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Integrated impact assessment of soil and water conservation structures on runoff and sediment yield through measurements and modeling in the Northern Ethiopian highlands

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ABSTRACT

Developing countries with an increasing population like Ethiopia experience degradation of land and water resources. To tackle this problem soil and water conservation (SWC) has been practiced and recently promoted by the Ethiopian government. However, the effectiveness of SWC practices on runoff and soil erosion have not been studied in detail for their long- and short-term effects. An integrated measurement and modeling study was conducted from 2012 to 2014 in the Gumara-Maksegnit sub watershed to assess the impacts of SWC structures on runoff and sediment yield using the Geospatial Interface for the Water Erosion Prediction Project (GeoWEPP) model. The study was conducted in two adjacent, smaller watersheds where SWC structures were constructed in one of the watersheds (treated sub watershed), while the other one was a control watershed without SWC structures (untreated sub watershed). The treated sub watershed has an area of 27.1 ha and the untreated sub watershed has an area of 31.7 ha. Runoff and sediment yield were compared based on the observations and GeoWEPP model simulations. The GeoWEPP model simulation results predicted the daily runoff satisfactorily for both sub watersheds (R^2 = 0.68 and NSE = 0.43 for untreated and R^2 = 0.61 and NSE = 0.84 for treated sub watershed). Similarly, the model prediction showed satisfactory results in sediment yield (R^2 = 0.61 and NSE = 0.59 for untreated and R^2 = 0.57 and NSE = 0.81 for treated sub watershed). SWC structures reduced slope gradient and changed flow accumulation. The observation and simulation study concluded that the treated sub watershed surface runoff was reduced by about 19% as compared to the untreated sub watershed. Similarly, the model estimated that SWC structures constructed in the treated sub watershed reduced the total area that generates soil loss above the set target limit of 10 t ha^{-1} y^{-1} from 49% to 38% of the watershed area. SWC has led to a significant reduction in sediment yield by 28 to 38% in these highland watersheds of Ethiopia. The results confirmed that SWC structures have a significant impact to prevent land degradation in the Ethiopian highlands.

1. Introduction

In Ethiopia soil erosion, and the consequent land degradation are recognized as major constraints to agricultural productivity and food security (Hengsdijk et al., 2005; Erkossa et al., 2015; Taguas et al., 2015; Ganasri and Ramesh, 2015; Keesstra et al., 2016; Nigussie et al., 2017), and the severity increases from the lower lying areas to the highlands of Northern Ethiopia (Yeshaneh et al., 2014; Jemberu et al., 2017). Continued soil erosion threatens peoples' livelihoods, especially in drought prone highlands, where arable land is a scarce resource. Research conducted in the highlands of Ethiopia shows that deforestation for the expansion of agricultural lands and rangelands has led to increased soil losses and the growth of rock outcrops, nutrient depletion, decreased agricultural productivity, and environmental degradation (Woldeamlak and Stroosnijder, 2003; Belay et al., 2014).

The Ethiopian government promotes soil and water conservation (SWC) technologies through community mobilization for improved agricultural productivity, food security, and the livelihood of the

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population, simultaneously mitigating environmental degradation (Tesfaye et al., 2014a, 2014b; Haregeweyn et al., 2015; Gessesse et al., 2016). Since 2010, a massive effort has been undertaken in constructing SWC structures on privately owned and community lands through community mobilization (Kebede, 2014; Teshome et al., 2016). These structural SWC Management Practices (MPs) such as stone bunds, soil bunds, percolation ditches, etc., are constructed (Amare et al., 2014; Teshome et al., 2016) in a coordinated effort by the government with local famers and community members. However, the effectiveness of these soil and water conservation measures on the dynamics of runoff and sediment loading has not been sufficiently studied and identified clearly for long and short-term effects in the Ethiopian highlands.

Sustainable development in SWC management requires long-term and reliable information on hydrological, soil, and vegetative characteristics of the region of interest. Poor and insufficient information on soil erosion and stream flow lead to unsound planning and inadequate design and operation of SWC measures (Poitras et al., 2011). The prediction and assessment of stream flow and sediment loss using a watershed model is important for agricultural watershed management, as watershed models are crucial tools in assessing hydrological processes.

The primary purpose of the watershed modeling exercise is to assist in the estimation of the parameters relevant for the water balance. However, the selection of an appropriate model depends on the function that the model desires to serve (Merritt et al., 2003). There are a number of factors which influence the performance of watershed modeling which include satellite image resolution and methods of classification, Digital Elevation Model (DEM) resolution, the sizes of measured sample volume, location, the spacing of weather stations, etc. Therefore, minimizing the uncertainty of the model input parameters is a challenging task.

GeoWEPP, the Geospatial interface of the Water Erosion Prediction Project (GeoWEPP) model, was developed to integrate the advanced features of GIS (Geographical Information System) within the WEPP (Water Erosion Prediction Project) model, such as processing digital data sources and generating digital outputs (Renschler et al., 2002a, 2002b; Renschler, 2003).

