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Using Computer Models to Design Gully Erosion Control Structures for Humid Northern Ethiopia

E.J. Langendoen
US Department of Agriculture, Agricultural Research Service, National Sediment Laboratory, Oxford, Mississippi, USA

A.D. Zegeye, T.Y. Tebebu & T.S. Steenhuis
Department of Biological and Environmental Engineering, Cornell University, Ithaca, New York, USA

G.K. Ayele, S.A. Tilahun & E.K. Ayana
School of Civil and Water Resources Engineering, Bahir Dar University, Bahir Dar, Ethiopia

ABSTRACT: Classic gully erosion control measures such as check dams have been unsuccessful in halting gully formation and growth in the humid northern Ethiopian highlands. Gullies are typically formed in vertisols and flow often bypasses the check dams as elevated groundwater tables make gully banks unstable. Check dams also have been unable to halt the formation and headward migration of head cuts, which often exceed heights of 3 to 4 m. Structural measures built from concrete, steel, and riprap, such as high drop structures with plunge pools, are too expensive for the local farmers to construct. Here we used the U.S. Department of Agriculture (USDA) computer model BSTEM to determine stable slopes of the gully head and banks in the Debre-Mewi watershed, northern Ethiopia, to arrest a rapidly migrating head cut exceeding 3 m in height with downstream gully depths exceeding 6 m. We then used the USDA model CONCEPTS to determine the required protective cover to prevent erosion of the regraded head cut. Given the cohesive strength of the soils (> 19 kPa), BSTEM calculated stable slopes that varied between 75 degrees for a bank height of 3 m to 47 degrees for a bank height of 6 m. CONCEPTS simulated flow velocities of 7 m/s and shear stresses exceeding 100 Pa at the upstream of the regraded gully head. A demonstration project has started that uses bamboo sheets to protect the soil surface against such forces. The introduction of computational modeling technology of increasing complexity, such as BSTEM and CONCEPTS, could have major benefits to develop cost-effective erosion control measures in developing countries such as Ethiopia.

Keywords: Gully erosion, Erosion control, Ethiopia, BSTEM, CONCEPTS

1 INTRODUCTION

Over the past three decades, gullying has been widespread and has become more severe in the Ethiopian highlands, contributing as much as 94% of total sediment yield (e.g., Poesen et al., 2003; Nyssen et al., 2004a). Gullies are formed in saturated and unstable bottom soils and are indirectly caused by deforestation and expansion of cultivation in steeper or marginal land, which shortens the flow path of the water. Although traditionally gully growth and extension is related to intense rain coupled with soils prone to sealing and crusting, generating high runoff volume and concentrated flow, gully growth in the humid Ethiopian highlands is significantly related to elevated groundwater tables that make gully banks unstable and cause slippage of banks (Tebebu et al., 2010).

Only in very few cases, rehabilitation of gullies has been successful in Ethiopia (Nyssen et al., 2004b) due to the high costs of constructing appropriate structural stabilization measures and the lack of suitable computational design tools in this developing country. Current best management practices to control gully erosion typically consist of closely-spaced check dams in the upper portions of degraded watersheds (Figure 1). Check dams reduce the effective slope of the channel, thereby reducing the velocity of flowing water, allowing sediment to settle and reducing channel erosion. Check dams have been fairly effective in the semi-arid Tigray Region of northeastern Ethiopia (Nyssen et al., 2004b). However, they have been ineffective to control gully erosion in the more humid Amhara region, where gullies are formed in vertisols and flow often bypasses the check dams. Check dams also have been unable to halt the formation and headward migration of head cuts, which can exceed heights of 3 to 4 m (Figure 1).

