Chapter 5

Quantifying Impacts of Climate and Land Use Changes on Soil and Water Management, Community Resilience, and Sustainable Development in Agricultural Watersheds

Chris S. Renschler et al.

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CHAPTER 5

QUANTIFYING IMPACTS OF CLIMATE AND LAND USE CHANGES ON SOIL AND WATER MANAGEMENT, COMMUNITY RESILIENCE, AND SUSTAINABLE DEVELOPMENT IN AGRICULTURAL WATERSHEDS

Chris S. Renschler
Department of Geography, University at Buffalo, Buffalo, NY, United States

Nigus D. Melaku
Gondar Agricultural Research Center, Gondar, Ethiopia

Akinjiyan O. Omotayo
Institute for Hydraulics and Rural Water Management, University of Natural Resources and Life Sciences, Vienna, Austria

Andreas Klik
Institute for Hydraulics and Rural Water Management, University of Natural Resources and Life Sciences, Vienna, Austria

Introduction

Soil erosion by water on agricultural land and naturally vegetated landscapes such as rangelands is a major current and future environmental threat to the sustainability and productive capacity of agriculture, forestry, etc. (on-site impacts). It also supplies sediment and associated chemical pollutants to vulnerable water bodies (off-site impacts). Pimentel et al. (1995) suggest that, during the past 40 years, nearly one-third of the world's arable land has been lost by erosion at a rate of more than 10 million ha per year. The off-site sediment damage is estimated to be far greater than the on-site productivity effects of erosion (Guntermann et al., 1976). Global change (i.e. climate change and associated major land use) is likely to exacerbate both the on- and off-site impacts of erosion in many locations worldwide.

Future shifts in the amount, intensity, and temporal distribution of rainfall will directly modify rates of soil loss in currently erosion-prone areas, along with rates of surface runoff (including peak flow discharge) and groundwater recharges. These shifts, along with spatial and temporal pattern changes in temperatures and precipitation, will affect rates of plant growth and crop yields as well as water use and, hence, soil-protective crop cover (Taub, 2010). In turn, these changes (in particular, shifts in the duration of time when unprotected soil is exposed before a protective plant cover is established) will also, more indirectly, modify runoff and soil loss. Faster residue decomposition from increased microbial activity may also increase erosion rates (Nearing et al., 2005) as will any changes in the timing of agricultural operations that leave even more areas with bare soil exposed to soil erosion. Finally, future climate changes will create opportunities for novel crops to be grown, which in some cases will give rise to new erosion problems. For example, maize and sunflower may be adopted in response to warmer conditions in temperate areas. However, these increase risk of erosion as both take a significant amount of time to provide adequate crop cover (Boardman and Favis-Mortlock, 1993).

The economy of Ethiopia, a country with a population of over 80 million inhabitants, is based on agriculture, especially production of coffee which is its major export crop. Ethiopia is also the leading African producer and exporter of coffee, cotton, cereal, vegetable products, and tea across the other continents, most especially Europe. According to a survey, agriculture accounts for about 83.9% of Ethiopia's export or half of its gross domestic product (GDP). About 80% of the total population of the Ethiopian economy are engaged in agriculture, making it the predominant occupation for Ethiopia's economy, with 25% of the population gaining their livelihood from the production of coffee alone (Devereux, 2000). Ethiopia depends mainly on low-productivity rain-fed agriculture for its national income.

While the Ethiopian economy is dependent on agricultural production, its crop yield is dependent on the weather condition. With such heavy dependence on rainfall, it should not be a surprise that impacts of climatic change like droughts, and decline in precipitation could lead to devastation of the Ethiopian economy and problems such as food insecurity, diseases, sickness, high poverty rate amongst farmers, and a decline in the country's GDP. Like many African countries, Ethiopia is confronted with environmental issues that are problematic for its agricultural sector (Gebremedhin Berhane, 2002). It is, therefore, imperative to study the trends in the temperature and precipitation pattern in Ethiopia. Several research studies have been conducted on temperature and precipitation around Ethiopia, the country being amongst areas of the world most likely to experience climate variations for short and long periods. Inter-annual variability of precipitation and temperature in Ethiopia is relatively large than the annual mean (Kahya and Kalaycı, 2004). As a result of climatic variations, the country's agricultural production is easily reduced.

The aim of this study is to assess the potential future temporal and spatial trend of temperature and precipitation pattern in Ethiopia as well as assess potential best management practices (e.g. soil conservation structures or non-structural vegetation cover changes in current crop rotations) to mitigate the problem of on-site soil erosion as well as the impact of off-site runoff and sediment yields.

Most developing countries like Ethiopia are experiencing degradation of land and water resources. To tackle this problem, soil and water conservation is now considered top priority to maintain Ethiopia's natural ecosystem and improve its agricultural productivity to be able to achieve food self-sufficiency (Melaku et al., 2017; Klik et al., 2017; Melaku et al., 2018). A massive effort in soil conservation strategies is being made by the government of Ethiopia. However, the effectiveness of soil and water conservation on the dynamics of the nutrient, stream flow, and sediment loading is not studied and identified clearly for long-term and short-term effects. Therefore, this project was designed to address gaps in the knowledge of the effectiveness of the soil and water structures. The study was done in two adjacent watersheds: one is equipped with soil and water conservation structures (stone bunds) while the other is without soil and water conservation structure. Streamflow, nutrient, and sediment loading will be compared based on the model output. Weather data were collected from the nearby station. Runoff was monitored with automatic cameras and flow sensors, and sediment samples were collected at the outlets of the two watersheds. The collected samples were analysed for sediment load and nutrients concentration. All collected data would be used to calibrate a simulation model and verify the same with it to compare the two watersheds to see the effectiveness of the soil conservation structures.