In the Ethiopian highlands deforestation for crop production dramatically increased the vulnerability of the soils for rainfall driven soil erosion (Nyssen et al., 2000). Intensive rainfalls during the rainy season (June to September) threaten the mountainous regions with severe land degradation especially on the steep sloped and unprotected areas (Addis et al., 2016). To tackle this problem, SWC measures in Ethiopia are now considered a top priority to maintain the natural ecosystem and improve agricultural productivity for achieving food self-sufficiency.

Massive efforts are being made in SWC strategies by the Ethiopian government agencies. However, the effectiveness of this soil and water conservation on the runoff dynamics and sediment loading is not studied and identified clearly for long- and short-term effects. Therefore, this watershed study was designed to address gaps in the knowledge of the effectiveness of one of the mostly applied SWC measures and to assess the effects of stone bunds in a treated watershed in comparison to an untreated watershed using observation and GeoWEPP model simulations.

2. Materials and methods

2.1. Description of the study area

The two Gumara-Maksegnit study watersheds in northwest Ethiopia – the treated watershed (TW) with SWC measures and untreated watershed (UW) (Fig. 1) drain next to each other into the Gumara River, which ultimately drains into Lake Tana, the largest lake in Ethiopia. The watershed outlets of the paired watersheds are located at 12°25′24″ and 12°25′54″ latitude and at 37°34′56″ and 37°35′38″ longitude and at an altitude ranging from 1998 to 2150 meter above sea level for the treated and untreated watershed (Fig. 1).

The two watersheds are experimental watersheds selected by researchers and scientists from different organizations (Bayu et al., 2015); ICARDA (International Center for Agricultural Research in Dry Areas, Aman, Jordan), GARC (Gondar Agricultural Research Center, Gondar, Ethiopia) ARARI (Amhara Agricultural Research Institute, Bahirdar, Ethiopia), and BOKU (University of Natural Resources and Life Sciences, Vienna, Austria). The paired watershed was selected by researchers in these participating organizations because it is representative for this region with respect to land use and topography (Bayu et al., 2015). Since there was no Digital Elevation Model (DEM) or official survey, a topographic survey was conducted in collaboration with these organizations. A total of 2256 surveying points were taken in both watersheds to interpolate a contour map and derive an accurate DEM. Especial emphasis was taken to measure the points where the topography changes drastically (higher point density) in contrast to consistently shaped areas (lower point density). From those points a 1 meter contour map was derived, a 5-m raster DEM was developed using the widely used ArcGIS interpolation method “Topo to raster”. After the interpolation each raster cell that included a stone bund was elevated by 0.4 m. The derived hydrological features such as flow accumulation and the starting points of channelized flow in the watersheds, were derived by TOPAZ and used to validate the observed drainage patterns in both watersheds treated and untreated. For both watersheds, a critical source area (CSA) of 5 ha and a minimum source channel length (MSCL) of 50 m were selected to match the observed channelized flow in the field. Even though the 5 m raster is relatively coarse the accumulated flow lines matched very well with the observed in the field. Having said that, higher resolution DEM lower than 5 m were deemed not appropriately addressed in the watershed.

The two study sub watersheds are neighboring each other at a distance of 1 km between the outlets. The TW has an area of 27.1 ha and the UW has an area of 31.7 ha. The slope of the sub watershed ranges from 2% to 69% with an average slope of 14.8%. The soil types in the sub watersheds are Cambisol and Leptosol, which are found in the upper and central part of the watershed, while Vertisol is found in the lower part of the sub watersheds. The sub watersheds have a long term average annual rainfall of 1157 mm (1997 to 2015), with 80% falling from June to September, and a mean monthly minimum and maximum temperature of 13.3 °C and 28.5 °C, respectively (Addis et al., 2016).

In 2011 stone bunds were constructed as SWC measures in the treated sub watershed (TW) (Fig. 2). On farmlands 40 cm high with average top width of 35 cm graded stone and soil bunds (Fig. 3) at distances ranging between 15 and 25 m depending on the steepness of the land were constructed along the contour. The main staple food crops in the watershed are sorghum, teff, barley, beans, wheat and corn. The main crop rotations are chickpea followed by teff followed by sorghum (rotation 1: chickpea-teff-sorghum), chickpea followed by wheat followed by sorghum (rotation 2: chickpea-wheat-sorghum), and beans followed, barley followed by corn (rotation 3: beans-barley-corn).

2.2. Runoff discharge and sediment yield monitoring

Runoff and sediment yield were determined at the outlet of both sub watersheds where rectangular v-notch weirs with flow sensors and automatic cameras were installed in 2011 (Fig. 4). Gauges were marked on the walls of the weirs and the cameras took pictures every 2 min during flow events (Fig. 4). Using proper weir equation, continuously measured water depth allows the calculation of run-off simultaneously (Bos, 1990).

$$Q = 4.28\, C\, \tan\left(\frac{\theta}{2}\right)(h + k)^{5/2}$$

where, Q = discharge, C = discharge coefficient, θ = Notch angle, h = head and k = head correction factor.