Langendoen et al. (2013) and Tebebu et al. (2013) tested the US Department of Agriculture computer models BSTEM and CONCEPTS for their ability to simulate gully-forming processes, and carried out preliminary simulations to develop effective gully stabilizing measures in vertisols. BSTEM is a spreadsheet tool for simulating stream bank erosion of a single bank profile (Simon et al., 2011). It has been used worldwide to evaluate bank stability conditions and to design stream bank stabilization measures. CONCEPTS is a process-based, dynamic computer model that simulates open-channel hydraulics, sediment transport, channel morphology and the impact of in-channel protection measures on channel morphology (Langendoen et al., 2008a; 2008b). CONCEPTS has been used throughout the mid-continental US to site grade control and to evaluate the impact of bank protection works at the reach and watershed scale. Both models predicted the location of gully bank failures well with the observed groundwater depth and vegetation characteristics in the Debre-Mewi watershed (Langendoen et al., 2013). Further, the validated models indicated that any gully rehabilitation project should first stabilize the gully bed by arresting the head cuts as any continued incision will destabilize gully banks (Tebebu et al., 2013).

The objective of this paper is to develop cost-effective measures to arrest gully formation in the Amhara Region of northern Ethiopia using the U.S. Department of Agriculture computer models BSTEM and CONCEPTS. It expands the work by Langendoen et al. (2013), Tebebu et al. (2013), and Zegeye et al. (2014).

Figure 1. Check dams in the Debre-Mewi watershed, Ethiopia. Left: newly constructed check dams to stabilize a gully. Right: gully head-cut migrating towards upstream check dams.

2 METHODS

2.1 *Model Overview*

2.1.1 *BSTEM*

BSTEM comprises three submodels to predict: 1) bank toe and surface hydraulic erosion; 2) geotechnical mass failure; and 3) mechanical, reinforcing effects of riparian vegetation (Simon et al., 2011). It is programmed in Visual Basic and executes in Microsoft Excel as a simple spreadsheet tool.

The bank toe erosion submodel is used to estimate erosion of bank and bank toe materials by hydraulic shear stresses. The effects of toe protection are incorporated into the analysis by changing the characteristics of the toe material in the model. The model calculates an average boundary shear stress from channel geometry and flow parameters using a rectangular-shaped hydrograph defined by flow depth and the duration of the flow (steady, uniform flow). The model also allows for different critical shear stress and erodibility of separate zones with potentially different materials at the bank and bank toe. Toe erosion by hydraulic shear is calculated using an excess shear approach. The average boundary shear stress acting on each node of the bank material is calculated. If the critical shear stress of the material is exceeded, entrainment occurs.

The bank stability submodel combines three limit equilibrium methods to calculate a factor of safety (F_S) for multilayered stream banks. The methods simulated are horizontal layers (Simon et al., 2000), vertical slices for failures with a tension crack (Langendoen and Simon, 2008b), and cantilever failures (Langendoen and Simon, 2008b). A value of $F_S = 1.0$ indicates the critical case and imminent failure;

values above one are theoretically viewed as stable. However, the uncertainty and variability of soil properties and failure geometries are such that we consider values between 1.0 and 1.3 conditionally stable. Groundwater table dynamics are reflected in the pore-water force in the soil shear strength equation.

BSTEM incorporates the RipRoot model to calculate the soil reinforcement provided by roots of riparian vegetation (Pollen and Simon, 2005). Riproot accounts for both root breaking and root pullout to estimate root reinforcement. A vegetation assemblage can be created by accessing the species database contained in the submodel; the user enters species, approximate vegetation ages, and approximate percent cover of each species at each site to estimate root density. This database includes tests performed across the United States. Root reinforcement values are then calculated automatically using RipRoot's progressive breaking algorithm.

2.1.2 *CONCEPTS*

The CONCEPTS computer model has been developed to simulate the evolution of incised streams and to evaluate the long-term impact of rehabilitation measures to stabilize stream systems and reduce sediment yield (Langendoen et al., 2008a; 2008b). CONCEPTS simulates unsteady, one-dimensional (1D) flow, graded sediment transport, and bank erosion processes in stream corridors. It can predict the dynamic response of flow and sediment transport to in-stream structures.

CONCEPTS models streamflow as 1D along the channel's centerline. Hence, it is limited to fairly straight channels; it cannot predict bar formation and channel migration. CONCEPTS simulates gradually varying flow (described by the Saint-Venant equations) as a function of time along a series of cross sections representing stream and floodplain geometry. The governing system of equations are solved using the generalized Preissmann scheme, allowing a variable spacing between cross sections and large time steps conducive to long-term simulations of channel evolution. The implementation of the solution method contains various enhancements to improve the robustness of the model, particularly for flashy runoff events.