Objectives and Methodology

The main objectives of this interdisciplinary research were to assist in communication and collaboration between natural resources and natural hazards/disaster managers about spatial and temporal land management options in response to the need to assess potential climate and/or land use changes. To gain enhanced understanding of both disciplines, the researchers facilitated the communication to understand the spatial and temporal dynamics and variability of processes and process-based modelling techniques, utilise mapping to represent scales and foremost important agreement on core principles, such as 'sustainability' and 'resilience'. Qualitative and quantitative techniques enabled the utilisation of the new modelling approach for slow-onset and fast-onset extreme events and related unfolding disasters (e.g. climate and/or land use/cover change, flooding, etc.). This enabled the assessment of complex, interdependent system functionalities such as the promotion of wetland creation or water harvesting to increase on-site infiltration and reduce/delay off-site runoff. Assessing flood risk reduction, the potential loss of agricultural production, and investment in infrastructure are keys in evaluating sustainable development and community resilience.

This experimental study developed and tested a combined landscape-based modelling and assessment platform to investigate impacts of land use/climate changes and management options on sustainability and resilience of agricultural communities in Ethiopia. The study was performed in two adjacent watersheds: one developed by soil and water conservation structures (stone bunds) and the other one without soil and water conservation structure. Streamflow, nutrient, and sediment loading would be compared based on the model output. Weather data were collected from the nearby station. Runoff was monitored with automatic cameras and flow sensors and sediment samples were collected at the outlets of the two watersheds. The collected samples were analysed for sediment load and nutrients concentration. All collected data would be used to calibrate and verify a simulation model to compare the two watersheds to see the effectiveness of the soil conservation structures.

The Geospatial Interface for the Water Erosion Prediction Project (GeoWEPP) (Renschler, 2003), a process-based watershed model, and the PEOPLES Resilience Framework (PEOPLES) (Renschler et al., 2010), a holistic landscape-based systems assessment approach, were the foundation of this experimental study. Case studies for this newly combined model and assessment approach account for the spatial-temporal changes and dynamics of interdependent systems, enabling users to explore the impacts of likely scenarios (Renschler, 2013).

With the stakeholders from the soil and water conservation community, the researchers defined simulation scenarios to assess the impact of environmental changes and land use policy for more sustainable and resilient watershed management. The quantitative model results enabled the collaborators and stakeholders to assess on-site ecosystem service functionality (e.g. infiltration, ground water recharge, biomass production, crop yields, carbon sequestration, soil loss, etc.) and off-site impacts (e.g. return periods of runoff volumes and peak discharges at the outlet). The off-site impacts on existing and repaired downstream infrastructure were used to assess the complexity of interdependent system functionalities.

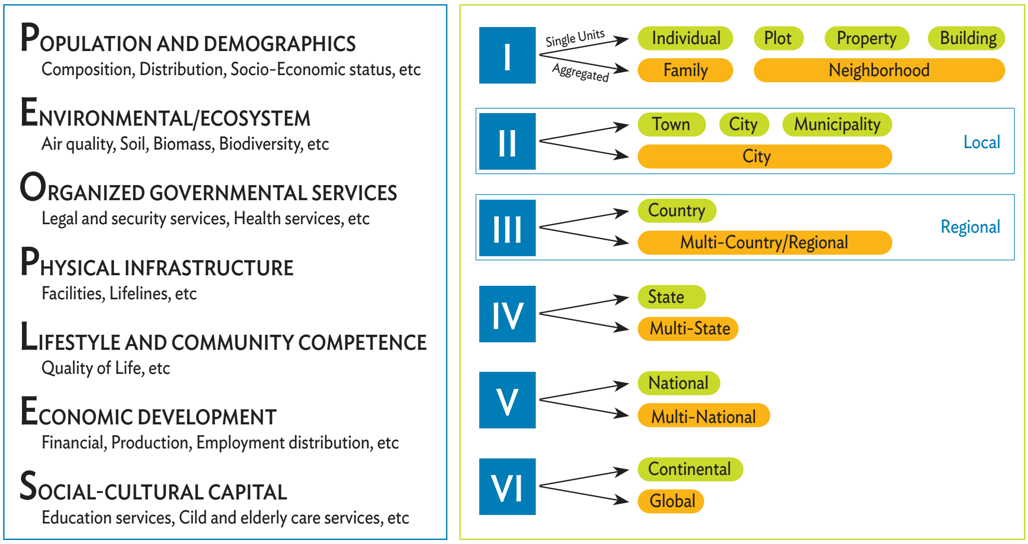
Natural Resources Modelling and Management

The model used in this study is the state-of-the-art, process-based Water Erosion Prediction Project (WEPP) model (Laflen et al., 1991; Flanagan and Nearing, 1995) and the Geospatial interface for WEPP (GeoWEPP) (Renschler, 2003; Flanagan et al., 2013). These freely available software packages simulate the effects of soil erosion by water on agricultural hillslopes and small watersheds. WEPP has been proven effective in assisting experts with the development of best management practices that aim to control soil loss and sediment export. WEPP has also been used to estimate water balances and sediment budgets under future climate and land use scenarios. However, as with any model, WEPP has its limitations such as zero representation of gully erosion or of permanent streamflow and those regarding the generation of multiple peak intensities during precipitation events. Nonetheless, it is one of the best-studied and validated soil erosion models currently available (Nearing et al, 2005; Flanagan et al., 2013) and frequently used by US agencies and researchers worldwide to develop and assess best management practices (Renschler and Lee, 2005).

