A low-cost subsurface drainage technique to enhance gully bank stability in the sub-humid highlands of Ethiopia

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Abstract: Gully erosion is the leading cause of elevated sediment yields in the world. Few low-cost techniques are available for rehabilitating gullies. The objective of this research was to evaluate the applicability of a low-cost horizontal sub-surface drainage system for decreasing gully erosion by stabilizing gully banks. The study was conducted in the sub-humid Ethiopian highlands in two active gullies, one in a Vertisol and another in a Nitisol. One bank was drained with a plastic pipe, and the other bank acted as the control. The two opposite banks are hydrologically isolated from one another. The surrounding groundwater tables were continuously monitored for two years. Over two wet seasons, the average bank retreat in the Vertisol gully was 0.62 m for the control and 0.15 m for the drained bank. Similarly, in the Nitisol gully, in 1.1 m for the control and 0.29 m for the drained bank. The average groundwater table of the drained bank was 20% lower than the non-drained banks during the monitoring periods. These results suggest that bank dewatering maintained higher levels of stability of gully banks and promoted lower rates of bank retreat on both soil types. The initial cost of the dewatering treatments was significantly less than the conventional bank stabilization measures. Bank dewatering could be one of the technologies for gully rehabilitation. Gully management techniques in Ethiopia and elsewhere could benefit from integrating bank drainage with other physical and biological protective measures.

Keywords: Ethiopian highlands; Debre Mawi; Gully; Bank retreat; Dewatering; Erosion.

1 INTRODUCTION

Gully erosion is one of the most damaging forms of soil erosion (Bartley et al., 2020; Tsegaye et al., 2020). Gully and riverbank failures and headcut retreats threaten agricultural land and infrastructure (Simon and Rinaldi, 2000). Valley bottom gullies are common in periodically saturated bottomlands and are silting up rivers and reservoirs (Addisie et al., 2016; Amare et al., 2019; Daba et al., 2003; Haregeweyn et al., 2013). Erosion from such gullies caused irreversible changes in soil productivity and food security (Sonneveld and Keyzer, 2016; Zegeye et al., 2017). Controlling and rehabilitating gully erosion is complex and expensive and requires knowledge of the gully formation.

Simon et al. (1999) reported that bank erosion is caused by the interaction of hydraulic forces operating at the bank toe (resulting in undercutting and steepening) and gravitational forces operating on the bank mass. Rates of bank failure are governed by bank height, angle, and the shear strength of the soil, which is highly sensitive to pore-water pressure within the bank material (Zegeye et al., 2020). When rainfall exceeds evaporation during the monsoon phase in Ethiopia, the water table rises and causes bank saturation. The increased saturation reduces the soil's shear strength (Simon et al., 1999) and increases the bank mass (Langendoen and Simon, 2008; Wilson et al., 2007; Zegeye et al., 2020). These shear strength and weight changes destabilize the bank and cause failures along incised channels (Langendoen et al., 2013; Simon et al., 2000). Thus, preventing water table rise and maintaining unsaturated conditions (negative pore water pressure) could provide greater bank stability and reduced mass failure frequency (Shields et al., 2009).

Gullies in the Ethiopian highlands formed after the deforestation in the late 1980s have been advancing uphill (Tebebu et al.,

2010; Zegeye et al., 2016). This upward headcut migration is one factor in gully expansion and sediment production (Addisie et al., 2016; Langendoen et al., 2013).

The soil and water conservation (SWC) measures introduced by the Ethiopian government in 2010, under the Growth and Transformation Program (GTP), have decreased soil loss in upland areas in northern Ethiopia when maintained properly (Dagneu et al., 2015; Mihret et al., 2019). However, any efforts to mitigate soil loss are jeopardized by eroding gullies downstream, increasing the sediment concentrations significantly (Zegeye et al., 2018). Thus, mitigating soil loss by gully erosion is essential in reducing soil loss from agricultural areas and siltation of reservoirs downstream.

