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MALAWI-Climate Change Adaptation

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UNON/UNEP Adaptation

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</table>

TABLE OF CONTENT

LIST OF TABLES

LIST OF ILLUSTRATIONS

1. INTRODUCTION

Soil degradation in Malawi is a significant problem that threatens agricultural productivity and food security in the country. The main causes include deforestation, overgrazing, unsustainable farming practices, and inappropriate irrigation methods which accelerate soil erosion, nutrient depletion, and salinization.

The contract "Advancing the NAP process: Climate resilience for sustainable development in Malawi" includes a study on climate hazards in Malawi with a specific analysis on 'soil erosion projections' in three River Catchments:

1. Catchment 6: Dwangwa,
2. Catchment 4: Linthipe Catchment,
3. Catchment 7: South Rukuru.

Land degradation in Malawi was the subject of an extensive study authored by Ronald Vargas (FAO, Italy) and Christian Omuto (University of Nairobi, Kenya). FAO, UNDP-UNEP, and the Ministry of Agriculture, Irrigation and Water Development, Malawi published this study in 2016[1]. Its results are included in the Global Land Outlook report published by FAO, UNEP, and UNDP in 2017[2]. A more recent work on soil and nutrient loss and economic impacts also used these results (Asfaw et al, 2018)[3]. These studies have been completed and included in the Malawi Soil Loss Atlas published by FAO in 2019[4].
The Vargas and Omuto study used field observations and satellite imagery. It trained people to monitor soil loss and analyse trends and used stochastic modelling to assess soil loss hazard, the Soil Loss Estimation Model for South Africa (SLEMSA)[5,6]. The Council Scientific and Industrial Research (CSIR) in South Africa developed this software tool to estimate soil erosion rates in various parts of the country. The model uses a combination of geographical information systems (GIS) and the Revised Universal Soil Loss Equation (RUSLE)[7] to calculate soil loss.

As the RUSLE, the SLEMSA model takes into account various factors that contribute to soil erosion, including climate, topography, soil type, land cover, and land use. The model uses these factors to estimate the amount of soil that is lost due to erosion on a yearly basis. Different studies used the SLEMSA in various applications, such as in the assessment of soil erosion risk in different parts of South Africa and in neighbouring countries, as well as in the development of erosion control strategies. They used it also in the monitoring of erosion rates over time, allowing for the evaluation of the effectiveness of erosion control measures.

[1] https://www.fao.org/documents/card/fr/c/I6387EN/

[2] https://www.unccd.int/sites/default/files/documents/2017-09/GLO_Full_Report_low_res.pdf,

[3] Asfaw S., Orecchia C., Pallante G. and Palma A.(2018) Soil and nutrients loss in Malawi: an economic assessment. © FAO, UNEP and UNDP, 2018. https://www.fao.org/3/CA2663EN/ca2663en.pdf

[4] Omuto CT and Vargas RR. 2019. Soil Loss Atlas of Malawi. 440 pp. Rome, FAO. https://www.fao.org/3/ca3624en/ca3624en.pdf

[5] Elwell, HA. 1978. Modeling soil losses in Southern Africa. Journal of Agricultural Engineering Research 23; pp. 117-127

[6] Hudson CA (1987) A Regional Application of the SLEMSA in the Cathedral Peak Area of the Drakensberg. M.Sc. Dissertation, University of Cape Town, Cape Town, South Africa.

[7] Wischmeier, W.H. and Smith, D.D. (1978). Predicting rainfall erosion losses: A guide to conservation planning. USDA Agricultural Handbook No. 537, Washington, DC.

In the context of this remote consultancy and mindful of the time constraints, we strategically pivoted from our original plan to gather specific field data from the studies by Ronald Vargas and Christian Omuto. Despite these changes, we have made significant strides in our research.
Our consultant developed an approach that highlights the capabilities and expertise of our team. Firstly, we successfully conducted a comprehensive assessment of soil erosion in Malawi. This was achieved through an extensive review of relevant literature and research, providing us with a broad perspective on the prevailing patterns and trends related to soil degradation in the region.
We decided to execute a geospatial adaptation of the Revised Universal Soil Loss Equation (RUSLE) parameters, grounded on the study by Renard et al., published in 1997[8]. In doing so, we harnessed various parameter estimation methodologies, each of which had been previously validated in intertropical regions across Africa.
While our revised approach did not include the specific field data initially envisioned, it nonetheless offered a robust, scientifically proven method for assessing soil loss across the targeted areas
The objective is to obtain orders of magnitude of real soil losses in order to carry out two types of simulation: i) with varying climatic parameters, ii) with the implementation of anti-erosion measures on the most fragile lands.

2. OVERVIEW OF SOIL LOSS IN MALAWI

2.1 Erosion over time

Apart from the FAO, UNDP-UNEP, and the Ministry of Agriculture, Irrigation and Water Development, Malawi, reports cited in the introduction, very few scientific publications with the key words, Malawi, erosion and/or soil degradation are available in the bibliographic databases.
Two publications on the long-term sedimentation of Lake Malawi shed light on the conditions of erosion, its importance and the nature of the material exported at the scale of the lake catchment. The first studies sediment cores taken to a depth of ten metres on a North South transect. It presents the inputs to the lake over a 10,000 years period (Finney, B. P. and Johnson, T. C., 1991)[9]. The second worked on deeper cores taken in the northern part of the lake (40 m) and analysed the sedimentary input to the lake over 75,000 years (Bown TE, 2011)[10].
These two articles show that geological “mega droughts”, which are prolonged periods of aridity lasting centuries (1350 and 1850 AD in the first publication) or even millennia (drought episodes at 62 and 72 ka in the second), have a significant impact on sedimentation in Lake Malawi. During “mega droughts”, there is reduced precipitation, which leads to a decrease in the inflow of sediment into the lake. This, in turn, can lead to changes in the sedimentation patterns and composition of the lakebed. During these periods, sedimentation rates in Lake Malawi were much lower than during wetter periods, resulting in a thinner sediment layer. The sediment that did accumulate during this time was composed mainly of clays and silts, which are indicative of low-energy depositional environments. In contrast, sediment cores from wetter periods show evidence of higher sedimentation rates and the presence of coarser sediments such as sands and gravels, which are indicative of high-energy depositional environments.
The impact of “mega droughts” on sedimentation in Lake Malawi is not only of scientific interest but also has practical implications for the region. For example, understanding the sedimentary record can

[8] Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., and Yoder, D.C. (1997). Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). USDA Agriculture Handbook No. 703, Washington, DC.

[9] Finney, B. P. and Johnson, T. C., (1991). Sedimentation in Lake Malawi (East Africa) during the past 10,000years: A continuous paleoclimatic record from the southern tropics. Palaeogeogr., Palaeoclimatol., Palaeoecol., 85: 351-366

[10] Brown E.T., (2011) Lake Malawi's response to “megadrought” terminations: Sedimentary records of flooding, weathering and erosion Palaeogeography, Palaeoclimatology, Palaeoecology 303 (2011) 120–125

help to inform water management and land use policies that aim to promote sustainable use of soil and water resources. Unfortunately, we have not found any detailed studies on the contemporary period that would allow us to take into account the effects of both climate and anthropogenic pressure.

2.2 Actual Erosion

The reports cited in the introduction show that soil erosion is a major problem in Malawi, affecting agricultural productivity, water quality, and ecosystem services. The country's high population density, steep slopes, and heavy rainfall make it vulnerable to erosion. Both natural and human factors are causes of soil erosion in Malawi.

2.2.1 Natural Factors of Erosion

The nature of soils in Malawi is an important natural factor that contributes to soil erosion. Low fertility, high acidity, and low organic matter content characterize Malawi's soils. These soil characteristics make them more susceptible to erosion, especially during heavy rainfall events.
Following FAO Soil Classification[11], soils in Malawi are predominantly classified as **Luvisol** (27,7 %), **Lixisol** (27%), and **Cambisol** (21.3%) (See Figure 1):

- **Luvisol** is a type of soil described by FAO by mixed mineralogy, high nutrient content, and good drainage. They are suitable for a wide range of agriculture, from grains to orchards. Luvisols in Malawi are also erodible and fragile.
- **Lixisols** develop on old landscapes in a tropical climate with a pronounced dry season. Their age and mineralogy have led to low levels of plant nutrients and a high erodibility, making agriculture possible only with frequent fertilizer applications, minimum tillage, and careful erosion control.
- **Cambisols** are characterized by the absence of a layer of accumulated clay, humus, soluble salts, or iron and aluminum oxides. Because of their favourable aggregate structure and high content of weatherable minerals, they usually can be exploited for agriculture subject to the limitations of terrain and climate. They are susceptible of erosion on steep slope.

The natural characteristics of Malawi's soils are further compounded by the country's topography, much of which is characterized by steep slopes and hilly terrain. These physical features increase the risk of erosion, as water flows more quickly down steep slopes, carrying away soil and nutrients in the process.
The country is known for its diverse topography, which includes highlands, plateaus, and plains. The country's highest point is Mount Mulanje, which rises to an elevation of 3,002 m. in the south of the country. Mount Mulanje is part of a large massif of granite rock that extends for over 32 km).
In addition to Mount Mulanje, Malawi has several other highlands and plateaus, including the Nyika Plateau in the north, which rises to an elevation of around 2,500 m., and the Zomba Plateau in the south, which rises to an elevation of around 1,800 m. The country also contains several plains, including the Shire Valley in the south and the Lake Chilwa Plain in the east.
In summary, Malawi's topography is diverse, with highlands, plateaus, and plains covering much of the country. Mount Mulanje, the Nyika Plateau, and the Zomba Plateau are some of the notable highland areas, while the Shire Valley and Lake Chilwa Plain are important plains in the country. Topography and landscapes play an important role in supporting the country's biodiversity and agricultural productivity.