Community Resilience Assessment

The PEOPLES Resilience Framework (Renschler et al., 2010) provided the platform to assess interdependencies. While PEOPLES can be used for scales ranging from individual, local, regional, and national to global, it was used in this study for watersheds of up to 100 ha. The PEOPLES acronym stands for a series of seven holistic, quantitative resilience dimensions and hierarchical lead indicators that stand for the state of functionality of systems in communities: population and demographics, environmental/ecosystem services, organised governmental services, physical infrastructure, lifestyle and community competence, economic development, and social-cultural capital (Renschler et al., 2010). This framework allows the assessment of the functionalities of each or interdependent systems using disaster or extreme events reduction measures (e.g. migration planning (P), implementing BMPs (E), disaster response and mitigation (O), reinforcing infrastructure (P), willingness for voluntary assistance (L), market development/subsidies (E), restrictive weekend activities (S), etc.). This combined assessment then uses lead indicators to assess the interdependencies between the seven defined systems for a more holistic review.

Figure 1: Seven Dimensions of Resilience and Scales of the PEOPLES Resilience Framework



Source: Renschler et al., 2010.

This review process utilises quantitative and qualitative lead indicators to compare stakeholder-defined management/hazard risk scenarios. The data formats for lead indicators consist of the respective PEOPLES dimension, functionality, and interdependency percentages at a particular time and geographical scale. Interdependencies can also be quantified by their relevance or weighted by their level of interdependencies with values between 1 (100% dependent) and 0 (0% or independent). This process was especially designed for supporting communication between both types of managers to better understand natural processes and their variability on a day-to-day-basis and to support decision-making in rapidly unfolding situations (e.g. rainfall runoff scenarios and return periods of peak runoff rates).

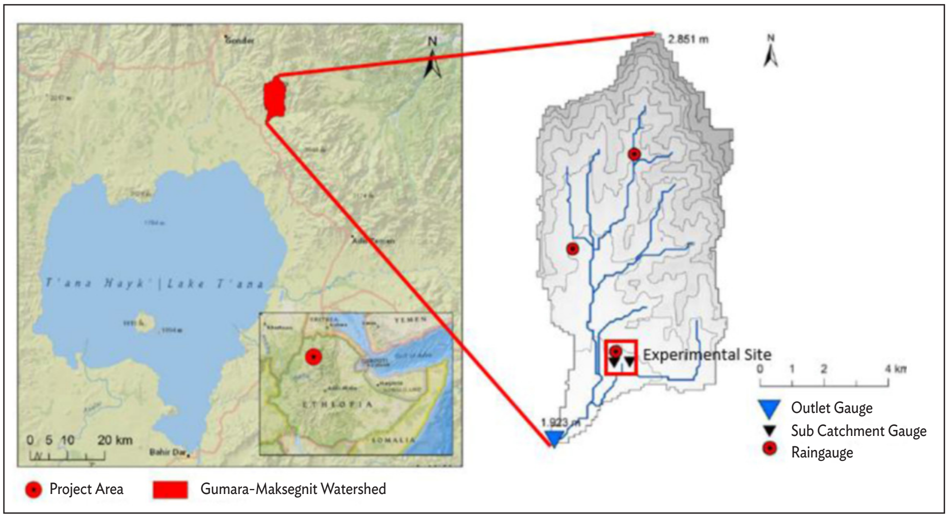
The collaborators in this experimental study worked with scientists, practitioners, and educators in natural resources management and natural hazards/disaster management. The collaborators developed the modelling approach in relative data-intensive watersheds by testing various levels of data granularity to evaluate its use with commonly available data and/or in data-poor watersheds. The project was designed to test relevant policy questions such as the implementation of best management practices (e.g. erosion control measures).

Study Area

In the Ethiopian Highlands, deforestation for crop production dramatically increased the vulnerability of the soils to rainfall-driven erosion (Nyssen et al., 2000; Melaku et al. 2017; Klik et al. 2017; Melaku et al. 2018). Intensive rainfalls during the rainy season (June to September) threaten the mountainous regions with severe land degradation especially the steep-sloped and unprotected areas (Addis et al., 2015).

