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Assessing the effect of water harvesting techniques on event-based hydrological responses and sediment yield at a catchment scale in northern Ethiopia using the Limburg Soil Erosion Model (LISEM)

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ABSTRACT

Runoff and sediment yield in semi-arid catchments are highly influenced by infrequent but very heavy rains. These events occur over short temporal scales, so runoff and sediment transport can only be understood using an event-based analysis. We applied a hydrological and soil-erosion model, LISEM, to the Gule catchment (~12 km^2) in northern Ethiopia. The objectives of the study were: (a) to evaluate the performance of LISEM in describing event-based hydrological processes and sediment yield in a catchment under the influence of different water harvesting techniques (WHTs), and (b) to study the effect of the WHTs on catchment-scale event-based runoff and sediment yield. The model performed satisfactorily (NSE > 0.5) for most of the events when discharge was calibrated at the main outlet (Gule) and at a sub-outlet (Misbar). Runoff coefficients for the Gule catchment and Misbar sub-catchment were expectedly low due to the implementation of WHTs, which can store runoff from the rains and increase infiltration into the soil. Simulated and measured sediment yields were of similar orders of magnitude. LISEM generally overestimated sediment yield compared to the measurements. The poor performance of LISEM in predicting sediment yield could be attributed to the uncertainty of several factors controlling soil erosion and the inadequacy of LISEM in describing soil erosion on steep slopes. Catchment-scale model simulations indicated that runoff and sediment yield could be effectively reduced by implementing WHTs. The model estimated 41 and 61% reductions in runoff and sediment yield at the Gule outlet, respectively. Similarly, runoff and sediment yield at the Misbar sub-outlet were reduced by 45 and 48%, respectively. LISEM can thus be used to simulate the effects of different existing or new WHTs on catchment hydrology and sediment yield. The results of scenario predictions could be useful for land-use planners who intend to implement different measures of catchment management.

1. Introduction

Land degradation is considered as a threat to the environment and for future sustainable agricultural production. Increased pressure on natural resources caused by high population density has led to land degradation in the Ethiopian highlands (Nyssen et al., 2009). Gully erosion, which is caused by the erosive action of flash floods, has a devastating effect especially in arid environments (Frankl et al., 2016). Gully erosion, for example, was responsible for the loss of 17.6 Mg ha^{-1} y^{-1} of soil loss over the years 1963 to 1994 in northern Ethiopia (Frankl et al., 2013). In south-west Ethiopia, land degradation is mainly caused by deforestation as a result of converting forests to agroforestry and cereal-based cropping systems (Kassa et al., 2017). Soil loss in the Ethiopian highlands is generally estimated to be around 1.9 billion Mg y^{-1} (FAO, 1986). Soil degradation by water erosion is the principal cause for low and declining agricultural productivity in Ethiopia (Araya et al., 2011). Runoff and soil erosion processes are complex at catchment scales and difficult to understand because of their non-linearity and scale dependency (Lesschen et al., 2009). Runoff and sediment yield are also characterised by high temporal and spatial

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variability within a catchment (Mohamadi and Kavian, 2015; Rai and Mathur, 2008). Sediment yield at catchment levels is controlled by many factors, such as rain intensity, soil and rock properties, vegetation cover, topography, soil-moisture content (SMC), infiltration rate, and natural and artificial geomorphic features (Medeiros et al., 2010). There are several studies about hydrological responses and sediment yield under different measures of land management (e.g. Betrie et al., 2011; Haregeweyn et al., 2008; Lanckriet et al., 2012; Nyssen et al., 2010; Nyssen et al., 2009) at catchment level. These studies were, however, carried out at a coarser temporal scale (e.g. daily or annual) and may miss to capture small-scale runoff and soil erosion processes in events of varying rain intensity (Kandel et al., 2004).

Soil erosion in semi-arid regions is exacerbated by the heavy but infrequent rains and the low protection of the soil surface due to sparse vegetation cover (Medeiros et al., 2010). Extreme runoffs must therefore be carefully assessed, because these events can control long-term sediment yield (White, 2005), and a few storms may cause most of the yearly total soil erosion. The design of strategies to combat the negative effects of runoff and soil loss from hillslopes also often require an understanding of the characteristics of individual rains such as rain amount, intensity and duration, which are important for quantifying the magnitude and timing of peak water and sediment discharges (Ramsankaran et al., 2013).

Runoff and soil erosion processes have on-site and off-site effects which could threaten the availability and sustainability of water resources in a catchment (Frankl et al., 2016; Haregeweyn et al., 2008). An understanding of event-based runoff and soil erosion not only helps for managing existing schemes of water harvesting but also for implementing new techniques, such as check dams, percolation ponds, and micro-dams. Recent endeavours in the Tigray region of northern Ethiopia have tried to rehabilitate the land by water harvesting techniques (WHTs). Water harvesting is defined as the collection of water for its productive use (Critchley and Siegert, 1991). WHTs which are commonly implemented in Tigray are stone bunds, infiltration or deep trenches, check dams, and percolation ponds (Desta et al., 2005; Nyssen et al., 2004; Vancampenhout et al., 2006; Walraevens et al., 2015).