[11] https://www.fao.org/soils-portal/data-hub/soil-classification/en/

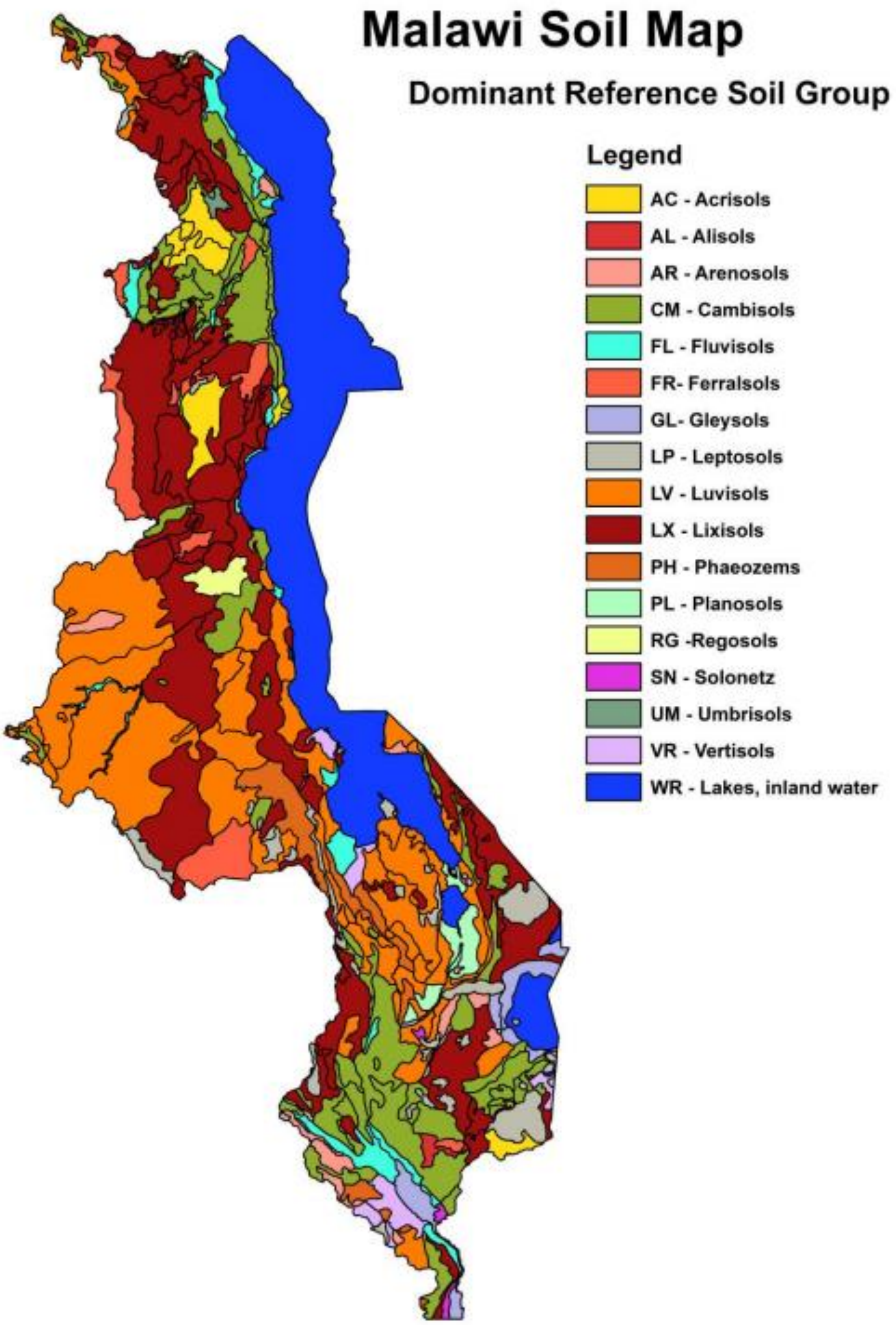

Figure 1: Malawi Soil Map (source: Soil and Terrain Database (SOTER) / ISRIC Data hub)

Climate in Malawi is a significant factor in soil erosion. Malawi has a tropical climate with distinct wet and dry seasons. The rainy season typically runs from November to April, while the dry season runs from May to October. During the rainy season, the country experiences heavy rainfall, which can lead to significant soil erosion.

High-intensity, short-duration events characterize the rainfall pattern in Malawi, resulting in surface runoff and soil erosion. Rainwater accumulates on the soil surface, causing it to become saturated and leading to soil particles being washed away by the runoff. This can result in the loss of topsoil, which is rich in nutrients and organic matter and is essential for supporting plant growth.

In addition to heavy rainfall, Malawi is also vulnerable to other climate-related hazards, such as floods, droughts and extreme heat events. Floods can cause significant soil erosion, as the force of the water can wash away soil particles and vegetation, while droughts and extreme heat can lead to dry and compacted soil, which is more susceptible to erosion.

Furthermore, changes in climate patterns, such as increased frequency and intensity of rainfall events, can exacerbate soil erosion in Malawi. Climate change is expected to increase the risk of extreme weather events, including tropical storms, which could have severe consequences for soil erosion and agricultural productivity in the country.

The country is situated on the East African Rift system, which is a region of tectonic plate boundaries and active faults. While Malawi has not experienced any major earthquakes in recent history, there have been a few notable seismic events in the region. One of the most significant seismic events in Malawi's recent history occurred in 2009 when a magnitude 6.0 earthquake struck the northern region of the country. In addition to the 2009 earthquake, there have been several smaller seismic events in Malawi in recent years, ranging in magnitude from 2.5 to 5.2. These events have mostly occurred in the northern and central regions of the country, which are closer to the tectonic plate boundaries (Gaherty, J B et al, 2019)[12].

While seismic risk and erosion risk are distinct hazards, they are interconnected in some cases. For example, seismic activity such as earthquakes can trigger soil erosion in areas with steep slopes or unstable soil. This can occur due to the shaking caused by the earthquake, which can loosen the soil and cause it to become more susceptible to erosion.

Similarly, erosion can also increase the risk of landslides and other types of mass movement, which can be triggered by seismic activity. This is because erosion can weaken the stability of the soil and rock layers, making them more vulnerable to displacement during an earthquake.

2.2.2 Anthropogenic Factors

Deforestation is a significant cause of erosion in Malawi, as it results in the removal of trees and other vegetation that help to stabilize the soil and prevent erosion. When forests are cleared for agriculture, timber, or other uses, the exposed soil is vulnerable to erosion by wind and water.

In Malawi, deforestation has been a persistent problem for several decades, with an estimated 35% of the country's forest cover lost between 1990 and 2015. This has had significant impacts on soil erosion, with some estimates suggesting that erosion rates in deforested areas can be up to 100 times higher than in forested areas[13].

The loss of forest cover can also exacerbate other factors that contribute to erosion, such as heavy rainfall and steep topography. Without the stabilizing influence of trees and other vegetation, runoff and streams, can easily wash soil away leading to loss of topsoil and diminished fertility of the land.

According to the study cited above, erosion rates in Malawi are highest in areas that have experienced the most deforestation: less than 10% forest cover, erosion rates averaged around 100 metric tons per hectare per year, versus areas with more than 30% forest cover rates are less than 10 metric tons per hectare per year.

Climate Data Set[14] provides global maps assigning the land surface into 22 classes, which have been defined using the FAO's Land Cover Classification System (LCCS). In addition to the land cover (LC) maps, four quality flags are produced to document the reliability of the classification. In order to ensure continuity, these land cover maps are consistent with the series of global annual LC maps from the

[12] Gaherty, J B, Zheng, W, Shillington, D J, Pritchard, M E, Henderson, S T, Chindandali, P R N, Mdala, H, Shuler, Lindsey, N, Oliva, S J, Nooner, S, Scholz, C A, Schaff, D, Ekström, G, Nettles, M. (2019) Faulting processes during early-stage rifting: seismic and geodetic analysis of the 2009–2010 Northern Malawi earthquake sequence JF Geophysical Journal International ; Geophysical Journal International, Volume 217, Issue 3, June 2019, Pages 1767–1782, https://doi.org/10.1093/gji/ggz119

[13] https://www.fao.org/documents/card/fr/c/I6387EN/

[14] https://cds.climate.copernicus.eu/

1990s to 2015 produced by the European Space Agency (ESA) Climate Change Initiative (CCI), which are also available on the ESA CCI LC viewer.