The study area – the Aba-Kaloye (untreated) and Ayaye (treated) sub-watersheds – lies within the Gumara-Maksegnit watershed, situated in the Lake Tana basin in the northwest Amhara region of Ethiopia (Figure 2). The watershed is dominated by steep slopes and ranges from about 1,920 m above sea level to 2,860 m above sea level in altitude. It covers an area of 54 sq km and is located between 12°24' N and 12°31' N and between 37°33' E and 37°37' E. The watershed drains into the Gumara River, which finally reaches Lake Tana (Addis et al., 2015). The two sub-watersheds are located in the southern lower part of Gumara-Maksegnit watershed between 12°25'26" N and 12°25'46" N and between 37°34'56" E and 37°35'38" E (Figure 2). They are neighbouring each other with a distance of about 1 km between the outlets (Figure 2). The Aba-Kaloye and Ayaye sub-watersheds embrace an area of 31 ha and 24 ha, respectively, while their altitude reaches from about 1998 m above sea level to about 2150 m above sea level. They are also characterised by a mountainous topography, where 80% of the area have slopes of 10% or higher.

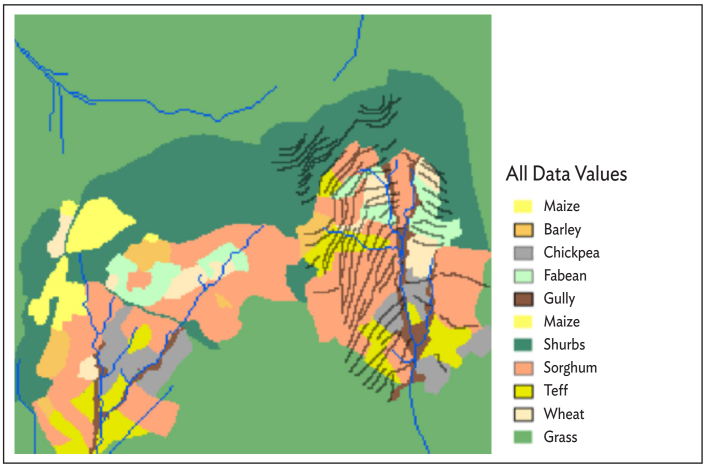
Figure 2: Map of the Study Area (Gumara-Maksegnit Watershed with Paired Sub-watersheds)



Source: Renschler et al., 2010.

The Aba-Kaloye and Ayaye sub-watersheds are involved in long-term soil erosion studies (Klik et al., 2015). Both sub-watersheds show severe soil erosion problems as manifested in the formation of deep gullies (Klik et al., 2016).

Figure 3: Sub-watersheds Abakaloye (West Side) and Ayaye (East Side), With and Without Stone Bunds as Best Management Practice, Respectively



Source: Authors.

While water and soil conservation measures are applied in the Ayaye sub-watershed through the construction of gabions within the gullies and the implementation of stone bunds, the Aba-Kaloye sub-watershed acts as a reference for gully development without measures. In the Ayaye sub-watershed, all fields at the west flake are treated with stone bunds except the southmost fields (Figure 3). According to Bosshart (1997), the potential short-term benefits of stone bunds are the reduction of slope length and the creation of small retention basins for runoff and sediments. These effects appear immediately after the construction of stone bunds and result in reduced soil loss. The major medium-term and long-term effect is the reduction in slope steepness by progressive formation of terraces through the filling up of the retention spaces with sediments. To achieve these results, maintenance of stone bunds every 3 years is needed.

Watershed Study for Stone Bunds Best Management Practice

The sediment accumulating on bunds gradually changes the original slope of the plot, making it more suitable for cultivation. Stone bunds of 20 cm to 50 cm high embankments built in shallow trenches along contour lines use large and medium-sized rock fragments from neighbouring fields for construction (Morgan, 2005, 2012; Nyssen et al., 2007; Melaku et al. 2017; Klik et al. 2017; Melaku et al., 2018). Construction of stone bunds requires less soil movement and is therefore more applicable to small farmers. These embankments change the inclination of the land and thus change the extent of slope gradient. In addition to slope gradient, the stone bunds change flow accumulation.

Immediately after construction, stone bunds reduce the slope length for surface runoff and provide retention space for runoff and sediments (Melaku et al., 2018). On medium-term and long-term bases, sediments accumulate and fill up the retention space. This leads to a reduction in slope steepness and subsequently the formation of bench terraces (Bosshart, 1997). Quantifying the effectiveness of this measure, various studies show different results for effects such as retention of soil and water or increase in crop yield. Nyssen et al. (2007), for example, found an average sediment accumulation rate of 58 t ha^{-1} yr^{-1}, an increase in mean crop yield of 0.58 to 0.65 t ha^{-1} yr^{-1} and enhanced moisture storage in deep soil horizons induced by stone bunds constructed in the Ethiopian Highlands.

The selection of an appropriate model structure depends on the function that the model desires to serve (Merritt et al., 2003). For this project, GeoWEPP was applied to selected target sites (Renschler, 2003). GeoWEPP uses the WEPP model (Laflen et al., 1991; Flanagan and Nearing, 1995), a continuous, process-based model that allows the simulation of small watersheds and hillslope profiles. The current version of GeoWEPP allows a user to process digital data such as Digital Elevation Model, soil surveys, land use maps, and precision farming data. Besides, required input data, including slope, land cover types, soil map, land use types, and climate, are integrated into spatial database of WEPP and necessary outputs are produced by using the geographic information system (GIS) functions of GeoWEPP.