Gully mitigation measures may include a combination of bank-toe protection to increase resistance to hydraulic forces (Clark and Wynn, 2007; Simon et al., 2008, 2011), decreasing soil saturation by the transpiration of vegetation (Langendoen and Simon, 2008; Simon and Collison, 2002), lowering water tables by artificial dewatering by installing horizontal drains (Crenshaw and Santi, 2004; Rahardjo et al., 2003) or regrading the bank slope to a smaller angle (Zegeye et al., 2017). Several studies have previously documented soil losses from upland and gully erosion in the Debre Mawi watershed (e.g., Tebebu et al., 2010; Zegeye et al., 2010, 2018). Previous attempts to stabilize gullies by gully plugs, vegetation, and decreasing the bank slope (Mihret et al., 2020; Zegeye et al., 2017, 2018) have not been successful (see Fig. 1b). The gully plug diverted the flow from the original streambed and initiated a new gully (Fig. 1a). Vegetation does not prevent bank failure for gullies more than 3 m deep (Fig. 1b; Zegeye et al., 2020). Regrading bank angle and installing check dams near the gully head significantly reduced the uphill migration initially (Zegeye et al., 2017). Still, the planted materials started to slide down, and this was due to the saturation of the surrounding area (Fig. 1b).

Fig. 1. a) Inappropriate diversion of flowing water created another new gully, b) physical and biological headcut treatment by Zegeye et al. (2017) and the red circle shows the failure of planted material on the reggraded bank due to wet bank, c) natural pipe dewatered the bank water and no failure was observed (Zegeye et al., 2016).

Therefore, stability might be increased by pumping subsurface water with vertical wells from the bank or providing passive dewatering through horizontal drains (Shields et al., 2009). In a previous study, Zegeye et al. (2016) observed that one of the monitored gullies did not advance uphill for two consecutive years because the bank was dewatered through natural conduits in the gully bank (Fig. 1c). Therefore, this research aimed to evaluate the applicability of a low-cost horizontal drain for stabilizing a rapidly eroding gully bank in the (sub) humid Ethiopian highlands.

2 MATERIALS AND METHOD

Area descriptions

The experiment was conducted in the 608 ha Debre Mawi watershed. This watershed is near Lake Tana, 40 km south of Bahir Dar in the upper Blue Nile Basin at 11°20'13" N and 37°25'55" E (Fig. 2b). The watershed is underlain by shallow, highly weathered, and fractured basalt overlain by dark brown compacted clay, followed by light brown wet and sticky clay soil and then finally by black clay and organic-rich soil se-

Fig. 2. Location and gully network of the Debre Mawi watershed. (a) Ethiopia with neighboring countries; (b) the gully network in 2013, with a combined surface area of about 20 ha, superimposed on the topographic wetness index (TWI) of the Debre Mawi watershed (the study gullies (G1 is at Nitisol, G2 is at Vertisol) are located in the red rectangles).

quences (Abiy, 2009). The thickness of the clay varies from shallow and highly eroded in the upper sections to deep in the valley bottoms. The area topography is hilly at the upper sides and gentle slope downstream, with slopes ranging from 1 to 30%. The climate is semi-humid with an average temperature of 20°C, and 1,240 mm a⁻¹ annual rainfall, of which more than 70% occur from June to August. In the Debre Mawi watershed, gullies are located in the periodically saturated bottomlands (Fig. 2b) and are expanding rapidly, increasing about four-fold from 2005 to 2013 (Mhired et al., 2019; Zegeye et al., 2016). On the cultivated slopes, sheet and rill erosion occurs, but soil loss from these is much less than from the gullies erosion (Amare et al., 2019; Zegeye et al., 2018).

Experimental setup

Two active gullies, one in a Vertisol and one in a Nitisol, were selected in the watershed in 2018 and with additional two gullies with similar soil characteristics in 2019 to represent gullies in similar agroecology settings. The study was conducted on the upper portions of gullies that were actively eroding and had vertical bank angles. For example, the length of one of the banks in each vertisol gully was 3 m in 2018 and 4 m in 2019. Similarly, in Nitisol gullies, it was 4 m in 2018 and 6 m long in 2019. The maximum gully depths were 2.5 m in Vertisol and 3.92 m in Nitisol gullies in 2018 and were 2.9 m in Vertisol and 4.68 m in Nitisol gullies in 2019. The reason for selecting different gullies in 2019 was modifications to the methodology during that year, as explained below. The hydrologically isolated left and right banks of a gully near the head cut were considered experimental plots. The left banks were control plots that were not dewatered, and the right banks were passively dewatered using horizontal drains.