We sorted land cover datasets for Malawi over the period 1992-2020 into 6 categories: Forest, Crops, Shrubs, Wetlands, Urban (which includes bare surfaces) and "Other," which corresponds mainly to areas covered by water bodies. Land cover areas in km² are given for each of these classes in Annex 1 and are represented Figure 2

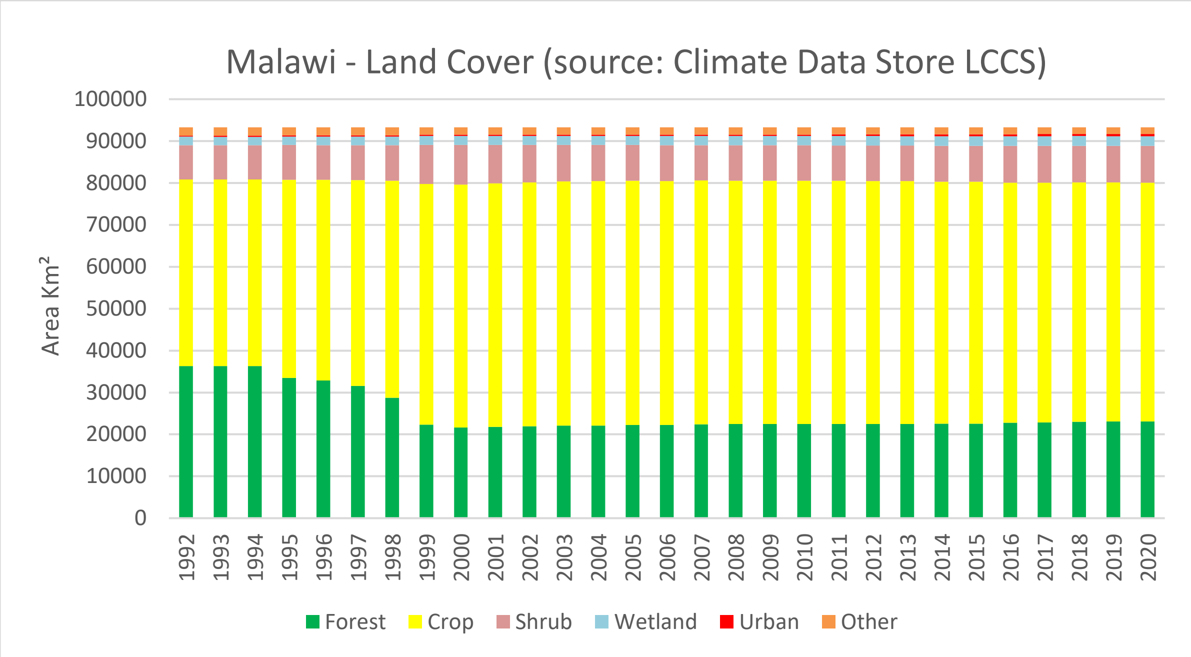

Figure 2: Stacked bar plot of Land Cover in km²

Heavy deforestation was observed at the end of the 1990s in favour of a generalized cultivation throughout the country (Figure 3). Forest and cultivated areas have remained constant since the early 2010s. There has been a slight decrease in agricultural activity in recent years, which is related to the increase in degraded land (shrubs) and wetlands.

There are several reasons that contributed to drastic deforestation in Malawi at the end of the 1990s, particularly in 1999. Malawi experienced significant population growth in the 1980s and 1990s, which have strained the available land and resources, leading to increased deforestation as people sought to meet their basic needs (World bank database on population[15]).

In Malawi, the growing population and increasing food demands have led to the clearing of forests for the expansion of farmland. Subsistence farming and the cultivation of cash crops such as tobacco are prevalent in the country, and the need for additional land have resulted in deforestation.

The commercial logging industry, both legal and illegal, contributed to deforestation. Writing for Malawi 24, Collins Mtika has explored how Chinese investors, aided by Malawians, have been illegally harvesting and trading the country's hard wood[16].

Forests serve as a vital source of fuelwood and charcoal for cooking and heating purposes. Increased demand for these resources due to population growth and limited access to alternative energy sources

[15] https://data.worldbank.org/indicator/SP.POP.TOTL?locations=MW

[16] http://www.wealth-of-nations.org/fr/i/?id=b49e8c37-6c0e-4577-9a9d-d1b3a07abb92

have driven people to engage in unsustainable logging practices, leading to deforestation (Mahonya *et al*, 2019[17].
The expansion of infrastructure in the 90s, such as roads, dams, and urban areas, required the clearing of forests. It contributed to deforestation.
In the early 2000s, the Malawian government, recognizing the importance of forests for ecosystem services and sustainable development, implemented measures to address deforestation. These included the establishment of protected areas, implementation of forestry regulations, and the promotion of sustainable land-use practices (Malawi's national forestry programme priorities for improving forestry and livelihoods, 2001[18]).
International organizations, non-governmental organizations (NGOs), and development agencies have provided assistance and resources to support forest conservation efforts in Malawi. This support has included funding for reforestation projects, capacity building, and technical expertise[19]. Engaging local communities in forest management and conservation efforts was crucial for this long-term success. Community-based initiatives, such as participatory forest management and community forestry, were established in Malawi during the early 2000s. These approaches empower local communities to take ownership of their forests and incentivize sustainable practices.
It is important to note that the reasons for the slowdown or stop to deforestation in Malawi during the early 2000s varied depending on specific local circumstances and initiatives. To obtain a more accurate understanding of the situation, it would be advisable to refer to studies, reports, and experts familiar with the historical context and developments in Malawi during that time period.
According to the LCCS database, the area occupied by forest fell from 36326.88 km² in 1992 to 22522.95 km² in 2020, i.e. 38%, which confirms the 35% loss estimated by the above-cited study. But in reality, the most important deforestation occurred between 1992 and 2002: 37%, then between 2003 and 2013 we see the effect of reforestation -1.6% and in the last years 2014 - 2020, the reforestation continues and even accelerates: -2.5%.

[17] Mahonya S, Shackleton CM and Schreckenberg K (2019) Non-timber Forest Product Use and Market Chains Along a Deforestation Gradient in Southwest Malawi. Front. For. Glob. Change 2:71. doi: 10.3389/ffgc.2019.00071

[18] https://www.dof.gov.mw/storage/app/media/Documents%20for%20Home%20page/Malawi%20National%20Forestry%20Programme%202001.pdf

19 https://www.thegef.org/projects-operations/country-profiles/malawi

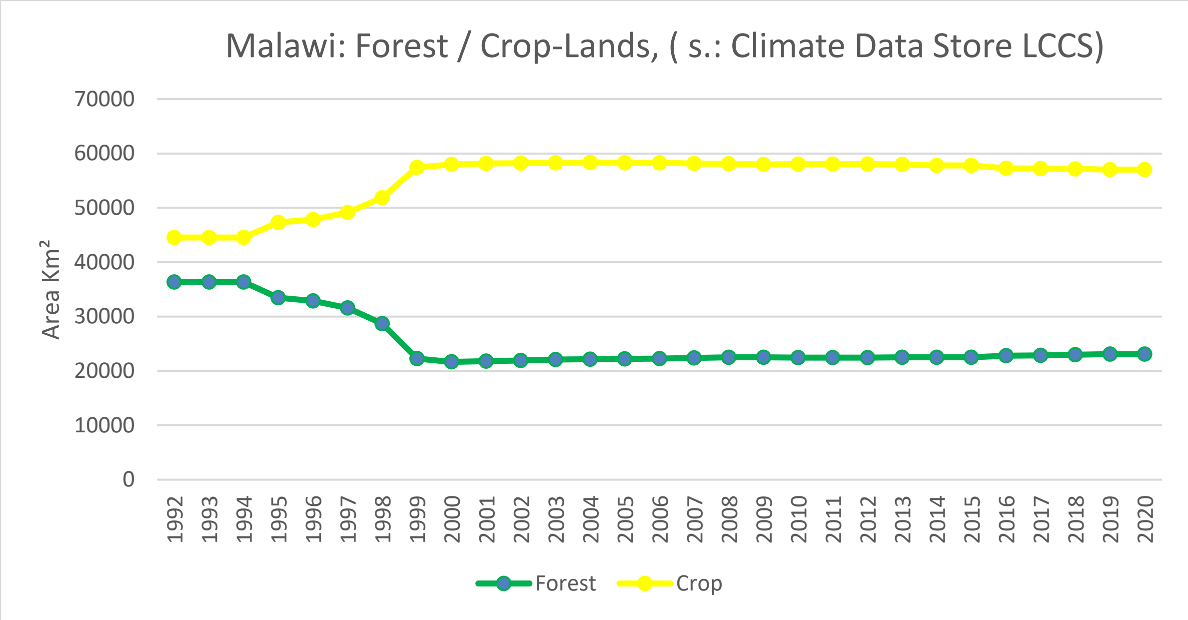

Figure 3: Evolution of forest cover and cultivated cover

Although remaining relatively moderate at the country scale, the urbanized areas are increasing in areal extent (Figure 4). Considering the importance of infrastructure in cities, this increases in urban land cover with low permeability increases flood as well as health risks and danger of damage to buildings, infrastructure as well as to lives and livelihoods.