Plot Study for Climate Change Scenarios

Ethiopia makes up the greater part of the East African Horn of Africa. At latitudes of 4°N to 15°N, Ethiopia's climate is typically tropical in the southeastern and northeastern lowland regions, but much cooler in the large central highland regions. Mean annual temperatures are around 15°C–20°C in these high-altitude regions, while they are 25°C–30°C in the lowlands. Seasonal rainfall in Ethiopia is driven mainly by the migration of the inter–tropical convergence zone (ITCZ). The exact position of ITCZ changes over the course of the year, oscillating across the equator from its northernmost position over northern Ethiopia in July and August to its southernmost position over southern Kenya in January and February. Most of Ethiopia experiences one main wet season (called *kiremt*) from mid–June to mid–September (up to 350 mm per month in the wettest regions), when ITCZ is at its northernmost position. Parts of northern and central Ethiopia also have a secondary wet season of sporadic, and considerably lesser, rainfall from February to May (called *belg*).

The southern regions of Ethiopia experience two distinct wet seasons which occur as ITCZ passes through this more southern position. The March–May *belg* season is the main rainfall season yielding 100 mm to 200 mm per month, followed by *bega* (around 100 mm per month) in October to December. The easternmost corner of Ethiopia receives very little rainfall at any time of year. The movements of ITCZ are sensitive to variations in Indian Ocean sea surface temperatures and vary from year to year. Hence, the onset and duration of the rainfall seasons vary considerably inter-annually, causing frequent droughts. The most well-documented cause of this variability is the El Niño Southern Oscillation.

Warm phases of El Niño have been associated with reduced rainfall in the main wet season in north and central Ethiopia causing severe drought and famine, but also with enhanced rainfalls in the earlier February to April rainfall season that mainly affect southern Ethiopia. Mean annual temperature increased by 1.3°C between 1960 and 2006, an average rate of 0.28°C per decade. The increase in temperature in Ethiopia has been most rapid in the main wet season at a rate of 0.32°C per decade. The strong inter–annual and inter–decadal variability in Ethiopia's rainfall makes it difficult to detect long–term trends. There was no statistically significant trend in observed mean rainfall in any season in Ethiopia between 1960 and 2006. Decreases in the main wet season rainfall observed in the 1980s showed recovery in the 1990s and 2000s.

The closest available long-term statistical climate data location with respect to the study site was available for Bahir Dar south of Lake Tana (Figure 2). The other short-term climate parameters (e.g. peak intensity precipitation, event duration, etc.) as well as daily values (e.g. maximum/minimum temperature, wind speed/direction, etc.) were derived by finding the most similar monthly statistics of a station in the US by comparing it to an international database with basic statistics climate data (USDA-ARS NSERL, 2006). The US climate data statistics were then adjusted to match the long-term monthly averages available and 100-year climate scenarios were derived and compared with long-term averages available for or near the study site.

Once the 100-year simulations of climate were comparable to long-term monthly average precipitation amounts as well as similar monthly average temperatures, these climate data sets were then used with WEPP to simulate plant growth, runoff, and sediment yields. These results were then compared to average annual crop yields (for correct plant growth; see Table 1), estimated runoff (water balance), and soil losses (sediment balance) (Table 2).

Climate change scenarios, provided by the United Nations Development Programme and the University of Oxford for Ethiopia, were then generated based on absolute and relative changes of precipitation and temperatures (McSweeney et al., 2010). The mean annual temperature is projected to increase by 1.1°C–3.1°C by the 2060s. Under a single emissions scenario, the projected changes from different models span a range of up to 2.1°C. Projections from different models in the ensemble are broadly consistent in indicating increases in annual rainfall in Ethiopia. These increases are largely a result of increasing rainfall in the 'short' rainfall season (OND) in southern Ethiopia. OND rainfall is projected to increase by 10%–70% over the whole area of Ethiopia. Proportional increases in OND rainfall in the driest, easternmost parts of Ethiopia are large. Projections of change in the rainy seasons AMJ and JAS which affect the larger portions of Ethiopia are more mixed but tend towards slight increases in the southwest and decreases in the northeast.

Plot Study Results for Climate Change Scenarios

Note that the following results are based on 100-year simulations with observed and predicted changes in rainfall and temperature characteristics. The representative agricultural field unit is a 25-m-long and 100-m-wide plot with a 10% slope on a clay loam soil with a 3-year Fabean-Barley-Wheat crop rotation. The anticipated changes in climate for 2030 and 2060 and their impact on average crop yields were compared to observed crop yields under current climate conditions (Table 1).

Table 1: Average Crop Yield, Precipitation, Runoff, and Soil Loss for a 100-year Climate Simulation (Crop Yield are Based on 33 Harvests of a 3-year Crop Rotation)

Crop Yields in t/ha	Observed (1970-1999)	Projected 2030	Projected 2060
Fabean	3.01	3.11	3.19
Barley	2.49	4.12	9.93
Wheat	2.53	1.70	0.92
Precipitation in mm/yr	1,268.86	1,264.00	1,268.59
Runoff in mm/yr	267.95	261.71	253.57
Soil Loss in t/ha/yr	56.87	64.13	65.59

mm = millimetre, ha = hectare, t = tonne, yr = year.

Source: Authors.