In the drained plots, the drainage systems installation and configuration were different in 2018 and 2019. In 2018, a total

of 28 (12 in Vertisol and 16 in Nitisol) 1.5 m long perforated pipes, 5-mm diameter, were mechanically inserted horizontally perpendicular to the bank with a one-meter vertical interval starting from the bank's top and with 0.5 m horizontal interval on July 1, 2018 (Fig. 3a). They were wrapped with filter fabric to prevent sediment entrance. However, when the pipe was pushed into the bank, the filter fabric sheared of the pipe. Consequently, the unprotected pipes without filter fabric were filled with sediment after a few days limiting the subsurface water drainage through the pipe. The pipes were installed too close to the surface, and few pipes in the Nitisol were above the water table.

In the second year (2019), the drainage installation method was modified. In the Vertisol 26 and the Nitisol 14, 3 m long holes with a diameter of 50 mm were drilled horizontally, just 50 cm from the bottom in the gully banks. Then, 3 m long and 50 mm diameter perforated PVC pipes wrapped with filter fabric were inserted into the holes in July 5, 2019.

Groundwater tables were measured with two 3 m long piezometers at each bank at distances of 3 and 6 m from the bank. The intrusion of sediment to the piezometer was prevented by wrapping filter fabric around the 40 cm long screened bottom end. All piezometers were capped to prevent rainwater entry and were set in concrete to prevent any physical damage. Groundwater table elevations were first measured using a stick, and then the wetted stick was again read using a measuring tape twice a day: in the morning and evening. The water table was recorded from July 09 to October 03, 2018, and from July 12 to October 19, 2019.

Gully geometry and soil loss

Cross-sectional geometry surveys were conducted twice a year before and after the rainfall. Three cross-sections, 3 m apart from each other, covering a total of 16 m length (i.e., the

sum of the lengths of experimental sections of the four gullies) from the gully head, were surveyed. The cross-section was vertically divided into trapezoidal segments at abrupt changes in the gully profile (Fig. 3b). To compute the bank erosion from the treated and control gully banks, the cross-section area of each gully bank was calculated. The width and depth of the gully were measured, and the cross-sectional area connecting the two opposite gully banks (A) and the cross-sectional area of a gully bank (a) were calculated as:

$$A = \frac{1}{2} \sum_{i=1}^{N-1} |(W_i H_{i+1} - W_{i+1} H_i)| \quad (1)$$

$$a = \frac{1}{2} \sum_{k=1}^{n-1} |(w_k h_{k+1} - w_{k+1} h_k)| \quad (2)$$

where N is the number of trapezoidal segment sides of height H and located a distance W from the left gully edge in a cross-section, i is a trapezoidal segment index, W is cross-section width, n is the number of triangular segment sides of the bank, and located a distance w from the right gully bed to the right gully edge for the right bank and or a distance w from the left gully bed to left gully edge for the left bank in a cross-section, k is a triangular segment index.

Fig. 3. (a) Experimental designs that show piezometers, pivots for gully dimension measurements, the white circles indicate where the horizontal drains are installed, (b) a trapezoidal cross sectional segmentation methodology to determine the cross-sectional area of Vertisol gully-2018 as an example.

The entire gully volume (V) and a gully bank volume (v) was determined as:

$$V = \sum_{j=1}^{m-1} \frac{1}{2} L_j (A_j + A_{j+1}) \quad (3)$$

$$v = \sum_{j=1}^{m-1} \frac{1}{2} L_j (a_j + a_{j+1}) \quad (4)$$

where j is cross-section index, m is the total number of cross-sections, and L_j is the length of the channel between cross-sections j and $j+1$.

3 RESULTS AND DISCUSSION

Gully bank volumetric retreat

Bank edge observations demonstrated that both banks initially experienced similar retreat rates, associated with wetting up after the first rainfalls in June until the treatment began during the last weeks of July on both study years. However, retreat slowed and stopped sooner on the drained banks, and thus total retreat was much less (Table 1, Fig. 4). The drained banks experienced a much slower retreat, with only minor sloughing off the bank face.