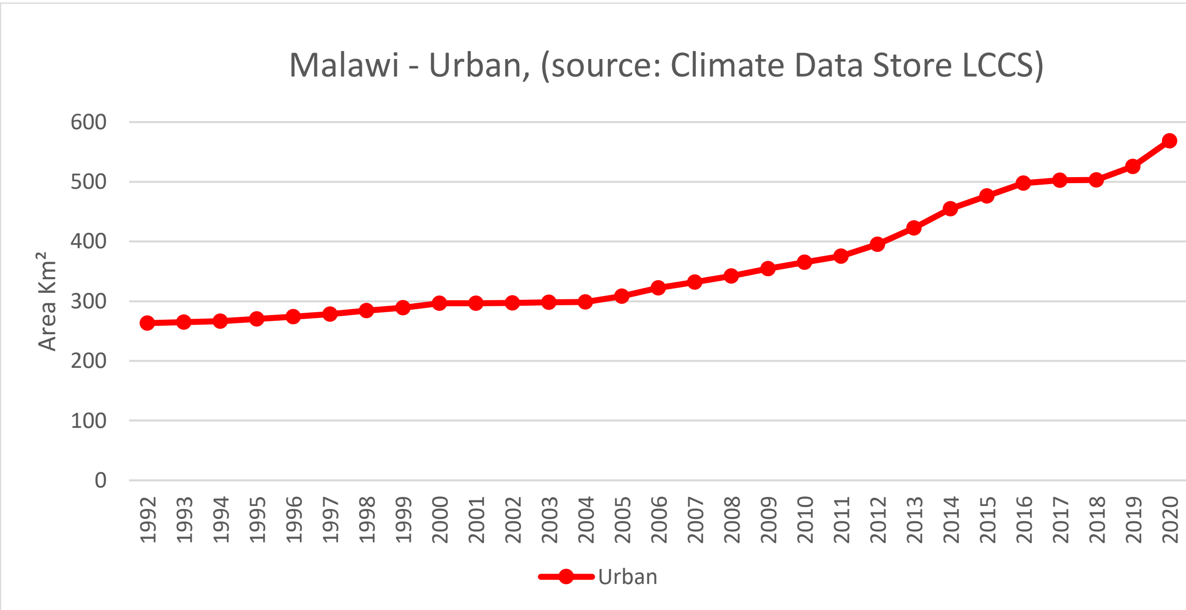

Figure 4: Urbanized area growth.

Deforestation and increasing urbanization have led to increased runoff and flooding, and to lower soil protection. This is a strong indicator of erosion.

Unsustainable agricultural practices are a significant contributor to soil erosion in Malawi. Of the unsustainable practices, the most commonly identified are:

1. **Overgrazing**: Livestock grazing on land for extended periods can cause soil compaction, which reduces the ability of soil to absorb water and leads to increased runoff and erosion. Overgrazing is a common unsustainable agricultural practice in Malawi, particularly in areas with high livestock populations. In many rural areas of Malawi, livestock are allowed to graze freely on communal lands, which can lead to overgrazing and soil exposure as the vegetation cover is removed and compaction. Due to the lack of sufficient fodder reserves, livestock owners in Malawi may resort to allowing their animals to graze for long periods in one area. The expansion of commercial ranching in Malawi has resulted in an increase in grazing pressure on communal lands, leading to overgrazing and soil degradation. According to Omuto CT and Vargas RR's study cited above, overgrazing is responsible for an estimated 15-20% of soil erosion in Malawi. The study found that overgrazing was most prevalent in the southern region of the country, where livestock populations are highest[20].

2. **Slash-and-burn agriculture**: This traditional farming method, also known as shifting cultivation, involves clearing land by cutting down trees and burning them. It can result in high erosion rates, especially in steeply sloping areas. In Malawi, this practice is not officially banned but is regulated under the country's Forestry Act and National Forest Policy (2016).[21] According to the Forestry Act, anyone who wishes to engage in slash-and-burn agriculture must first obtain permission from the Ministry of Forestry and Natural Resources. The act also requires that farmers who engage in this practice must implement measures to prevent soil erosion, such as constructing terraces or planting cover crops. Despite these regulations, slash-and-burn agriculture remains a common practice in some rural areas of Malawi, particularly among smallholder farmers who lack access to modern agricultural inputs and technologies. However, the practice has been identified as a major contributor to soil erosion, deforestation, and land degradation in the country.

3. **Tillage**: Conventional tillage practices, such as ploughing, can disrupt soil structure and expose soil to erosion by wind and water.

Mining and quarrying activities can cause significant soil erosion by altering the topography of the land and removing vegetation cover. This can result in increased soil erosion and sedimentation of waterways, which can have negative impacts on aquatic ecosystems.
In Karongo district, the Kayelekera uranium mine and Kasikizi surface coalmine have caused extensive land clearance. Degradation exposed the soil to contamination from effluents and tailings, and from the coal mine, considerable dust, which then, due to heightened erosion from removal of the vegetation cover, are carried into water courses such as (in the case of Kayelekera), the North Rukuru and, subsequently, are washed into Lake Malawi close to the town of Karonga. On the way, people extract water for lives and livelihoods with a consequent set of risks from the pollution from the mine while eroded silt containing pollutants wash int the lake with impacts on the hydrological ecosystems[22]. Google Earth clearly shows the land degradation on these two sites (Picture 1 & 2).
In 2014, the the Kayelekera uranium mine entered care and maintenance mode owing to a depressed uranium market. The mine met opposition from organisations and individuals concerned about the

[20] Omuto CT and Vargas RR. 2019. Soil Loss Atlas of Malawi. 440 pp. Rome, FAO. https://www.fao.org/3/ca3624en/ca3624en.pdf

[21] https://www.dof.gov.mw/storage/app/media/Policies%20and%20Strategies/National%20Forest%20Policy%202016.pdf

[22] https://www.hrw.org/news/2016/09/27/malawi-mining-puts-residents-risk

mine's tax concessions, operation, adherence to law and regulation and its potential impacts on human and environmental safety[23]. The mine could be re-opened as the uranium market improves[24]

Figure 5: Uranium mine site in the Karango district

The Malawi government has implemented regulations and policies aimed at minimizing the negative impacts of mining and quarrying activities on the environment. The Environmental Management Act of 2017[25], for example, requires mining companies to conduct environmental impact assessments and obtain permits before beginning mining activities. The Act also requires mining companies to implement measures to minimize the environmental impacts of their operations, including measures to prevent soil erosion.

Despite these regulations, illegal mining activities are still a problem in Malawi, particularly in areas where artisanal miners operate. These activities are often carried out without proper environmental safeguards, leading to significant negative impacts on the environment, including soil erosion and land degradation.

23 "Malawian dies on duty at Kayelekera uranium mine in Karonga". Nyasa Times. 2013-07-31 https://web.archive.org/web/20150204063449/http://www.nyasatimes.com/2013/07/31/malawian-dies-on-duty-at-kayelekera-uranium-mine-in-karonga/

24 https://www.miningmx.com/news/energy/50433-malawis-kayelekera-mine-could-be-re-opened-as-the-uranium-market-improves/

25 https://www.climate-laws.org/document/environment-management-act-no-19-of-2017_1fcd

Figure 6: Kasikizi surface coalmine site in the Karango district

Construction and development activities, such as road building and urbanization, can also contribute to soil erosion by altering the landscape and removing vegetation cover. In Malawi, as elsewhere in sub-Saharan Africa, wood remains an important source of energy. Traders fetch charcoal by clearing the forests in ever-larger areas around the cities.

2.3 Estimates of Soil Losses

We did not find data on sediment export measured at the outlets of major catchments in the bibliography or international databases. Our enquiry to the relevant departments shows that Malawi does not have continuous solid transport measurements at its hydrological stations, which would provide a good estimate of soil loss from the main catchments.

The monitoring of solid transport in rivers requires sampling for analysis, which can be combined with turbidity measurements of the water. Hydrological stations can be equipped with automatic samplers that save time in the field.

In Malawi, measurements of soil loss on plots set up according to the experimental Wishmeier[26] protocol have been available in several regions since the early 1980s. Amphlett (1984)[27] carried out soil loss studies in small plots in Bvumbwe, Mindawo, and Mphezo basins in the south of Malawi and found seasonal soil loss rate to be between 0.15 and 16 ton/ha.

Mwendera (1988) compared SLEMSA results with measured soil erosion values from a long-term soil erosion study-site on four catchment areas near and around the Bvumbwe Agricultural Research

[26] Wischmeier, W.H. & Smith, D.O., 1978. Predicting rainfall erosion losses - a guide to conservation planning. USDA, Agric. Handbook No. 537. Washington

[27] Amphlett, MB. 1984. Measurement of soilloss from experimental basins in Malawi. Challenges in African Hydrology and Water Resources (Proceedings of the Harare Symposium, July 1984). IAHS Publ. no. 144

Station in the south of the country. The estimated erosion was 10 ton/ha/yr for an area without proper conservation and 0.05 ton/ha/yr from a Eucalyptus tree plantation. [28]
In 1998, Malawi Environmental Monitoring Program (MEMP) studied soil loss in five small catchments located in various parts of the country and found the soil loss rate between 1 and 5 ton/ha/yr (Mahmoud and Burger 1998).[29] In 1999, Jamu and Brummett (1999) studied soil loss in Zomba and found the soil loss rate between 1.2 and 100 ton/ha/year. [30]
Using the SLEMSA model with a calibration on different plots, Vargas R. and Omuto C. (2016) provide an overview of the topsoil loss trends between 2000 and 2014 (Soil loss assessment in Malawi). Soil loss rates vary greatly from year to year and regionally. They vary according to the year from 20 to 35 tonnes/ha/year.
The FAO soil loss atlas of Malawi 2019,[31] cited in the introduction, builds a comprehensive picture of soils in the country by examining different types of soil loss and their drivers across the 27 districts of Malawi. The publication captures information on soil types, land cover and land use types, topography, mean annual rainfall, soil loss rates and soil-nutrient loss rates. All of this data is mapped by district through photographic evidence, graphs and maps, which effectively illustrate the scale and range of soil loss across the country.
Overall, these studies suggest that soil erosion is a significant problem in Malawi, with estimated soil loss rates ranging from 1 to 200 tons of soil per hectare per year with an average erosion rate of 30 tons per hectare per year. Efforts to address soil erosion in Malawi include promoting sustainable land use practices and implementing policies and regulations aimed at reducing the impact of anthropogenic factors on the environment.

