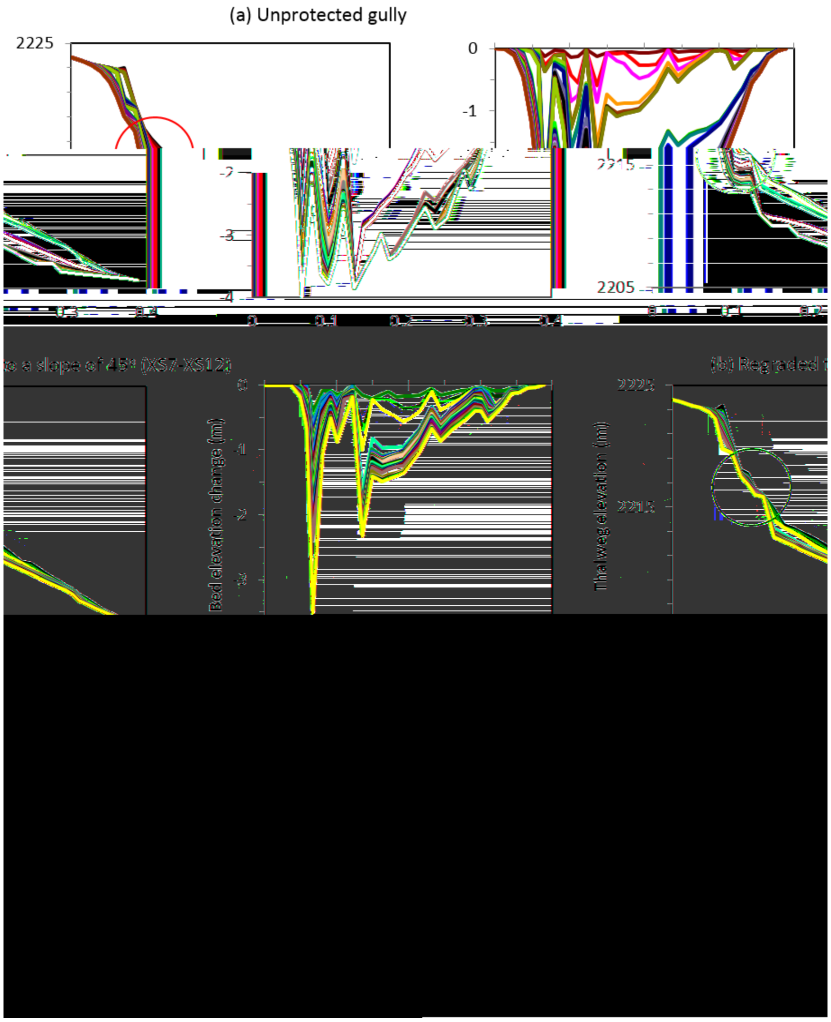

Figure 7. Effect of best management practices (BMPs) on simulated bed erosion: (a) no BMPs; (b) regrading bank slope to a 45° angle (XS-7 to XS-12); and (c) targeted bed and toe erosion protection measures (XS-8 to XS-12). The circles on the left figures indicate the effects of the three conditions on simulated bed erosion between XS-8 and XS-12. The left figures plot thalweg elevation, whereas the right figures plot change in thalweg elevation.

In the study area, Langendoen et al (2014) tested CONCEPTS model to determine the shear stresses for a range of flows that may occur over a 45-degrees regraded head cut and 45-degrees regraded sidewalls near the head of our studied gully and found the maximum shear stress is located at the upstream end of the gully head where water surface slope is largest. Similarly, the result is supported by Langendoen et al (2014) who conducted BSTEM model in our study area and reported that gully heads and banks with angles not exceeding 45-degrees should be stable under fully saturated conditions. The CONCEPTS model in our study was also used to evaluate the effect of these measures on sediment reduction (Figure 8(c)). Regrading XS-9 to a slope of 45° can reduce sediment yield by 33%, whereas controlling the bed and its toe erosion using different measures can reduce the sediment yield by 90%. This indicates protecting bed erosion is the most important strategy in reducing both sidewall and bed erosion.