As observed in Fig. 4, the second cross-section (CS-2) of Vertisol in 2018 showed that the saturated untreated (control) bank failure debris filled the gully channel that reduced the channel depth until moved by the flowing water downstream. However, the positive change in the same cross-section area (0.6 m^2) was due to the sidewall retreat that compensated the area filled by the bank debris. Generally, the annual average cumulative bank retreat in the three cross-sections on the drained banks of the Vertisol was smaller than the controlled banks by 52% in 2018 and by 84% in 2019. Similarly, in Nitisol, the bank retreat was reduced by 72% in 2018 and 81% in 2019 (Table 1). Over the entire experiment, the 16 m long drained banks lost about 14 m^3 of soil, 70% less than the control. The results show that dewatered banks retreated about one-fourth as fast as the control. The greater stability of the drained bank over the control bank is that the pore-water pressure in the drained bank is less, resulting in a reduced bank mass and an increase in the shear strength of the bank material. This result is supported by Léonard and Richard (2004) and De Beets et al. (2008). They reported a significant linear relationship between saturated soil shear strength and critical shear stress (defined as the stress at which soil detachment begins or the condition that initiates soil detachment). If the critical stress is greater than the effective stress, the erosion rate is zero (Clark and Wynn, 2007).

Table 1. Average groundwater table (GWT) depth, average bank retreat, increase in cross-sectional area, and the change in volume in 6 m length gully from the gully head.

Parameter	2018				2019			
	Vertisol		Nitisol		Vertisol		Nitisol	
	Contr.	Drained	Contr.	Drained	Contr.	Drained	Contr.	Drained
Aver. groundwater depth (m)	0.73	1.1	2.36	2.54	0.49	0.84	2.46	2.76
Aver. bank retreat (m)	0.42	0.2	1.7	0.48	0.83	0.13	0.53	0.1
Aver. Incr. cross-sectional area (m^2)	1.4	0.6	6.3	2.0	3.75	1.62	3.14	0.03
Ave, Incr. in volume (m^3)	7.1	3.3	17.7	5.6	12.7	4.87	9.43	0.09

Fig. 4. Observed changes in gully geometry at Vertisol and Nitisol in 2018 and 2019 during the study periods at Debre Mawi. 'ARF' stands for 'after rainfall', 'BRF' for 'before rainfall', 'CS-1' for 'cross-section near the head' (a total of three CSs spaced by 3m from the head to downwards).

Effect of dewatering on the groundwater table

The effectiveness of artificial dewatering was evaluated by comparing data from the piezometer readings at 3 m and 6 m away from both control and treated banks (Table 1, Fig. 5). A lower water table level indicates lower pore water pressure that translates to greater resistance to mass failure through its effect on apparent cohesion.

As indicated in Fig. 5, piezometers installed near the gully edge showed that the water table in these areas was deeper than elsewhere. On the other hand, the water table elevation (Fig. 5) was entirely above the gully bottom, indicating that the gully bank is highly saturated. This lowers the shear strength of the bank material, destabilizing the gully banks. Tebebu et al. (2010) and Zegeye et al. (2016) reported that saturation is the leading cause of gully formation and gully bank sliding. Since the gully bank was saturated (Fig. 4), the pore-water pressure due to rising groundwater elevation has played a crucial role in triggering gully formation. This result is supported by several authors (e.g., Langendoen et al., 2013; Simon et al., 2008; Tebebu et al., 2010; Zegeye et al., 2016, 2020).

In the study gullies, the piezometer readings show that the control gully banks were wetter than the treated (drained) right banks during the testing periods (Table 1, Fig. 5). It means that gully banks in which draining pipes were installed were relatively stable as water drains out through the pipes resulting in water table drawdown resulting in lower pore-water pressures.

In this case, the shear strength of the bank materials increases and reduces bank failure, which is in line with the studies of Simon et al. (2011) and Zegeye et al. (2020).

As shown partially in Figure 6, the discharge of the five pipes was different. The upper two stopped quickly two days after the installation when the water table dropped below the inlet. Apparent differences in the volume of water discharged through the pipes suggest that perhaps groundwater movement through the site was heterogeneous. Direct comparison of bank dewatering between the two gullies is not possible due to the site-specific conditions at each gully. Nevertheless, the result demonstrated that the comparison is still possible within the gullies between left and right banks.