2.4 Impacts of Soil Erosion:

Soil erosion has numerous impacts on Malawi's agriculture, food security, environment, economy, and society. It reduces soil fertility, which in turn reduces crop yields and food security. It also leads to sedimentation of rivers and lakes, which affects water quality and aquatic ecosystems. Soil erosion can also damage infrastructure, such as roads and buildings, and increase the risk of landslides and flooding.
Asfaw et al 2020 investigate the economic distributional effects of soil loss in Malawi.[32] Malawi offers a favourable setting for their analysis, being a country with a severe soil erosion problem and, increasing exposure to climate shocks that contribute to worsening the erosion process. They carried out a micro-econometric analysis using socio-economic, climatic and topsoil loss data both at plot and household level. They considered the role of different agricultural practices in mitigating the negative impacts of soil loss to assess cost-effective policy options and compensation mechanisms and to provide aggregated effects. They show that the topsoil loss severely affects the productivity and welfare of most vulnerable households, undermining the capacity to escape from poverty.

[28] Mwendera, E J. 1988. Preliminary evaluation of soil loss estimation model for Southern Africa (SLEMSA) under Malawi conditions. Land Husbandry Senior Staf Seminar

[29] Mohamoud, Y. and Burger, K. 1998, An Overview of the Malawi Environmental Monitoring Programmes' Small Catchment Monitoring Component with Recommendations to Meet Malawi's National Environmental Monitoring Requirements. University of Arizona, Tucson, AZ
https://cals.arizona.edu/OALS/malawi/Papers/Catchment_Overview.pdf

[30] Jamu, DM and Brummett, RE. 1999. Fish reproduction in Lake Chilwa with special emphasis on Barbus paludinosus and the status of the watershed. State of the Environment Study No. 5, Danida./Ministry of Natural Resources and Environmental Afairs. Lilongwe, Malawi

[31] https://www.fao.org/3/ca3624en/ca3624en.pdf

[32] Asfaw S., Pallante G., Palma A., Distributional impacts of soil erosion on agricultural productivity and welfare in Malawi, Ecological Economics, Volume 177, 2020, 106764,
https://doi.org/10.1016/j.ecolecon.2020.106764.

Asfaw et al's analysis on the aggregated effects indicates that the impact of topsoil loss on the Malawian economy is sizeable, corresponding to a reduction of national maize production ranging from 6.8% to 20%, the monetary value of which, ranges from 1% to 3% of GDP for a topsoil loss of 10% and 30%, respectively. Moreover, effects on agricultural productivity and social welfare are not equally distributed, instead disproportionately affecting least-productive households and worsening their condition.

2.5 Potential Solutions:

Addressing soil erosion in Malawi requires a multifaceted approach that combines policy, technology, and education. Policies that promote sustainable land use practices, such as agroforestry and conservation agriculture, can help reduce erosion. Technologies such as terracing contour farming and cover cropping can also be effective in reducing erosion. Education and outreach programmes can raise awareness about the importance of soil conservation and help farmers adopt sustainable practices.

The Government of Malawi has implemented several policies and programs aimed at promoting soil conservation and land management practices.

The Land Act of 2016 includes provisions for the conservation and sustainable use of land and natural resources. The Act requires that land use plans be developed at the district level and includes provisions for the protection of wetlands, forests, and other critical ecosystems.[33]

The National Forestry Policy: The National Forestry Policy of 2016 aims to promote the sustainable management and conservation of forests in Malawi. The policy includes provisions for community forestry management, forest conservation, and reforestation (cited above).[34]

The Farm Input Subsidy Program (FISP)[35]: The FISP provides subsidized inputs such as fertilizer and improved seeds to smallholder farmers in Malawi. The program includes a component for soil conservation that provides training and support for farmers to adopt conservation agriculture practices.

2.6 Soil degradation and Gender issue

Few publications on the net show that soil loss and land degradation in Malawi exacerbate existing gender inequalities, as women are often the primary caregivers and providers of food for their families and rely heavily on natural resources for their livelihoods. Here are some ways that soil loss and land degradation can affect women in Malawi[36],[37]:

i) **Reduced agricultural productivity:** As soil fertility declines due to erosion and degradation, women farmers may experience reduced yields and productivity, which can have a direct impact on their ability to provide for their families.

ii) **Limited access to resources:** Women in Malawi often have limited access to resources like land, water, and credit, which can further limit their ability to cope with the impacts of soil loss and land degradation.

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33 https://www.ecolex.org/details/legislation/land-act-cap-5701-lex-faoc041845/**?**

34https://www.dof.gov.mw/storage/app/media/Policies%20and%20Strategies/National%20Forest%20Policy%202016.pdf

35 Schiesari, C. Mockshell, J. and Zeller, M. (2016) Farm input subsidy program in Malawi: the rationale behind the policy. University of Hohenheim. 30 p. https://mpra.ub.uni-muenchen.de/81409/1/MPRA_paper_81409.pdf

36 Family Planning and Gender Equality: Paving the Road to Prosperity in Malawi, USAID, 2014, https://www.prb.org/wp-content/uploads/2014/09/malawi-gender-brief.pdf

37 Stella Gama & Mphatso Kalemba Gender and Biodiversity in Malawi. 2020. https://www.cbd.int/gender/doc/malawi-gender-and-biodiversity-12-august-2020.pptx

iii) **Increased labour burden:** As soil quality declines, women may need to spend more time and effort on land preparation, weeding, and other activities to maintain their crop yields, which can increase their labour burden and reduce the time available for other female dominated roles such as caring for their families.

iv) **Health impacts:** Women and children in Malawi are mostly responsible for collecting firewood and water, which can become more difficult as soil loss and land degradation lead to deforestation, reduced water availability, and longer travel distances. This can increase the risk of illness and injury, as well as exacerbate existing health issues.

2.7 Soil loss hazard modelling and simulation with climate change

As we were unable to get the data from the SLEMSA model, we built a model based on the revised RUSLE land loss equation of Renard KG (1997) mentioned above and on the layering of the parameters of this equation with the GIS software QGIS. To estimate the different parameters of the RUSLE equation, we used the full work of Eric Roose in the tropics of sub-Saharan Africa, which is summarised in FAO's Gide (1996) Land husbandry: Components and strategy[38].

2.7.1 The Revised Universal Soil Loss Equation (RUSLE) model

The Revised Universal Soil Loss Equation (RUSLE) predicts the average annual rate of long-term erosion on a field slope as a function of rainfall pattern, soil type, topography, cropping system and management practices. The RUSLE predicts only the amount of soil loss that results from sheet or rill erosion on a single slope but does not consider additional soil loss that may be due to other forms of erosion associated with gullying, wind or tillage.
This model to predict erosion was designed for agricultural land, but it is currently used to predict erosion in a non-agricultural land, such as forestry land and construction sites. In agriculture, the RUSLE can be used to compare soil erosion rates associated with current management practices with tolerable soil loss rates for a given field. Combinations of cropping and tillage systems can also be evaluated to determine the suitability of soil conservation measures in agricultural planning. By changing the rainfall erodibility parameter, it is also possible to simulate a soil loss rate in the case of a change in weather type.
RUSLE uses five main factors to calculate the soil loss at a given location. Each factor is a numerical estimate of a specific component that affects the severity of soil erosion at that location. The erosion values obtained by applying these factors can vary considerably depending on weather conditions. Therefore, the values given by the USLE represent long-term temporal averages.

RUSLE equation is:

$$A = R \times K \times LS \times C \times P$$

- **A** is the possible long-term average annual soil loss in tonnes/hectare (metric tonnes). This value can then be compared to the limits of "tolerable soil loss" (Table 1).
- **R** is the rainfall-runoff factor for a geographical area.
- **K** is the soil erodibility factor, reflecting the susceptibility of soil particles to be detached and transported. It depends on soil properties such as structure, organic matter content, and texture.
- **LS** is the slope length and steepness factor, which considers the topography of the land. Steeper and longer slopes tend to have higher erosion rates.

[38] Roose E (1996) Land Husbandry - Components and Strategy- 70 FAO SOILS BULLETIN, Food and Agriculture Organization of the United Nations, Rome 302p.

- **C** is the cover-management factor, reflecting the effect of cropping and management practices on soil erosion rates. For instance, a well-established vegetative cover will significantly reduce erosion**.**
- **P** is the support practice factor, which accounts for the effects of practices that reduce the amount and rate of water runoff, such as contouring, strip-cropping, and terracing

Table 1 : Tolerable loss rates in the soil (K. McKague, ing. 2023)[39]

	Soil erosion potential class	Possible loss of soil
1	Very low (tolerable)	<6.7 tonnes/ha/year (3 tonnes/acre/year)
2	Low	6.7-11.2 tonnes/ha/year (3-5 tonnes/acre/year)
3	Moderate	11.2-22.4 tonnes/ha/year (5-10 tonnes/acre/year)
4	High	22.4-33.6 tonnes/ha/year (10-15 tonnes/acre/year)
5	Very high	>33.6 tonnes/ha/year (15 tonnes/acre/year)

2.7.2 Rainfall-Runoff Factor (R)

The more intense the rainfall and the longer it lasts, the greater the risk of erosion. For many regions of the world, the competent departments of the ministries of agriculture or academics have defined possible values for this parameter using the most accessible rainfall factors. We use the relationship proposed by Eric Roose[40] for tropical sub-Saharan Africa. From extensive rain gauge data, Eric Roose found that there was a simple relationship between the mean annual index ($\boldsymbol{R_{am}}$) over a sufficiently long period (5 to 10 years) and the mean annual rainfall ($\boldsymbol{H_{am}}$) during the same period in intertropical Africa

$$\frac{\boldsymbol{R_{am}}}{\boldsymbol{H_{am}}} = \mathbf{0.50 \pm 0.05}$$

This ratio is particularly constant at about 20 points in Côte d'Ivoire, Burkina-Faso, Senegal, Niger, Chad, Cameroon and Madagascar at rain gauges with 20 years of data.