Alluvial stream banks are typically composed of fine-grained deposits containing clays, silts, and fine sands (hereafter referred to as fines), which may overlay coarser relic point bars. Streambeds are more commonly composed of sands and gravels, resistant clay layers, or bedrock. Therefore, the range in particle sizes being transported in alluvial streams may be quite large, and the composition of the sediment mixture in transport may be quite different from that of the bed material if a majority of the sediments are fines transported in suspension. CONCEPTS therefore calculates sediment transport rates by size fraction for 14 predefined sediment size classes ranging from 10 μm to 64 mm. CONCEPTS uses a total-load evaluation of bed-material transport and treats movement of clays and fine silts (<10 μm) as pass-through background wash load. The differences in transport mechanics of suspended and bed load movement are accounted for through nonequilibrium effects. The composition of bed surface and substrate is tracked, enabling the simulation of vertical and longitudinal fining or coarsening of the bed material.

CONCEPTS simulates channel width adjustment by incorporating the two fundamental physical processes responsible for bank retreat: fluvial erosion or entrainment of bank material particles by flow and bank mass failure due to gravity. Bank material may be cohesive or noncohesive 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. This is slightly different from the method used by BSTEM, which calculates an average shear stress for each node in the bank profile. If the critical shear stress of the material is exceeded, entrainment occurs. CONCEPTS is able to simulate the development of overhanging banks. Stream bank failure occurs when gravitational forces that tend to move soil downslope exceed the forces of friction and cohesion that resist movement. The risk of failure is expressed by a factor of safety, defined as the ratio of resisting to driving forces or moments, using the method slices. CONCEPTS performs stability analyses of wedge-type failures and cantilever failures of overhanging banks. The effects of pore water pressure and confining pressure exerted by the water in the stream are accounted for.

2.2 *Study Area*

The research was conducted in the Debre-Mewi watershed located about 30 km south of Bahir Dar, Ethiopia (Figure 2). Gullying commenced in the 1980s following the clearance of indigenous vegetation and intensive agricultural cultivation, leading to an increase of surface and subsurface runoff from the hillside to the valley bottoms. Gully erosion rates were 10 to 20 times the measured upland soil losses. Water levels, measured with piezometers, showed that in the actively eroding sections, the water table was in general above the gully bottom and below it in the (self-) stabilized sections (Tebebu et al., 2010).

The elevation ranges from 2184 to 2300 m above sea level. The slope gradient of the watershed ranges from 8 to 30%. Average annual rainfall is about 1240 mm, while the minimum and maximum monthly temperatures are 9.3°C and 25.7°C, respectively. June, July and August receive the largest portions of the annual rainfall. The local geology is characterized by volcanic basalt flows and Cenozoic pyroclastic fall deposits (Abiy, 2009). The dominant soil types are nitisol, vertisol, and regosol. Nitisol dominates the upper parts of the watershed and is highly suitable for crop production. Vertisols are found in the lower parts of the watershed, while regosols are mainly located on the steep and highly eroded parts of the watershed. Cultivated land covers more than 70% of the watershed. The main crops are teff (Eragrostis tef), chick pea (Cicer arietinum), and grass pea (Lathyrus sativus). The remaining portion of the watershed is covered with communal grazing areas, bush lands, and eucalyptus woodlots. BSTEM and CONCEPTS were used to evaluate the gully (labeled "Study site" in Figure 2 and see Figure 3) previously studied by Tebebu et al. (2010). The drainage area of the runoff contributing area for this gully is 17.4 ha (or 3% of the total Debre-Mewi watershed).