From our field observation, although the water table was near the surface in Vertisol gully banks, the pipes installed in these banks drained very slowly compared to the Nitisol banks. The soil hydraulic conductivity and stratigraphy between the two soil types explain the different behavior. Valentin et al. (2005) and Frankl et al. (2016) reported about Vertisols that consist of deep clay material which has relatively poor hydraulic conductivity (lower porosity and permeability) than nitisols. The smaller the sediment grains' size, the larger the surface area the water contacts that increases the frictional resistance to flow, which reduces the permeability, as reported by Norris and Fidler (1965) as the intrinsic permeability is proportional to the grain size of the sediment. Moreover, Nitisols have more stable aggregates than a swelled Vertisol.

Fig. 5. Groundwater table at 3 m and 6 m from the edge of Vertisol and Nitisol in 2018 and 2019 during the study periods at Debre Mawi. 'LB' stands for 'left bank and represents the control' and 'RB' for 'right bank' and is the drained site of the gully bank. The Nth day stands for the water table (WT) recording date, i.e., from July 9 to October 3 in 2018 and from July 12 to October 19 in 2019.

Fig. 6. Observed discharges during installing the horizontal drain pipes in Vertisol gully at Debre Mawi watershed (2019). The man is drilling the bank using an auger with a similar diameter with PVC pipes to be inserted.

4 CONCLUSION AND RECOMMENDATION

Only a few studies worldwide have documented the relationship between dewatering gully banks and bank stability. During the study periods, the groundwater table monitoring demonstrated that dewatering gully banks lowered the level of the surrounding groundwater table. Bank dewatering may be practical to protect critical infrastructure and provide a potential means of temporarily stabilizing a bank until vegetation is established. Passive drains are a promising method to improve bank stability by lowering the water table. The results suggest that bank dewatering promoted lower bank retreat rates and a greater level of stability of gully banks on both soil types with a low initial cost compared with other bank stabilization methods; the total initial cost was 400 Ethiopian Birr (10 USD) for drained plots. Each plot stabilized about 4 m of bank length for 100 Ethiopian Birr m^{-1} . In comparison, the costs of approximately 300 Ethiopian Birr m^{-1} for gully stabilization using regrading and riprap, though there are recurrent costs associated with the dewatering system maintenance.

The discharge from the draining pipes should be safely disposed of and join to the main channel. It may be advisable to install an apron below each drain to dissipate the falling discharge energy scour under the pipe. Generally, integrating bank dewatering with other gully rehabilitation measures, including physical and biological measures, should be considered on future gully rehabilitation packages.

Further research on improving the drain's performance could be by modifying drain design parameters (depth and spacing) using better information regarding soil permeability and hydraulic characteristics than we had available.

Acknowledgements. This research was financially supported by the second Agricultural Growth Program (AGP II) of the Amhara Agricultural Research Institute (ARARI). Our thanks go to

Mr. Mulugeta Worku, Mrs. Debebe Alemu, and Assefa Admassu for their field assistance.

REFERENCES

- Abiy, A.Z., 2009. Geological Controls in the Formations and Expansions of Gullies over Hillslope Hydrological Processes in the Highlands of Ethiopia. Cornell University, Northern Blue Nile Region.
- Addisie, M., Ayele, G., Gessess, A., Tilahun, S., Zegeye, A., Moges, M., Schmitter, P., Langendoen, E., Steenhuis, T., 2017. Gully head retreat in the sub-humid Ethiopian highlands: The Ene-Chilala catchment. *Land Degradation & Development*, 28, 5, 1579–1588. DOI: 10.1002/ldr.2688
- Amare, S., Keesstra, S., van der Ploeg, M., Langendoen, E., Steenhuis, T.S., Tilahun, S., 2019. Causes and controlling factors of valley bottom gullies. *Land*, 8, 9, 141. <https://doi.org/10.3390/land8090141>
- Bartley, R., Poesen, J., Wilkinson, S., Vanmaercke, M., 2020. A review of the magnitude and response times for sediment yield reductions following the rehabilitation of gullied landscapes. *Earth Surf. Proc. Land.*, 45, 13, 3250–3279.
- Clark, L.A., Wynn, T.M., 2007. Methods for determining stream-bank critical shear stress and soil erodibility: Implications for erosion rate predictions. *Transactions of the ASABE*, 50, 1, 95–106.
- Crenshaw, B.A., Santi, P.A., 2004. Water table profiles in the vicinity of horizontal drains. *Environmental & Engineering Geoscience*, 10, 191–201.
- Daba, S., Rieger, W., Strauss, P., 2003. Assessment of gully erosion in eastern Ethiopia using photogrammetric techniques. *Catena*, 50, 2, 273–291.
- Dagnaw, D.C., Guzman, C.D., Zegeye, A.D., Tibebe, T.Y., Getaneh, M., Abate, S., Zemale, F.A., Ayana, E.K., Tilahun, S.A., Steenhuis, T.S., 2015. Impact of conservation practices on runoff and soil loss in the sub-humid Ethiopian Highlands: The Debre Mawi watershed. *Journal of Hydrology and*