Assessment 1: We use this formula on the 1958-2021 interannual average of rainfall data from the ERA5 - ECMWF database. This assumption is justified by the fact that we seek to express average soil losses and to avoid inter-annual climate variability. This approach is different from the one adopted for the SLEMSA modelling which reconstituted soil losses on an annual basis between 2009 and 2014.

2.7.3 Soil Erodibility Factor (K).

K is the soil erodibility factor. The K-factor is a measure of the vulnerability of soil particles to detachment and transport by rain and runoff. Texture is the main factor influencing the K-factor, but soil structure, organic matter content and permeability also play a role. Based on the nature of the soils according to map 1 established from the Soil and Terrain Database (SOTER) / ISRIC Data hub data,

[39] https://www.ontario.ca/fr/page/equation-universelle-des-pertes-en-terre

[40] Roose Eric. (1975). Application de l'équation de prévision de l'érosion de Wischmeier et Smith en Afrique de l'Ouest. In : La conservation et l'aménagement du sol dans les tropiques humides. Adiopodoumé : ORSTOM, 22 p. multigr. La Conservation et l'Aménagement du Sol dans les Tropiques Humides : Colloque, Ibadan (NG), 1975/06/30. https://www.documentation.ird.fr/hor/fdi:08469

we used the method described by Vopravil et al 2007[41] to calculate at each point of this map a K. We obtained the following values for the indicated soils:

Assessment 2 : This assessment gives the K values used for Malawi CRA study (Table 2**)**

Table 2 : Suggested Values of Soil Erodibility Factor K For Malawi

Type of soil	K
Luvisols	**0.4**
Lixisols	**0.4**
Cambisols	**0.2**
All others	**0.15**

2.7.4 Slope Length Steepness Factor (LS)

LS is the slope length and slope steepness factor. The LS factor is determined using the following equation:

$$LS = \frac{\sqrt{L}}{100} * (0.76 + 0.53\,S + 0.076\,S^2)$$

Where:

- S = Slope gradient (percentage)
- L = Slope length (feet)

The LS factor represents the combined effect of slope length and steepness on soil erosion. It takes into account the fact that longer slopes, and steeper slopes are more prone to erosion than shorter and gentler slopes. The LS factor is dimensionless and typically ranges from 0 to 100. If a plot with a 9% slope and 72.6 feet in length is chosen the topographical factor SL is reduced to 1 –

The equation for LS in the RUSLE model was developed based on data from field studies and represents an empirical relationship between slope length, slope steepness, and soil erosion.

2.7.5 Cover and Management Factor

C represents the cover and management factor. It takes into account the effect of vegetation cover and land management practices on soil erosion.

The C factor is a dimensionless parameter that ranges from 0 to 1, with lower values indicating less soil erosion. It is based on the type and amount of vegetation cover, as well as the land management practices used on the site. For example, a site with a dense cover of perennial vegetation such as grass or trees will have a high C factor, indicating that it is less prone to erosion. In contrast, a site with no vegetation or with bare soil will have a low C factor, indicating that it is more prone to erosion.

The C factor can be estimated using a table of values that takes into account the type of vegetation cover and land management practices on the site. The table assigns values ranging from 0 to 1 based on the condition of the vegetation cover and the land management practices used. These values are then used to calculate the overall C factor for the site.

Eric Roose proposes the following values in sub-Saharan Africa:

[41] Vopravil J., Janeček M. and Tippl M. (2007) Revised Soil Erodibility K-factor for Soils in the Czech Republic. Soil & Water Res., 2, 2007 (1): 1–9. https://www.researchgate.net/publication/238067662_Revised_Soil_Erodibility_Kfactor_for_Soils_in_the_Czech_Republic#fullTextFileContent

- Forest -> C=0.001
- Tabaco, Coffee, Tea -> C=0.1
- Cassava and tuber plants -> C=0.2
- Cereals, sorghum, maize -> C=0.7

Assessment 3: As we do not have the ability to distinguish between the different crops and crop rotations on the land use maps given by the Climate Data Store LCCS, we have taken the following values (Table 3):

Table 3: Values of The Cover Factor C as Selected for the Present Study

Type of Land use		C
Forest		**0.001**
Cultivated areas		**0.4**
Shrubs		**0.5**
Build areas		**0.6**

We use the land use map of 2020. The distribution of land between cultivated and forested areas seems to have stabilised. Despite a rapid increase in urbanised areas, these will still be in the minority on a national scale.

P represents the support practice factor. It takes into account the effect of conservation practices such as terracing, contouring, and other measures on reducing soil erosion. A high P value in the RUSLE model indicates a lower degree of soil conservation and more erosion, while a low P value indicates a higher degree of soil conservation and less erosion.

Assessment 4: In our model, we used a P = 1 (no conservation practice) in a first time, and we simulated with P = 0.4 in the areas the most affected by erosion. P = 0.4 is for conservation practice as terracing, contouring. We know that Malawi implemented many anti-erosive devices in different districts. As we are not able to map them, we have made this assumption with the understanding that our estimates at the country level may be overestimated.

2.7.6 Model Result

We simulated potential soil losses pixel by pixel and obtained values ranging from 0.19 t/ha/yr to 182 t/ha/yr and an average of **46.8 t/ha/yr** at the country level. This result classifies the whole country as suffering a “very high” erosion hazard. We classified pixels by “Soil erosion potential class” and Figure 7 shows the result of the model on Malawi.

This average value of soil loss at the country level remains within the order of magnitude of that given in the literature, even if it is higher than that found in the literature (between 30 and 35 t/ha/year). The failure to take into account anti-erosion measures may partly explain this overestimation. Locally, the values obtained are of the order of magnitude of those quoted in the works cited above.

Located near Lilongwe, the capital city, the Chitedze Research Station has been conducting studies on soil erosion. Their research has highlighted soil loss rates ranging from 10 to 20 tons per hectare per year in certain areas. Research conducted by Mzuzu University has focused on soil erosion and conservation in northern Malawi. It has identified erosion rates of up to 50 tons per hectare per year in certain locations (Vargas R. and Omuto C, 2016)[42]. The Soil Conservation Department (SCD) has been

[42] https://www.fao.org/3/I6387EN/i6387en.pdf

actively working on soil conservation efforts. They have published reports and guidelines related to soil erosion and conservation practices, which contain specific soil loss values in the same order.

The visual analysis of the resulting map also provides a perception of the erosion hazard across the country (see Figure 7) and Table 4 gives the distribution of the territory by erosion classes in Malawi.

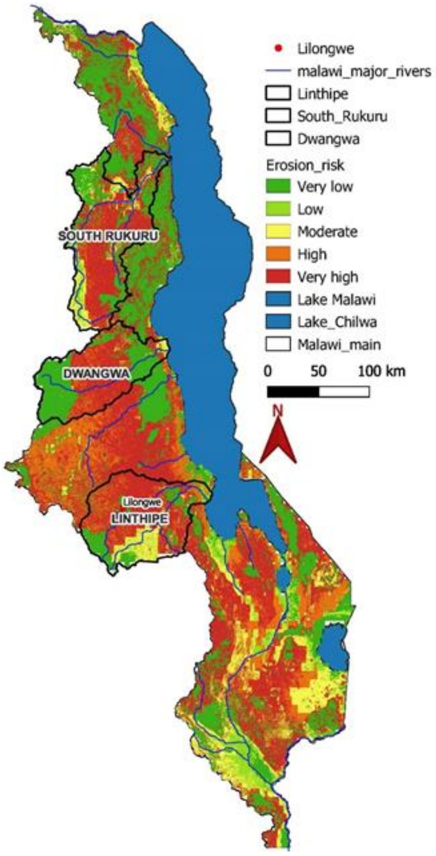

Figure 7: Map of soil losses in Malawi according to the RUSLE equation using the assumptions outlined above

Table 4: Distribution of potential soil losses in Malawi

No erosion control / soil uses map 2020 / rainfall 1958 - 2021						
	Hazard					Av. soil loss t/ha/yr
Erosion class	Very low	Low	Moderate	High	Very High	
Km²	27651	3986	8827	14577	35060	46.84
%	30.7	4.4	9.8	16.2	38.9	

The "P" factor represents the support practices factor, which measures the effectiveness of various conservation practices in reducing soil erosion. The P factor accounts for the impact of practices such as contour ploughing, terracing, crop residue management, and other erosion control measures.

- Contour ploughing: P values for contour ploughing can range from 0.1 to 0.5, depending on the degree of contouring and effectiveness in reducing water runoff and erosion.
- Terracing: Terracing is an effective erosion control measure, and P values for terraces can range from 0.3 to 1, depending on the design, maintenance, and effectiveness in reducing slope length and gradient.

- Conservation tillage: Conservation tillage practices, such as minimum tillage or no-till farming, can significantly reduce soil erosion. P values for conservation tillage can range from 0.1 to 0.8, depending on the level of soil disturbance and residue cover.
- Crop residue management: Retaining crop residues on the soil surface provides protection against erosion. P values for effective residue management can range from 0.1 to 0.5, considering the amount and distribution of residue cover.