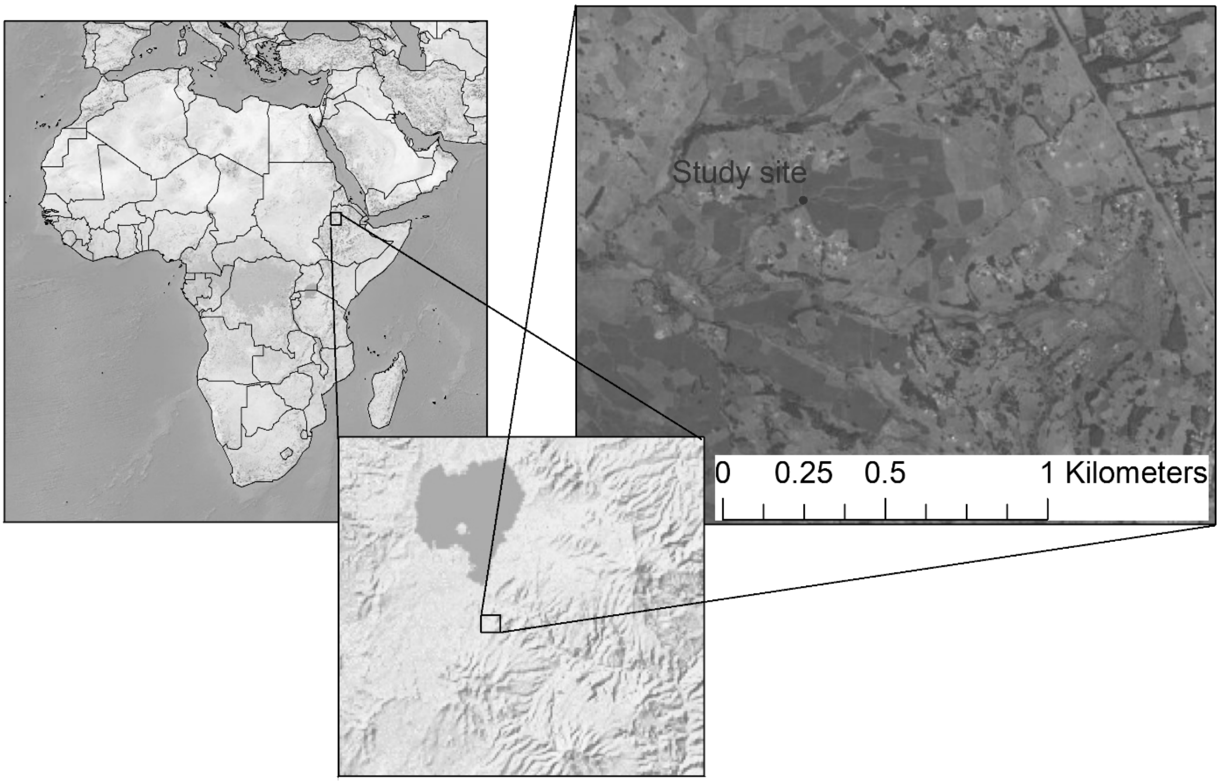

Figure 2. Map of study area in the Debre-Mewi watershed, northern Ethiopia.

Figure 3. Photos of studied gully and head cut taken before the 2013 rainy season (May 2013). Left: looking upslope. Right looking downslope.

2.3 *Model Data Collection*

The data required to operate BSTEM and CONCEPTS are related to quantifying the driving and resisting forces that control the hydraulic and geotechnical erosional processes that act on the gully boundary. Input-parameter values can all be obtained directly from field studies and laboratory analyses. Data characterizing gully geometry, runoff, and boundary material properties were collected before, during and after the 2013 rainy season (Zegeye et al., 2014).

Ten cross sections near the gully head cut were repeatedly surveyed using a combination of tape meter and total station. The top-bank of the entire gully was also delineated using a hand-held GPS system. The gully head migrated about 12 m upslope between July and September, 2013, which resulted in a soil loss of 460 m^3 (or about 515 metric tons using the mean measured bulk density of 1.12 g/cm^3). The total soil loss of the entire gully was 23,360 m^3 or 26,163 tons, which is about three fold that of the previous study by Tebebu et al. (2010). This indicates that stabilization of this gully and its head is critical.