The durability and sustainability of water storage structures, however, can be threatened by siltation due to excessive soil erosion from brief but heavy rains (Haregeweyn et al., 2008; Ramsankaran et al., 2013). Check dams, for example, are useful for stabilising gullies by controlling runoff and peak discharges and by reducing the velocity of flow and settling sediment behind the structures (Nyssen et al., 2009). These structures, however, can be damaged by peak flows during periods of intense rains. For example, 39% of 400 loose-rock check dams in Tigray have been damaged by intensive rainstorms (Nyssen et al., 2004).

The design, implementation, and operation of water harvesting structures requires an understanding of site-specific peak water and sediment discharges during periods of extreme events, which can be attained by applying event-based hydrological and soil erosion models. Several studies of event-based catchment-scale runoff and sediment yield have been carried out worldwide (e.g. Baartman et al., 2012; Gao and Josefson, 2012; Hessel et al., 2006; Medeiros et al., 2010; Rai and Mathur, 2008; Ramsankaran et al., 2013). Process-based runoff and sediment yield at a catchment scale in Ethiopia have also been modelled (e.g. Betrie et al., 2011; Gebreyohannes et al., 2013; Haregeweyn et al., 2013). Event-based runoff and sediment yield, however, have not yet been modelled for Ethiopia. The effect of extreme events on catchment hydrology and sediment yield in the Ethiopian highlands is not well understood, especially under the influence of different WHTs.

We used the Limburg Soil Erosion Model (LISEM) to study the effect of WHTs on event-based hydrological processes and soil erosion. LISEM was first developed and applied in the province of South Limburg in the Netherlands (De Roo et al., 1996a). Since its development, LISEM was continuously updated and applied in different parts of the world for modelling runoff and soil erosion. Takken et al. (1999) used LISEM to predict spatial soil erosion and deposition patterns in a small catchment in eastern Belgium. It was also successfully applied in other areas, for example in the Chinese loess plateau (Hessel et al., 2003a, 2003b), southern Spain (Baartman et al., 2012) and Iran (Sheikh et al., 2010). Even though LISEM was evaluated in the tropics, for example, in Kenya (Hessel et al., 2006) and Brazil (De Barros et al., 2014) for modelling soil erosion processes at catchment scale, it was less frequently applied in catchments with WHTs. LISEM is, however, a physically event-based hydrological and soil erosion model and so is suitable for the planning and evaluation of measures for mitigating soil erosion (De Roo et al., 1996b).

The objectives of this study were therefore to (a) evaluate the performance of LISEM in predicting hydrological responses and sediment yield under different WHTs in the Gule catchment in semi-arid northern Ethiopia, and (b) investigate the effect of WHTs on catchment runoff and sediment yield.

2. Materials and methods

2.1. Description of study area

The study was conducted in the Gule catchment in the northern Ethiopian highlands (Fig. 1), located between 13°51′59″-13°54′40″N and 39°27′16″-39°29′49″E. The Gule catchment lies within the upper Geba catchment, which drains to the Tekeze River basin. The Gule catchment has a rugged topography, with mountains, hillslopes, and flat valley floors, with altitudes ranging between 2008 and 2408 m a.s.l.

The catchment has a semi-arid climate, with distinct dry and wet (rainy) seasons. The rainy season is relatively short and occurs between June and September (Nyssen et al., 2010). The dry season (October to May) is characterised by little or no rainfall, except for some rains towards the beginning of the rainy season. Rain gauges installed at the study site recorded mean annual rainfall of 465 mm between 2013 and 2015. Temperatures in the Gule catchment vary little throughout the year compared to the considerable diurnal variations. Average daily temperature in the Gule catchment ranges between 15 and 25 °C.

The study area is dominated by different rock and soil types (Fig. 2): (a) steep slopes and cliff-forming areas dominated by Adigrat sandstone, which is fractured and has a high infiltration capacity, (b) intermediate slopes of mainly siltstone and claystone, which have low permeability, and (c) flat areas dominated by unconsolidated sediments, which have high permeability and infiltration capacity. These unconsolidated sediments are underlain by Edaga Arbi tillite and metamorphic rocks (metavolcanic and metasedimentary), which have low to moderate permeability. The rock and soil properties along the landscapes are generally characterised as rocky in the upper section, gravelly and sandy in the central section, and sandy and silty in the lower section. The soils in the lower sections of the landscape have large capacities to store water, which can reduce subsurface outflow and enhance groundwater storage. The underlying Edaga Arbi tillite layer and metamorphic rocks prevent deep percolation of water and encourage the storage of subsurface water in the weathered rocks and overlying unconsolidated sediments. This setting is geologically ideal for the development of shallow (hand dug) groundwater wells in the lower section of the catchment.

The Gule catchment has a total area of ~12 km^2. The major land uses are cultivated land (48%), shrub land (46%), grass land (5%), and wood land (1%) (Grum et al., 2017). The most widely cultivated crops are wheat, barley, millet and teff (*Eragrostis tef*). The catchment is characterised by fine- to coarse-textured soils with the major textural classes consisting of sandy loam (24%), sandy clay (21%), sandy clay loam (14%), clay loam (13%), loam (13%), and silty loam (12%).

The catchment is currently well managed with various WHTs, such as stone bunds, deep trenches, check dams, and percolation ponds (Figs. 1 and 3). Stone bunds have been constructed along the contours of the slopes mainly in the hilly and shrub-dominated areas. Deep