The design of the two climate change scenarios considered spatially distributed (regional grid pattern) and temporally distributed (quarterly, Jan/Feb/Mar, April/.., etc.) changing temperatures and precipitation patterns. The plant growth model in the process-based WEPP illustrates that fabean crop yields could slightly increase, while barley and wheat yields could drastically increase or decrease, respectively. Please note that the two climate scenarios did not include the change in the crop management calendar, and while increase in barley production would be certainly welcome, one might have to adjust the temporal scheduling for wheat production to adjust to expected changes in climate. With regard to the slight changes of average annual precipitation in the two climate scenarios (Table 2), the average annual runoff is expected to decrease by 2.3% and 5.4%, while the average sediment yield is expected to increase by 12.8% and 15.3% in 2030 and 2060, respectively. That means less water will be flowing downhill to other agricultural sites, but likely with more sediments. The analysis of the 100 years of predicted runoff and sediment yields illustrates that the total runoff of return periods for 50 years only slightly increases by 2.2% while those of sediment yield increases drastically by 39.5% in 2060.

Table 2: Return Periods for Daily Runoff and Sediment Yields

Runoff (mm)	Observed	Projected 2030	Projected 2060
2-year	39.6	39.4	38.7
5-year	52.2	52.5	52.7
10-year	70.8	66.6	70.0
25-year	86.1	85.1	85.5
50-year	95.2	94.2	97.1
Sediment Yield (t/ha)	**Observed**	**Projected 2030**	**Projected 2060**
2-year	20.6	23.8	25.7
5-year	34.1	38.0	44.3
10-year	41.7	49.8	60.7
25-year	69.5	86.7	107.1
50-year	79.5	101.9	110.9

ha = hectare, mm = millimetre, t = tonne.

Note: The rainfall intensities of a single precipitation event were not considered. The impacts are therefore solely on climate-driven changes to soils and plant parameters (e.g. soil moisture and infiltration capacity, leave area index, or plant residues depending on growth/harvesting).

Source: Authors.

Watershed Study Results for Stone Bunds Best Management Practice

GeoWEPP (WEPP v2012.8) was used to estimate the sediment yield and runoff in the Abakaloye (west watershed without BMP) and Ayaye sub-watersheds (east watershed with BMP stone bunds) of the Gumara-Maksegnit watershed in the Lake Tana basin. The initial sediment yield and runoff results from the GeoWEPP model were compared with the observed monthly data collected from the watershed to evaluate the performance of the model. The simulated paired Gumara-Maksegnit watersheds for 2012–2014 were able to assess the effectiveness of stone bunds BMPs on soil erosion, runoff, and sediment yields (Figure 4).

The preliminary simulation results show that the west watershed without stone bunds produced 184.2 mm of runoff and 126 t ha^{-1} y^{-1} sediment yield, while the east watershed with BMP stone bunds produced lower runoff of 151.62 mm and lower sediment yields of 86.2 t ha^{-1} y^{-1}. If the stone bunds had been removed from the eastern watershed, the runoff and sediment yields would have been 2,006.22 mm and 105.3 t ha^{-1} y^{-1} and therefore 36% and 22.2% higher, respectively. That means that an implementation of stone bunds in the western watershed could potentially reduce the runoff by about 26% or 53 mm and sediment yields by about 18% or 22 t ha^{-1} y^{-1}. The sediment yields of about 100 t ha^{-1} y^{-1} are still very high, but it is the first step in the right direction to reduce runoff and sediments.

Figure 4: Simulation Results for Watershed Outlets With and Without Stone Bunds BMP

71 storms produced 808.53 mm of rainfall for three year period (2011 to 2014)

West Watershed without Stonebunds	
45 events produced 184.20 mm of runoff	
Total contributing area to outlet	: 31.70 ha
Avg. Ann sediment discharge from outlet	**: 3,995.4 tonnes/yr**
Avg. Ann sediment delivery per unit area of watershed	**: 126.0 T/ha/yr**

East Watershed with Stonebunds	
41 events produced 151.62 mm of runoff	
Total contributing area to outlet	: 24.00 ha
Avg. Ann sediment discharge from outlet	**: 2,069.8 tonnes/yr**
Avg. Ann sediment delivery per unit area of watershed	**: 86.2 T/ha/yr**

East Watershed without Stonebunds	
41 events produced 206.22 mm of runoff	
Total contributing area to outlet	: 25.76 ha
Avg. Ann sediment discharge from outlet	**: 2,711.8 tonnes/yr**
Avg. Ann sediment delivery per unit area of watershed	**: 105.3 T/ha/yr**

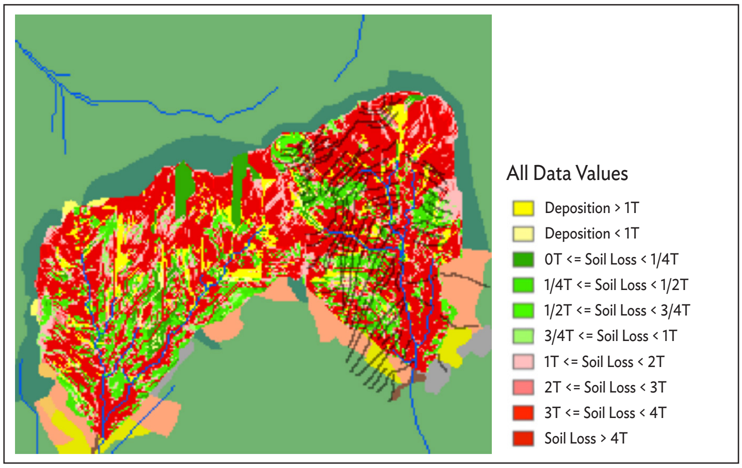
BMP = best management practice, ha = hectare, mm = millimetre, T = tonne, yr = year.