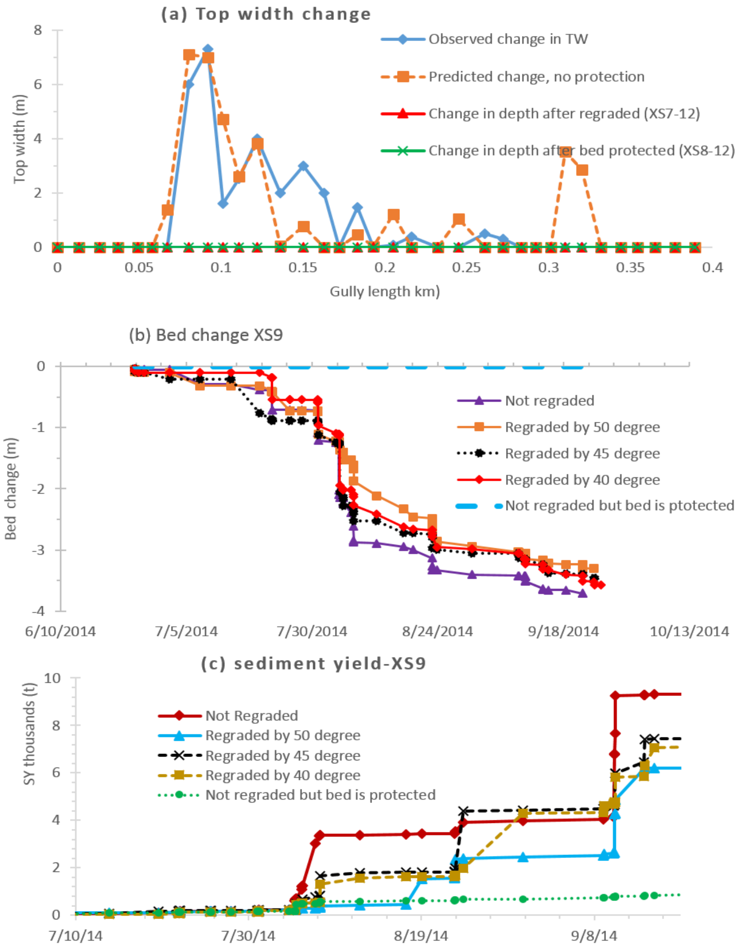

Figure 8. Effect of gully erosion control measures on (a) sidewall erosion, (b) bed erosion and (c) sediment yield during the 2014 rainy season of a large gully in the Debre Mawi watershed.

CONCLUSION

The USDA CONCEPTS model was used to aid in the design of new gully erosion control measures in Debre Mawi watershed representing the humid highlands of Northern Ethiopia. A gradual introduction of computational modeling technology of increasing complexity, such as CONCEPTS, has major benefits in designing cost-effective erosion control measures. Based on the model efficiency criteria, the calibrated model predicted well both the top width (R^2 = 0.99) and depth (R^2 = 0.88). The CONCEPTS model predicted an increase in sidewall retreat and bed erosion when the water table was elevated which implies that lowering or draining the subsurface water can significantly reduce gully erosion and hence sediment yield. The result demonstrated that regrading the bank to a slope of 45° reduced bed erosion only by 25% and sediment yield by 33%, whereas controlling the bed and bank-toe erosion by protective measures reduced the sediment yield by 90%. Regrading gully sidewall or lowering water table can significantly reduce gully bank erosion. However, these measures do not significantly reduce the bed and bank toe erosion (Figures 6-8) caused by the flowing water force, which ultimately resulted in bank failure. This indicates that effective gully treatment requires integrated measures, i.e., both regrading gully banks and lowering water table should be integrated with bed protection measures such as check dams. Preventing bed erosion is critical in reducing both sidewall and bed erosion.

Although the validation results show that CONCEPTS can successfully simulate gully erosion using calibrated input parameters, which fall within the typical range expected for the soils surrounding the gully, some discrepancies were observed between the simulated and observed gully evaluation. Possible reasons for such discrepancies are: the assumptions of similar gully bank materials in each layer or horizon along the 389 m gully reach, which is not likely; and the model assumption of a straight channel, which may over-or underestimate boundary forces when there are abrupt cross-sectional changes. This indicates that the CONCEPTS model has possibilities for further improvements.

From all collected parameters, effective cohesion and internal friction angle were the only calibrated parameters. Sensitivity analysis supports this concept through iterative improvement of our quantitative understanding of what is important for validation and how priorities should be established at given points in time. This study lacks this important analysis. Therefore, future studies should also focus on sensitivity analysis and select which parameters are very important with respect to healing gully erosion.