Two reinforced concrete, rectangular weirs were constructed to measure sediment concentration and discharge at the upstream and downstream ends of the gully. During runoff events a one liter sample was collected every 10 minutes at both weirs. At the same time a sediment sample was collected, the flow depth at each weir was read from a staff gage. The samples were processed in the laboratory using Whatman filter paper followed by oven-drying to determine the sediment mass in the bottle. Discharge was calculated as $Q = Av$, where A is flow area and v is water velocity measured by timing the displacement distance of water surface floats. The measured discharge record comprised 35 runoff events, and the maximum measured discharge was 0.5 m^3/s at the upstream weir and 1.4 m^3/s at the downstream weir.

The gully bank soil profile characteristics (such as soil texture, bulk density, particle density, particle size) and bank material shear strength were determined in the laboratory by collecting samples from four layers of gully bank and bed (see Table 1). Bank material shear strength was measured using a direct shear test device.

Table 1. Physical properties of gully bank material layers in Debre Mewi watershed, northern Ethiopia.

	Soil texture			Bulk density	Effective cohesion	Friction angle
Gully bank layer	%clay	%silt	%sand	(g/cm^3)	(kPa)	(°)
1	64	16	20	1.15	23	16
2	62	24	14	1.05	19	18
3	74	2	24	1.10	32	11
4	72	12	16	1.19	22	19

3 MODEL APPLICATION

BSTEM was used to determine stable head cut and sidewall slopes for the studied gully in the Debre-Mewi watershed given the measured soil properties. CONCEPTS was then used to determine the surface protection needed to prevent erosion of the head cuts regraded at stable slopes.

3.1 *BSTEM*

Although the cohesive strength of the clay soils comprising the gully boundary materials (Table 1) is quite large, it is insufficient to maintain a stable vertical profile of gully head cut and sidewalls. Figure 4 plots the Factor of safety of a 3 m vertical head cut as a function of groundwater elevation and tension crack depth. The tension crack depth (z_c) is usually equated to the depth at which the active pressure is zero (e.g., Lambe and Whitman, 1969):

$$z_c = \frac{2c}{\gamma} \tan(45° + \phi/2) \quad (1)$$

where c is effective cohesion, γ is bulk soil unit weight, and ϕ is soil friction angle. For the soil properties listed in Table 1 the tension crack depth varies between 4.5 and 7.2 m. In the BSTEM simulations the maximum tension crack depth used was 2.4 m.

Figure 4 shows that both tension crack depth and groundwater table can significantly affect factor of safety. Both a tension crack and an elevated groundwater table may have to occur to destabilize a 3 m vertical head cut. For example, for a tension crack depth of 2.4 m, groundwater table has to exceed half the height of the head cut (1.5 m) to cause collapse ($F_s < 1$).

During runoff events the free overfall 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 shows that the reduction in factor of safety is higher for larger tension cracks. For a triangular-shaped 30 cm undercut over the bottom 0.5 m, the gully head becomes unstable even for groundwater tables located at the gully bottom (Figure 4).

Using the properties listed in Table 1, BSTEM was used to determine the angle at which slopes of varying height would be unconditionally stable ($F_s > 1.3$). Figure 5 plots the stable slope angles as a function of slope height. The groundwater elevation was assumed to be 3 m. Gully heads and banks with angles not exceeding 45 degrees should be stable under fully saturated conditions in our study area.