Note: The values above presented at the meeting in 2016 were preliminary results to illustrate the potential for the proposed assessment methodology. The final results documented in Melaku et al. (2018) were about half these amounts with 64.1 t $ha^{-1}y^{-1}$ for the untreated and 39.9 t $ha^{-1}y^{-1}$ for the treated sub-watershed.

Source: Authors.

Implementing BMP requires spatial and temporal scheduling of management activities in a watershed. GeoWEPP assists stakeholders in comparing spatial patterns of non-existing and existing stone bunds (see Figure 5) and enables designing and optimising the location of stone bunds to reduce runoff and sediment yields. This was not done in this study, but could be performed in collaboration with stakeholders in the study area.

Figure 5: Predicted Soil Redistribution Pattern Without (Western Sub-watershed) and with BMP Stone Bunds (Eastern Sub-watershed) (Target T = 10 t ha^{-1}yr^{-1})



ha = hectare, t = tonne, yr = year.

Note: Soil loss above (red), soil loss below (green), and soil deposition (yellow).

Source: Authors.

Combined Natural Resources Management and Community Resilience

Since the impact analysis also considered plot-based, on-site economic productivity of crop yields (e.g. sorghum, wheat, teff, etc.), and watershed-based, off-site peak runoff, discharge, and sediment yields potentially damaging downstream fields and road infrastructure, one can now assess natural resources management and community resilience from a more holistic perspective. Utilising the PEOPLES Resilience Framework, one can answer different kinds of questions when assessing the impact of spatial and temporal BMP strategies from on-site and off-site decision-making and policymaking perspectives (Table 3).

For example, the planning of BMPs to promote water harvesting and ground water recharge can be quantified in its impact compared to the potential loss of land being taken out of crop production. In fact, in addition to the economic impact, one can assess impacts on the functionality of the other six dimensions of the PEOPLES Resilience Framework. Similarly, one could potentially assess other land use and/or land cover management strategies of creating wetlands or sediment control structures such as check dams. One could assess the impact not only on agriculture but also on other natural resources management businesses; infrastructure; and life lines such as roads, bridges, or electricity, etc.

Table 3: Potential Intended Goals Impacting Various PEOPLES Resilience Framework Dimensions

Natural Resources or Hazard Management Goals	P	E	O	P	L	E	S
Promote water harvesting/ground water recharge	–	X	X	X	x	X	–
Create wetland/nature reserve/impoundment	–	X	X	X	x	X	X
Sustain crop/timber/fishing harvest yields	x	X	–	x	–	X	X
Design resilient bridges/culverts against runoff/flood	X	x	x	x	–	X	X
Access shelter/food/hospital/emergency facility	X	x	X	X	x	X	x

Note: '–' has no impact, while 'x' and 'X' indicate potential minor and major impacts, respectively.

Source: Authors.

Conclusions

The stone bunds form a barrier that slows down water runoff, allowing rainwater to seep into the soil and spread more evenly over the land. This slowing down of water runoff helps in building up a layer of nutrient-rich fine soil and manure particles. The layers have impact on slope, flow direction, and flow accumulation changes. Based on the results of the two DEMs, the GeoWEPP model will be used to simulate the effects of stone bunds on runoff, sediment, and nutrient flow of the Abakaloye and Ayaye watersheds. The simulation results will be further compared with the observed values. Stone bunds on cultivated land reduce slope length and slope gradient but increase the number of boundaries of the cultivated plots, which aggravates tillage erosion.

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References

Addis, H.K., A. Klik, and S. Strohmeier (2015), 'Spatial Variability of Selected Soil Attributes under Agricultural Land Use System in a Mountainous Watershed, Ethiopia', *International Journal of Geosciences*, 6, pp.605–13.

Boardman, J. and D.T. Favis-Mortlock (1993), 'Climate Change and Soil Erosion in Britain', *The Geographical Journal*, 159(2), pp.179–83.

Bosshart, U. (1997), 'Catchment Discharge and Suspended Sediment Transport as Indicators of Physical Soil and Water Conservation in the Mayketin Catchment, Afdeyu Research Unit: A Case Study in the Northern Highlands of Eritrea', Volume 39, *Soil conservation research project: research report*, University of Bern, Bern.

Ethiopian Mapping Agency (1981), *Atlas of Ethiopia*. Addis Ababa: Ethiopian Mapping Agency.

Flanagan, D.C. and M.A. Nearing (eds.) (1995), 'USDA-Water Erosion Prediction Project (WEPP) Hillslope Profile and Watershed Model Documentation', *NSERL Report No. 10*, National Soil Erosion Research Laboratory, USDA-Agricultural Research Service, West Lafayette, Indiana.