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REFERENCES

Ayele G K, Gessess A A, Addisie M B, Tilahun S A, Tebebu T Y, Tenessa D B, Langendoen E J, Nicholson C F and Steenhuis T S (2015). A Biophysical and economic assessment of a community-based rehabilitated gully in the Ethiopian highlands. , 10.1002/ldr.2425: DOI: 10.1002/ldr.2425.

Amare T, Zegeye A D, Yitaferu B, Steenhuis T S, Hurni H and Zeleke G (2014). Combined effect of soil bund with biological soil and water conservation measures in the northwestern Ethiopian highlands. 14:192-199. DOI: 10.1016/j.ecohyd.2014.07.002.

Arnold J, Moriasi D, Gassman P, Abbaspour K, White M, Srinivasan R, Santhi C, Harmel R, van Griensven A and van Liew M (2012). SWAT: Model use, calibration, and validation. 55, 1491-1508.

Bayabil H K, Tilahun S A, Collick A S, Yitaferu B and Steenhuis T S (2010). Are runoff processes ecologically or topographically driven in the (sub) humid Ethiopian highlands? The case of the Maybar watershed. 3, 457-466.

Bradford J M, Farrell D and Larson W (1973). Mathematical evaluation of factors affecting gully stability. 37, 103-107.

Casalı J, Lopez J and Giraldez J (2003). A process-based model for channel degradation: application to ephemeral gully erosion. 50, 435-447.

Clark L, Wynn T. (2007). Methods for determining streambank critical shear stress and soil erodibility: implications for erosion rate predictions. 50, 95-106.

Dagnew D C, Guzman C D, Zegeye A D, Tibebu T Y, Getaneh M, Abate S, Zemale F A, Ayana E K, Tilahun S A and Steenhuis T S (2015). Impact of conservation practices on runoff and soil loss in the sub-humid Ethiopian Highlands: The Debre Mawi watershed. 63, 214-223.

Day P R (1965). Particle fractionation and particle-size analysis. 9, 545-567

Frankl A, Poesen J, Deckers J, Haile M and Nyssen J (2012). Gully head retreat rates in the semi-arid highlands of Northern Ethiopia. 173, 185-195.

Frankl A, Poesen J, Haile M, Deckers J and Nyssen J (2013). Quantifying long-term changes in gully networks and volumes in dryland environments: The case of Northern Ethiopia. 201, 254-263.

Gessesse B, Bewket W and Bräuning A (2015). Model-based characterization and monitoring of runoff and soil erosion in response to land use/land cover changes in the Modjo watershed, Ethiopia. 26, 711-724. doi:DOI: 10.1002/ldr.2276.

Kou M, Jiao J, Yin Q, Wang N, Wang Z, Li Y, Yu W, Wei Y, Yan F and Cao B (2015). Successional Trajectory Over 10 Years of Vegetation Restoration of Abandoned Slope Croplands in the Hill-Gully Region of the Loess Plateau. , 10.1002/ldr.2356: DOI: 10.1002/ldr.2356.

Krause P, Boyle D and Bäse F (2005). Comparison of different efficiency criteria for hydrological model assessment. 5, 89-97.

Langendoen E, Tebebu T, Steenhuis T and Tilahun S (2013). Assessing gully widening and its control in the Debra-Mawi watershed, northern Ethiopia. In: Gabbiye N, Kaba E, Monocha Singh K K and Sharma S(eds). 214-222.

Langendoen E, Zegeye A, Tebebu T, Steenhuis T, Ayele G, Tilahun S and Ayana E (2014). Using computer models to design gully erosion control structures for humid Northern Ethiopia. :

Langendoen E J and Alonso C V (2008). Modeling the evolution of incised streams: I. Model formulation and validation of flow and streambed evolution components. 134, 749-762.

Langendoen E J, Richard Lowrance R and Simon A (2009). Assessing the impact of riparian processes on streambank stability. 2, 360-369.

Langendoen E J and Simon A (2008). Modeling the evolution of incised streams. II: Streambank erosion. 134, 905-915.

Legates D R and McCabe G J (1999). Evaluating the use of “goodness-of-fit” measures in hydrologic and hydroclimatic model validation. 35, 233-241.

Léonard J and Richard G (2004). Estimation of runoff critical shear stress for soil erosion from soil shear strength. 57, 233-249.