- Hydromechanics, 63, 214–223.
- De Baets, S., Poesen, J., Reubens, B., Wemans, K., De Baerde-maeker, J., Muys, B., 2008. Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. *Plant and Soil*, 305, 207–226.
- Frankl, A., Deckers, J., Moulart, L., Van Damme, A., Haile, M., Poesen, J., Nyssen, J., 2016. Integrated solutions for combating gully erosion in areas prone to soil piping: Innovations from the drylands of Northern Ethiopia. *Land Degradation & Development*, 27, 8, 1797–1804F. DOI: 10.1002/ldr.2301
- Haregeweyn, N., Poesen, J., Verstraeten, G., Govers, G., Vente, J., Nyssen J., Deckers, J., Moeyersons, J., 2013. Assessing the performance of a spatially distributed soil erosion and sediment delivery model (WATEM/SEDEM) in Northern Ethiopia. *Land Degradation & Development*, 24, 2, 188–204.
- Langendoen, E.J., Simon, A., 2008. Modeling the evolution of incised streams. II: streambank erosion. *Journal of Hydraulic Engineering*, 134, 905–915.
- Langendoen, E., Tebebu, T., Steenhuis T., 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., Sharma, S. (Eds.): *Proceedings Conference on Science and Technology Towards the Development of East Africa (ICST 2013)*. Bahir Dar University Institute of Technology, Ethiopia.
- Léonard, J., Richard, G., 2004. Estimation of runoff critical shear stress for soil erosion from soil shear strength. *Catena*, 57, 233–249. DOI: 10.1016/j.catena.2003.11.007
- Mhired, D.A., Dagnew, D.C., Assefa, T.T., Tilahun, S.A., Zaitchik, B.F., Steenhuis, T.S., 2019. Erosion hotspot identification in the sub-humid Ethiopian highlands, *Ecohydrology & Hydrobiology*, 19, 1, 146–154. <https://doi.org/10.1016/j.ecohyd.2018.08.004>
- Mhired, D.A., Dagnew, D.C., Guzman, C.D., Alemie, T.C., Zegeye, A.D., Tebebu, T.Y., Langendoen, E.J., Zaitchik, B.F., Tilahun, S.A., Steenhuis, T.S., 2020. A nine-year study on the benefits and risks of soil and water conservation practices in the humid highlands of Ethiopia: The Debre Mawi watershed. *Journal of Environmental Management*, 270, 110885
- Norris, S.E., Fidler, R.E., 1965. Relation of particle size to permeability of a glacial outwash aquifer at Piketon, Ohio. *U.S. Geol. Survey Prof. Paper* 525-D, pp. D203–D206.
- Rahardjo, H., Hritzk, K.J., Leong, E.C., Reza, R.B. 2003. Effectiveness of horizontal drains for slope stability. *Engineering Geology*, 69, 295–308.
- Shields Jr., F.D., Simon, A., Dabney, S.M., 2009. Streambank dewatering for increased stability. *Hydrol. Process.*, 23, 1537–1547. DOI: 10.1002/hyp.7286
- Simon, A., Curini, A., Darby, S.E., Langendoen, E.J., 1999. Streambank mechanics and the role of bank and near-bank processes in incised channels. In: Darby SE, Simon, A. (Eds): *Incised River Channels: Processes, Forms, Engineering and Management*. John Wiley and Sons, Chichester, pp. 123–152.
- Simon, A., Rinaldi, M., 2000. Channel instability in the loess area of the Midwestern United States. *Journal of American Water Resources Association*, 36, 133–150.
- Simon, A., Curini, A., Darby, S.E., Langendoen, E.J., 2000. Bank and near-bank processes in an incised channel. *Geomorphology*, 35, 183–217.