It's important to note that the specific P values for conservation practices may vary depending on the region, soil type, climate, and specific conditions of the area being evaluated.
We propose to make a new assumption: the implementation of average conservation practices P = 0.4 on all the areas in class “high” and “very high” then run the simulations for a climate change that would lead to a 10% higher climate erosivity than today.
While all models predict an increase in extreme events, they do not agree on the evolution of annual rainfall. An increase of 10% in R seems a reasonable basis for implementing climate-change adaptation policies in the fight against soil degradation.
We simulated potential soil losses pixel by pixel and obtained values ranging from 0.19 t/ha/yr to 77 t/ha/yr and an average of **19.9 t/ha/yr** at the country level (Figure 8). The country's average soil losses decrease by almost 60% compared to no conservation measures. The country's soil losses become overall in the "moderate" class.
Table 5 gives the distribution of the territory by erosion classes in Malawi when we simulate the implementation of a soil conservation measures on places.

Table 5: Distribution of potential soil losses in Malawi, simulation with P=0.4 on lands with a high or very high soil-loss potential

Erosion control P=0.4 for classes “High and “Very High” / soil uses map 2020 / rainfall 1958 - 2021						
	Hazard					Av. soil loss t/ha/yr
Erosion class	Very low	Low	Moderate	High	Very high	
Km²	27651	9110	35040	8236	10065	19.92
%	30.7	10.1	38.9	9.1	11.2	

Figure 8 shows the map of potential soil losses applying a uniform 10% increase in climatic erodibility R and without conservation practices and Figure 9 is the map resulting from the simulation of soil losses applying the same 10% increase in climatic erodibility but applying soil conservation measures P = 0.4 on the classes “high” and “very high” erosion hazards.

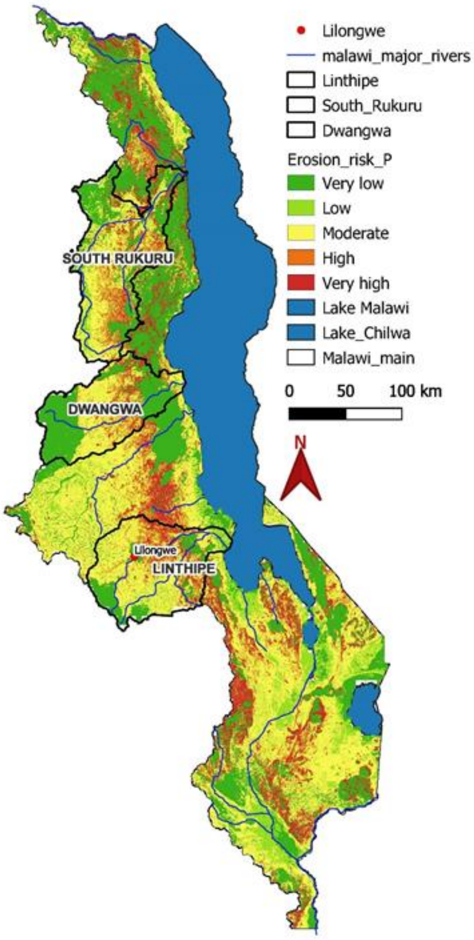

Figure 8: Map of soil losses in Malawi according to the RUSLE equation and P=0.4 on lands with a high or very-high soil-loss potential.

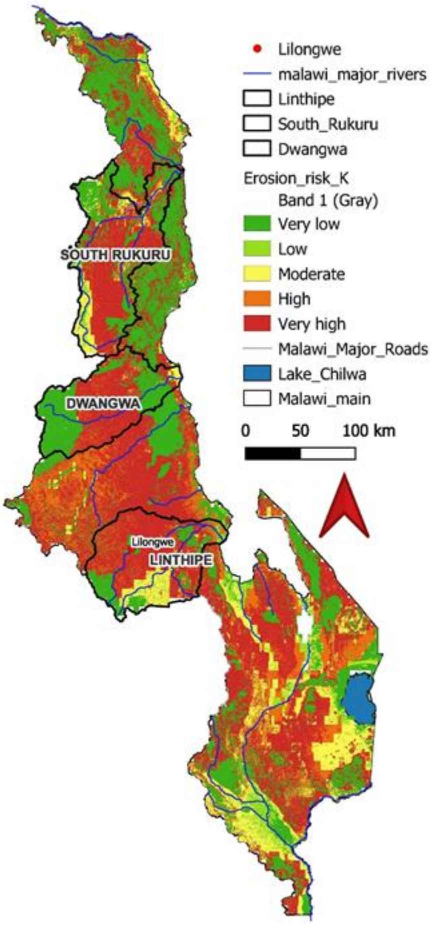

Figure 9: Map of potential soil losses applying a uniform 10% increase in climatic erodibility R and without conservation practices

Table 6: Distribution of potential soil losses in Malawi, simulation for R = R+10%

Erosion control 1.10 R / soil uses map 2020 / rainfall 1958 - 2021						
	Hazard					Av. soil loss t/ha/yr
Erosion class	Very low	Low	Moderate	High	Very-high	
Km²	27650	2580	9114	11785	38973	51.52
%	30.7	2.9	10.1	13.1	43.2	

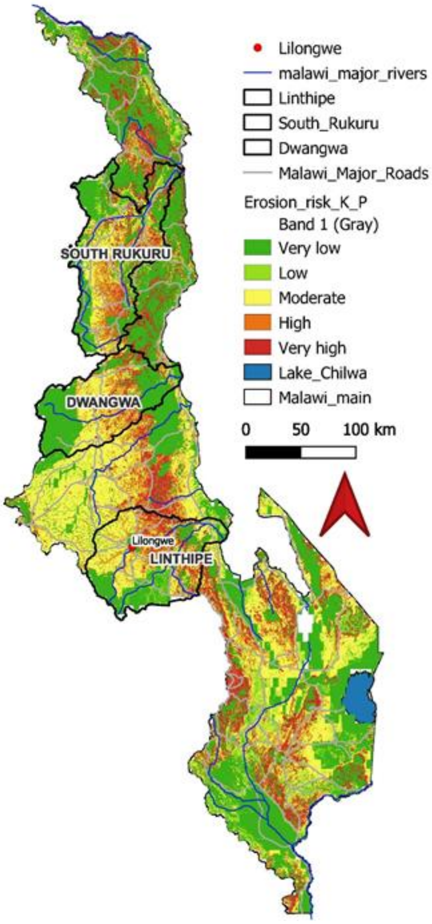

Figure 10: Map of potential soil losses applying a uniform 10% increase in climatic erodibility R and conservation practices P=0.4 on "High" an "Severe" classes

Table 7: Distribution of potential soil losses in Malawi, simulation for R = R+10% and soil conservation measures

Erosion control 1.10 R and P=0.4 for "high" & "very-high" / soil uses map 2020 / rainfall 1958 - 21						
	Hazard					Av. soil loss t/ha/yr
Erosion class	Very low	Low	Moderate	High	Very-high	
Km²	36457	6138	26413	9759	11335	20.61
%	40.5	6.8	29.3	10.8	12.6	

3. POTENTIAL SOIL LOSSES IN THE TARGETED CATCHMENTS

To locate the most fragile surfaces within the catchments in Malawi, several elements can be considered at the catchment scale. These elements help identify areas that are highly susceptible to erosion and prioritize them for targeted intervention:

1. **Topography:** The slope and elevation of the land are crucial factors in determining erosion vulnerability. Steeper slopes are more prone to erosion as gravity accelerates the flow of water, increasing runoff and the potential for soil displacement. Digital Elevation Models (DEMs) and topographic maps can be used to analyse the topography and identify areas with higher slopes.

2. **Soil type and quality:** Different soil types have varying levels of erosion susceptibility. Soils with loose texture, low organic matter content, and low water-holding capacity are more vulnerable to erosion. Soil surveys and analysis can provide information on soil types, fertility, and erosion risk, allowing for targeted interventions in areas with fragile soils.
3. **Land cover and vegetation:** The presence or absence of vegetation cover greatly influences erosion susceptibility. Vegetation, particularly trees and grasses with deep root systems, help stabilize the soil, reduce surface runoff, and enhance water infiltration. Remote sensing techniques, such as satellite imagery or aerial photography, can be used to assess land cover and identify areas lacking adequate vegetation cover.
4. **Hydrological characteristics:** Understanding the flow paths of water within the catchment is essential for locating fragile surfaces. Analysis of hydrological patterns, including drainage networks, stream networks, and watershed boundaries, can help identify areas with high water flow and concentration, which are prone to erosion. Hydrological modelling and analysis can assist in determining areas with increased erosion risk.
5. **Land-use and land-management practices:** Examining the type of land use and land-management practices in a given area is crucial for assessing erosion vulnerability. Areas with intensive agriculture, inappropriate ploughing techniques, overgrazing, or inadequate soil conservation measures are more likely to experience erosion. Field surveys, interviews with local communities, and land-use mapping can provide valuable insights into land-management practices and identify areas with higher erosion potential.

By integrating and analysing these elements, it is possible to identify the most fragile surfaces within the catchment. This information guides decision-making processes and help prioritize the implementation of erosion control measures in areas that require immediate attention.