McMichael C E, Hope A S and Loaiciga H A (2006). Distributed hydrological modelling in California semi-arid shrublands: MIKE SHE model calibration and uncertainty estimation. 317, 307-324.

Nyssen J, Poesen J, Veyret-Picot M, Moeyersons J, Haile M, Deckers J, Dewit J, Naudts J, Teka K and Govers G (2006). Assessment of gully erosion rates through interviews and measurements: a case study from Northern Ethiopia. 31, 167-185.

Noor M, Jidin R and Hafez M (2008). Effective Stress and Complex Soil Settlement Behavior. **13**, Bund.H, 1-13.

Owoputi L and Stolte W (1995). Soil detachment in the physically based soil erosion process: A review. 38, 1099-1110.

Poesen J, Nachtergaele J, Verstraeten G and Valentin C (2003). Gully erosion and environmental change: importance and research needs. 50, 91-133.

Simon A and Rinaldi M (2006). Disturbance, stream incision, and channel evolution: The roles of excess transport capacity and boundary materials in controlling channel response. 79, 361-383.

Simon A, Pollen-Bankhead N and Thomas R E (2011). Development and application of a deterministic bank stability and toe erosion model for stream restoration. In: Simon A, Bennett S J and Castro J M (eds). AGU, Washington, DC, 453–474.

Smerdon E T and Beasley R P (1961). Critical tractive forces in cohesive soils. 42, 26-29.

Tague C, McMichael C, Allen H, Choate J and Clark R (2004). Application of the rhessys model to a California semiarid shrubland watershed1. 40, 575.

Tebebu T, Abiy A, Dahlke H, Easton Z, Zegeye A, Tilahun S, Collick A, Kidnau S, Moges S and Dadgari F (2010). Surface and subsurface flow effect on permanent gully formation and upland erosion near Lake Tana in the northern highlands of Ethiopia. **7,** 5235-5265.

Tilahun S, Guzman C, Zegeye A, Engda T, Collick A, Rimmer A and Steenhuis T (2013). An efficient semi-distributed hillslope erosion model for the subhumid Ethiopian Highlands. 17, 1051-1063.

Tilahun S A, Guzman C D, Zegeye A D, Dagnew D C, Collick A S, Yitaferu B and Steenhuis T S (2015). Distributed discharge and sediment concentration predictions in the sub-humid Ethiopian highlands: the Debre Mawi watershed. 29, 1817-1828.

Willmott C J, Robeson S M and Matsuura K (2012). A refined index of model performance. 32, 2088-2094.

Zegeye A D, Steenhuis T S, Blake R W, Kidnau S, Collick A S and Dadgari F (2010). Assessment of soil erosion processes and farmer perception of land conservation in Debre Mawi watershed near Lake Tana, Ethiopia. 10, 297-306.

Zegeye A, Damtew S, Tilahun A, Langendoen E, Dagnew D, Guzman C, Tebeby T and Steenhuis T (2014). Gully development processes in the Ethiopian Highlands. In: Bantyirga B, Mehari M, Rao V S, Manocha B L, Singh K K, Geremew S and Tadesse E (eds). Bahir Dar: Bahir Dar Institute of Technology, 220-229.

Zegeye A D, Langendoen E J, Stoof C R, Tilahun S A, Dagnew D C, Zimale F A, Guzman C D, Yitaferu B and Steenhuis T S (2016). Morphological dynamics of gully systems in the sub-humid Ethiopian Highlands: The Debre Mawi watershed. 2, 443-458. DOI: 10.5194/soil-2-443-2016.

Zegeye A D, Steebhuis T S, Mekuria W, Dagnew D C, Addisse M D, Tilahun S A and Kasse T A (2017). Effect of gully headcut treatment on sediment load and gully expansion in the sub-humid Ethiopian highlands. 5(2), 138-144. DOI:10.13189/eer2017.050208.

Zegeye A D, Langendoen E J, Guzman C D, Dagnew D C, Tilahun S A and Steenhuis T S (2018).Gullies, a critical link in landscape soil loss: A case study in the sub-humid highlands of Ethiopia.

Zema D, Bingner R, Denisi P, Govers G, Licciardello F and Zimbone S (2012). Evaluation of runoff, peak flow and sediment yield for events simulated by the AnnAGNPS model in a Belgian agricultural watershed. 23, 205-215. doi:10.1002/ldr.1068.