- Simon, A., Derrick, D., Alonso, C.V., Pollen, N., 2008. Application of a deterministic bank-stability model to design a reach-scale restoration project. In: Babcock Jr., R.W., Walton, R. (Eds.): *Proceedings of the World Environmental and Water Resources Congress 2008 Ahupua'a* [CD-ROM]. Am. Soc. of Civ. Eng., Reston, Va.
- Simon, A., Pollen-Bankhead, N., 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., Castro, J.M. (Eds.): *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*. AGU, Washington, DC, pp. 453–474.
- Simon, A., Collison, A.J.C., 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. *Earth Surface Processes and Landforms*, 27, 5, 527–546.
- Sonneveld, B., Keyzer, M., 2003. Land under pressure: soil conservation concerns and opportunities for Ethiopia. *Land Degradation & Development*, 14, 1, 5–23.
- Tebebu, T.Y., Abiy, A.Z., Zegeye, A.D., Dahlke, H.E., Easton, Z.M., Tilahun, S.A., Collick, A.S., Kidnau, S., Moges, S., Dadgari, F., Steenhuis, T.S., 2010. Surface and subsurface flow effect on permanent gully formation and upland erosion near Lake Tana in the northern highlands of Ethiopia. *Hydrology and Earth System Sciences*, 14, 2207–2217.
- Tsegaye, T., Mekonnen, M., Zegeye, A.D., 2020. Gully erosion and its impacts on soil loss and crop yield in three decades, northwest Ethiopia, *Model. Earth Syst. Environ.*, ISSN 2363-6203. DOI 10.1007/s40808-020-01018-y
- Yazie, T., Mekonnen, M., Derebe, A., 2020. Gully erosion and its impacts on soil loss and crop yield in three decades, northwest Ethiopia. *Modeling Earth Systems and Environment*. <https://doi.org/10.1007/s40808-020-01018-y>
- Valentin, C., Poesen, J., Li, Y., 2005. Gully erosion: Impacts, factors and control. *Catena*, 63, 132–153.
- Wilson, G.V., Periketi, R., Fox, G.A., Dabney, S., Shields Jr., F.D., Cullum, R.F., 2007. Soil properties controlling seepage erosion contributions to streambank failure. *Earth Surface Processes and Landforms*, 32, 447–459.
- Zegeye, A.D., Steenhuis, T.S.; Blake, R.W., Kidnau, S., Collick, A.S., Dadgari, F., 2010. Assessment of soil erosion processes and farmer perception of land conservation in Debre Mawi watershed near Lake Tana, Ethiopia. *Ecohydrology & Hydrobiology*, 10, 2, 297–306.
- Zegeye, A.D., Langendoen, E.J., Stoof, C.R. Tilahun, S.A., Dagnew, D.C., Zimale, F.A., Guzman, C.D., Yitaferu, B., Steenhuis, T.S., 2016. Morphological dynamics of gully systems in the sub-humid Ethiopian Highlands: The Debre Mawi watershed. *Soil*, 2, 443–458.
- Zegeye, A.D., Steenhuis, T.S., Mekuria M., Dagnew D.C., Addisie M.D., Tilahun, S.A., Tadele, A.K., 2017. Effect of gully headcut treatment on sediment load and gully expansion in the sub-humid Ethiopian highlands. *Environment and Ecology Research*, 5, 2, 138–144. DOI: 10.13189/eer2017.050208
- Zegeye, A.D., Langendoen, E.J., Guzman, C.D., Dagnew, D.C., Amare, S.D., Tilahun, S.A., Steenhuis, T.S., 2018. Gullies, a critical link in landscape soil loss: A case study in the sub-humid highlands of Ethiopia. *Land Degradation & Development*, 29, 4, 1222–1232. DOI: 10.1002/ldr.2875
- Zegeye, A.D., Langendoen, E.J., Steenhuis, T.S., Tilahun, S.A., 2020. Bank stability and toe erosion model as a decision tool for gully bank stabilization in sub humid Ethiopian highlands. *Ecohydrology & Hydrobiology*, 20, 2, 301–311. <https://doi.org/10.1016/j.ecohyd.2020.02.003>

Received 28 August 2020

Accepted 30 June 2021