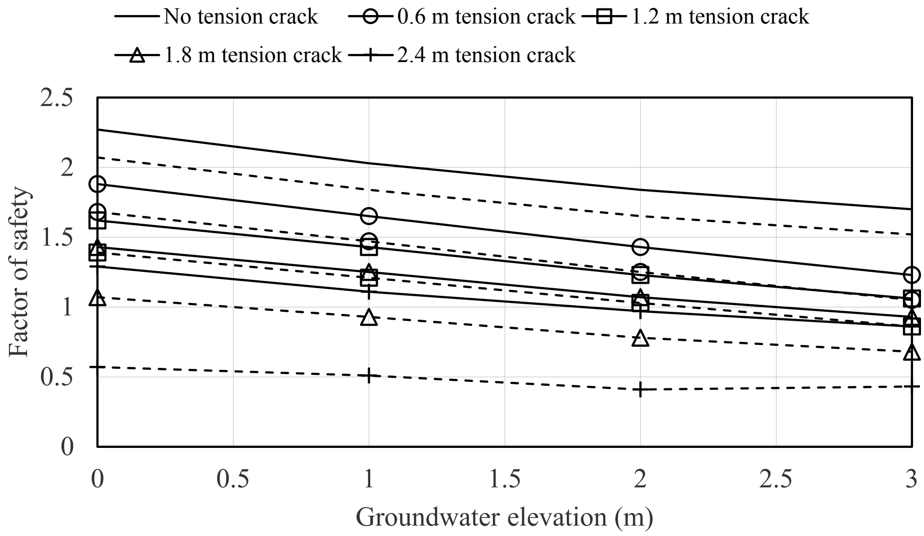

Figure 4. Factor of safety as a function of groundwater table and tension crack depth for a 3 m vertical head cut. Solid lines plot factor of safety without an undercut bank. Dashed lines plot factor of safety for a bank with a 30 cm undercut along the bottom 0.5 m of the bank.

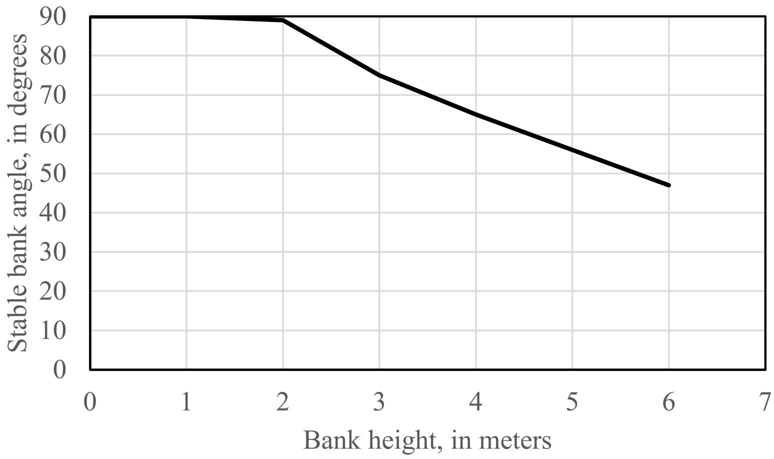

Figure 5. Stable slope angle for varying gully head or bank heights calculated by BSTEM using the soil properties listed in Table 1.

3.2 *CONCEPTS*

CONCEPTS was used 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. The measured cross-sectional profiles using total station and tape meter were used to build the CONCEPTS model geometry. The model geometry was constructed using the following parameters: channel slope is 3%, gully head cut and bank slopes are 100%, gully head height is 3 m, channel depth upstream is 1.5 m, and channel depth downstream is 4.5 m. The Manning n roughness coefficient was assumed to be 0.05 for the gully sidewalls and 0.03 for the gully bed. Two discharges were evaluated: the largest observed discharge of 0.5 m^3/s during the 2013 rainy season, and the largest to be expected discharge of 2 m^3/s calculated using the rational method.

Figure 6 plots the simulated water surface profiles. Flow depth for $Q = 0.5$ m^3/s equals about 0.15 m for most of the gully except immediately upstream of the gully head where flow depth reduces to 0.035 m. Water surface slope increases from 3.0% to 5.4% at the upstream end of the regraded head cut. For $Q = 2.0$ m^3/s, flow depth equals about 0.35 m for most of the gully except immediately upstream of the gully head where flow depth decreases to 0.11 m. Water surface slope increases from 3.0% to 8.0% at the upstream end of the regraded gully head cut.

The maximum shear stress is located at the upstream end of the gully head where water surface slope is largest. Simulated shear stresses for $Q = 0.5$ m^3/s vary between 45 Pa away from the gully head to 103 Pa at the upstream end of the gully head where flow velocity is about 7.2 m/s. For $Q = 2.0$ m^3/s, simulated shear stresses vary between 100 Pa away from the gully head to a little over 400 Pa at the upstream end of the gully head, where the velocity approaches 8 m/s. Note that the simulated flow is supercritical, and the values calculated by CONCEPTS, which uses a diffusion wave model, could therefore be overpredicted. Hydraulic Engineering Circular No. 11 (HEC-11) used by the US Federal Highway Administration to design riprap revetments (Brown and Clyde, 1989) gives a median particle size of 7.3 m for loose riprap to protect the regraded gully head against surface erosion. As those particle sizes are unrealistic for the studied gully, other means of surface protection need to be used. A rock and wire mattress with a thickness of 0.5 m would prevent erosion for flow velocities exceeding 7 m/s (Brown and Clyde, 1989). As this is too expensive to fabricate, it was decided to use bamboo sheets to protect the regraded gully head and sidewalls (Figure 7). The gully erosion control measure will be tested for the 2014 rainy season.