Flanagan, D.C., J.R. Frankenberger, T.A. Cochrane, C.S. Renschler, and W.J. Elliot (2013), 'Geospatial Application of the Water Erosion Prediction Project Model. Trans.', *ASABE*, 56(2), pp.591–601.

Guntermann, K.L., M.T, Lee, and E.R. Swanson (1976), 'The economics of off-site erosion', *The Annals of Regional Science*, 10(3), 117–26.

Klik, A., C. Schürz, S. Strohmeier, N.D. Melaku, F. Ziadat, A. Schwen, and C. Zucca (2017), 'Impact of stone bunds on temporal and spatial variability of soil physical properties: A field study from northern Ethiopia', *Land Degradation & Development*, 2018, pp.1–11.

Klik, A., S. Strohmeier, C. Schürz, C. Brenner, I. Zehetbauer, F. Kluibenschädl, G. Schuster, W. Bayu, and F. Ziadat (2015), 'Monitoring of surface run-off and soil erosion processes', in Ziadat, F. and W. Bayu (eds.), *Mitigating Land Degradation and Improving Livelihoods – An integrated watershed approach*. Earth Scan Studies in Natural Resource Management series, New York: Routledge, pp.127–52.

Klik, A., F. Kluibenschädl, S. Strohmeier, and C. Zucca (2016), 'Assessment of gully erosion using conventional field measurements: A case study from northern Ethiopia', *Journal of Soil and Water Conservation*, 71(6), pp.134A–39A.

Laflen, J.M., L.J. Lane, and G.R. Foster (1991), 'WEPP—a next generation of erosion prediction technology', *Journal of Soil Water Conservation*, 46(1), pp.34–38.

McSweeney, C., M. New, and G. Lizcano (2010), 'UNDP Climate Change Country Profiles: Ethiopia', School of Geography and Environment, University of Oxford.

Melaku, N.D., C.S. Renschler, W. Bayu, C. Zucca, and A. Klik (2018), 'Integrated impact assessment of soil and water conservation structures on runoff and sediment yield through measurements and modeling in the Northern Ethiopian highlands', *Catena*, 169, https://doi.org/10.1016/j.catena.2018.05.035

Melaku, N.D., C.S. Renschler, H. Holzmann, S. Strohmeier, W. Bayu, C. Zucca, F. Ziadat, and A. Klik (2017), 'Prediction of soil and water conservation structure impacts on runoff and erosion processes using SWAT model in the northern Ethiopian highlands', *Journal of Soils and Sediments*, 18, pp.1743–55, https://doi.org/10.1007/s11368-017-1901-3.

Merritt, W.S., R.A. Letcher, and A.J. Jakeman (2003), 'A review of erosion and sediment transport models', *Environmental Modelling & Software*, 18(8), pp.761–99.

Morgan, R.P.C. (2005), *Soil erosion and conservation*. Malden, MA: Blackwell.

Nearing, M.A., V. Jetten, C. Baffaut, O. Cerdan, A. Couturier, M. Hernandez, Y. Le Bissonnais, M.H. Nichols, J.P. Nunes, C.S. Renschler, V. Souchère, and K. van Oost (2005), 'Modeling response of soil erosion and runoff to changes in precipitation and cover', *Catena*, 61, pp.131–54.

Nyssen, J. et al. (2007), 'Interdisciplinary on-site evaluation of stone bunds to control soil erosion on cropland in Northern Ethiopia', *Soil & Tillage Research*, 94, pp.151–63.

Pimentel, D. et al. (1995), 'Environmental and economic costs of soil erosion and conservation benefits', *Science-AAAS-Weekly Paper Edition* 267(5201), pp.1117–22.

Renschler, C.S. (2003), 'Designing geo-spatial interfaces to scale process models: The GeoWEPP approach', *Hydrologic Processes*, 17(5), pp.1005–17.

Renschler, C.S. and T. Lee (2005), 'Spatially Distributed Assessment of Short- and Long-term Impacts of Multiple Best Management Practices in Agricultural Watersheds', *Journal of Soil and Water Conservation*, 60(6), pp.446–56.

Renschler, C.S. (2013), 'The PEOPLES Resilience Framework – An Integrated Quantitative Measure and Modeling of Sustainable Development and Disaster Risk Reduction', *United Nations (UN) Global Assessment Report (GAR) on Disaster Risk Reduction 2015*, UN Office for Disaster Risk Reduction, Geneva, Switzerland.

Renschler, C.S., A.E. Frazier, L.A. Arendt, G.P. Cimellaro, A.M. Reinhorn, and M. Bruneau (2010), 'Developing the 'PEOPLES' resilience framework for defining and measuring disaster resilience at the community scale', *9th US and 10th Canadian Conference on Earthquake Engineering*, Toronto, Canada, 25–29 July 2010.

Taub, D. (2010), 'Effects of Rising Atmospheric Concentrations of Carbon Dioxide on Plants', *Nature Education Knowledge*, 3(10), 21.

USDA-ARS NSERL (2006), 'Using Climate Data in the WEPP Windows Interface - Updated version May 19, 2006', United States Department of Agriculture Agricultural Research Service, National Soil Erosion Research Laboratory, West Lafayette, Indiana. https://www.ars.usda.gov/ARSUserFiles/50201000/WEPP/usingclimate.pdf