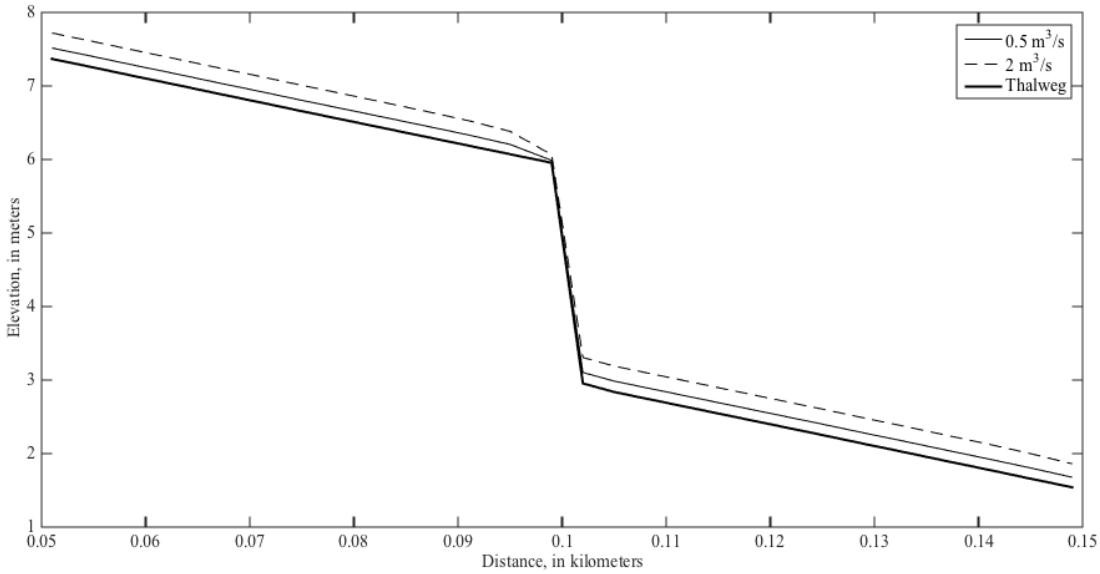

Figure 6. Simulated water surface profiles (thin lines) over a gully head regraded to 45 degrees (fat line) for discharges of 0.5 m^3/s and 2 m^3/s.

4 CONCLUSIONS

The USDA BSTEM and CONCEPTS computer models were used to aid in the design of new gully erosion control measures in the humid northern Ethiopian highlands, specifically the Debre-Mewi watershed. The developed measure consisted of the regrading of gully head cut and sidewalls to a stable slope and protection of the regraded soil surface. The main conclusions of the modeling effort are:

1. 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.
2. CONCEPTS predicted flow velocities up to 8 m/s and shear stresses as large as 400 Pa on the upstream end of the regraded gully head.
3. Natural, technical, and computational resources in developing countries such as Ethiopia to design and implement effective measures to halt pervasive land degradation processes are lacking or severely limited. A gradual introduction of computational modeling technology of increasing complexity, such as BSTEM and CONCEPTS, have major benefits in designing cost-effective erosion control measures.

NOTATION

A	flow area
c	effective cohesion
F_s	factor of safety
n	Manning roughness coefficient
Q	flow discharge
v	flow velocity
z_c	tension crack depth
γ	bulk soil unit weight
ϕ	friction angle

Figure 7. Construction of gully erosion control measure in the Debre-Mewi watershed, Ethiopia. Erosion control consists of regrading the gully head cut and sidewalls to approximately 40-45 degrees and protecting the soil surface with bamboo sheets and vegetation.

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