3.1 The South Rukuru Catchment

The South Rukuru River rises in southern Mzimba District and flows roughly north-northeast to empty into Lake Malawi. Its watershed mostly lies in the Mzimba Plain. Its tributaries drain the western slopes of the Viphya Mountains. To the east, a low divide, which forms the Malawi-Zambia border, separates the South Rukuru's watershed from that of Luangwa River in Zambia. The lower valley of the river separates the northern end of the Viphya Range from the Nyika Plateau to the north.
The exact size of the South Rukuru Catchment can vary depending on the source (12,110 km^2 according to Shela (2000) and 12,719 km^2 according to JICA (2014), including the North Rumphi catchment. According to the shape file provided by the Water Department, its surface is 10,596 km^2 and its perimeter is 794 km. The catchment includes the South Rukuru River and its tributaries, as well as the surrounding land area that drains into the river.
The South Rukuru River is the second largest tributary to Lake Malawi and is the significant stream in the Water Resource Area (WRA) 7 system. It is an important water resource in the region, used for irrigation, domestic use and fishing whilst also supporting a diverse range of aquatic and, in the wider riverine ecosystem, terrestrial species.
The Department of Irrigation is currently developing a large irrigation scheme, which will cover an area of 4,000 hectares in the Rumphi district on the left bank of the South Rukuru River. The project is supported by the European Union and will benefit almost 2,300 farmers in the region.
However, as with many rivers in Malawi, the South Rukuru River is facing environmental challenges such as deforestation, soil erosion, and pollution, which can negatively affect the health of the river ecosystem and the communities that depend on it. We applied the model developed above to this catchment, using the shapefile provided by the Water Department.

Several factors contribute to soil erosion in the South Rukuru Catchment, Figure 9 is a map of soil loss by class of severity with no conservation measures and Figure 12 considers soil loss with conservation measures in the most fragile areas, including:

- **Steep slopes:** The catchment's hilly topography, characterized by steep slopes, increases the vulnerability of the soil to erosion. Rainwater flows rapidly down these slopes, leading to the removal of the topsoil.
- **Deforestation:** Widespread deforestation has occurred in the catchment due to the clearing of land for agriculture, fuelwood collection, and timber extraction at the end of the 90's (refer to the study on the flooding). The removal of trees and vegetation exposes the soil to the erosive forces of rainfall and wind.
- **Unsustainable agricultural practices**: Poor land management practices, such as inappropriate ploughing techniques, overgrazing, and lack of crop rotation, contribute to soil degradation and erosion. Inadequate soil conservation measures exacerbate the problem.
- **Climate change:** Climate change is resulting in changes in rainfall patterns in Malawi, including increased intensity and frequency of rainfall events. These intense rains can lead to increased runoff and erosion, particularly on unprotected or poorly managed lands.

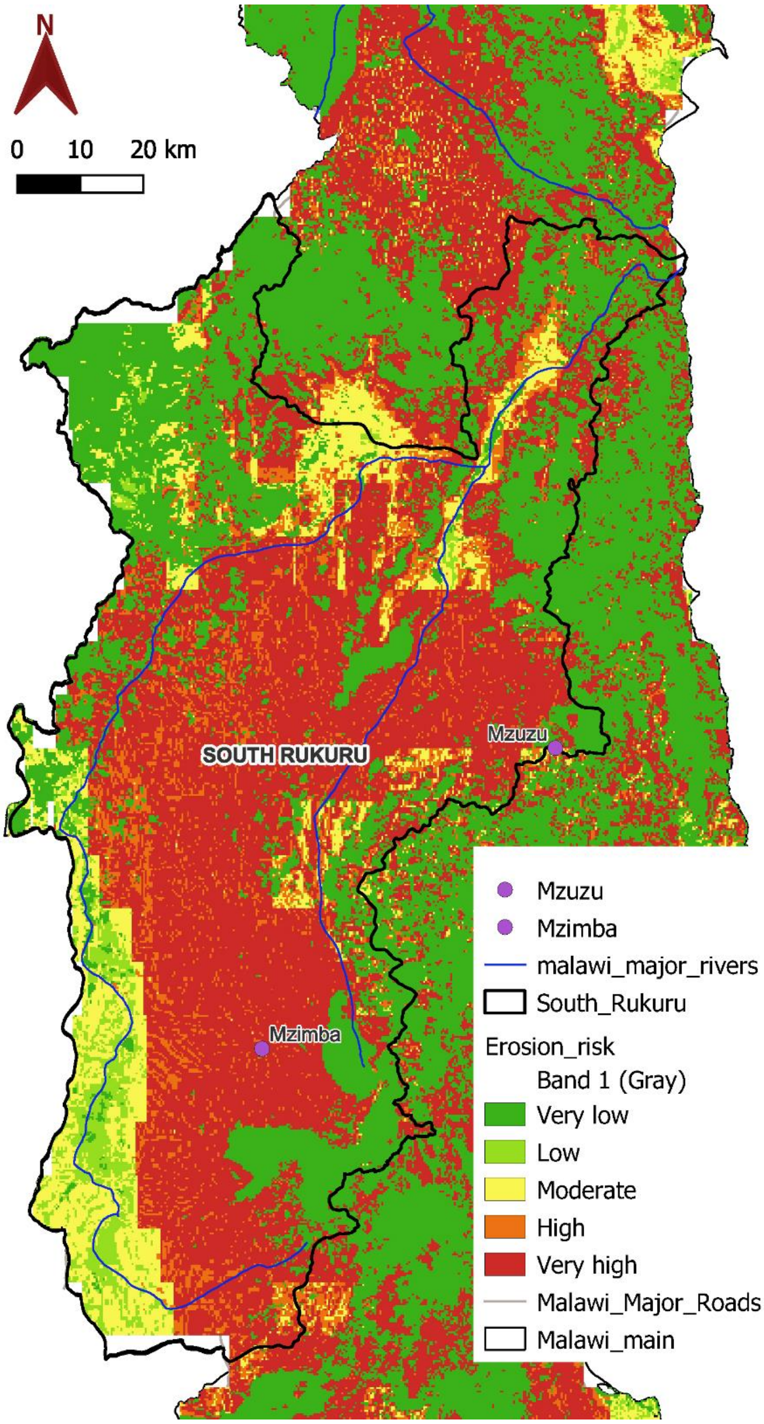

Figure 11: Map of soil losses in Rukuru according to the RUSLE equation with the same assumptions outlined at the country level

Table 8: Distribution of potential soil losses in South Rukuru, without any conservation measure

Erosion / soil uses map 2020 / rainfall 1958 - 2021						
	Hazard					Av. soil loss t/ha/yr
Erosion class	Very low	Low	Moderate	High	Very high	
Hectares	295 830	39 420	103 788	95 787	470 538	41.1
% total area	29.4	3.9	10.3	9.5	46,8	

As we have seen at the country level, the implementation of conservation measures on the "High" and "very high" classes reduces the erosion hazard and protects relatively well from the effects of climate change (Figure 12).

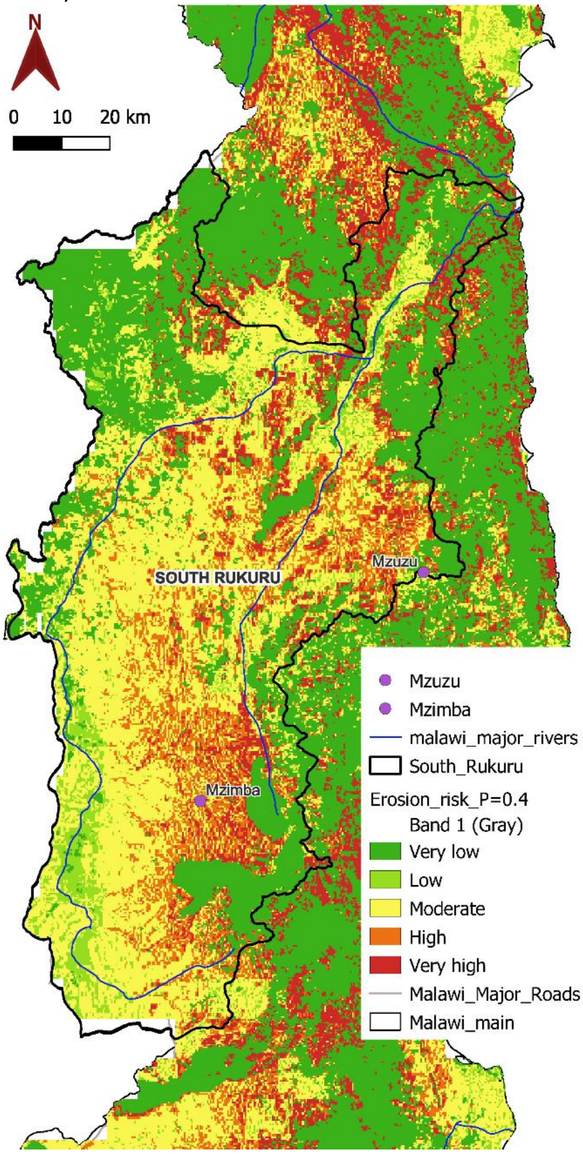

Figure 12: Map of soil losses in South Rukuru catchment according to the RUSLE equation and P=0.4 on lands with a high or very high soil-loss potential

Table 9: Distribution of potential soil losses in South Rukuru catchment, simulation with P=0.4 on lands with a high or very high soil-loss potential

Erosion control P=0.4 for classes “High and “Vey high” / soil uses map 2020 / rainfall 1958 - 2021						
	Hazard					Av. soil loss t/ha/yr
Erosion class	Very low	Low	Moderate	High	Very high	
Hectares	295 380	67 680	406 296	142 173	93 384	17.7
% total area	29.4	6.8	40.4	14.1	9.3	

These conservation measures drastically reduce the potential loss of land (Figure 13). Average soil loss decreases from 41 t/ha/yr to 18 t/ha/yr and the very high erosion class drops from 466 956 (47% of the catchment area) to 90 990 (9% of the catchment area).

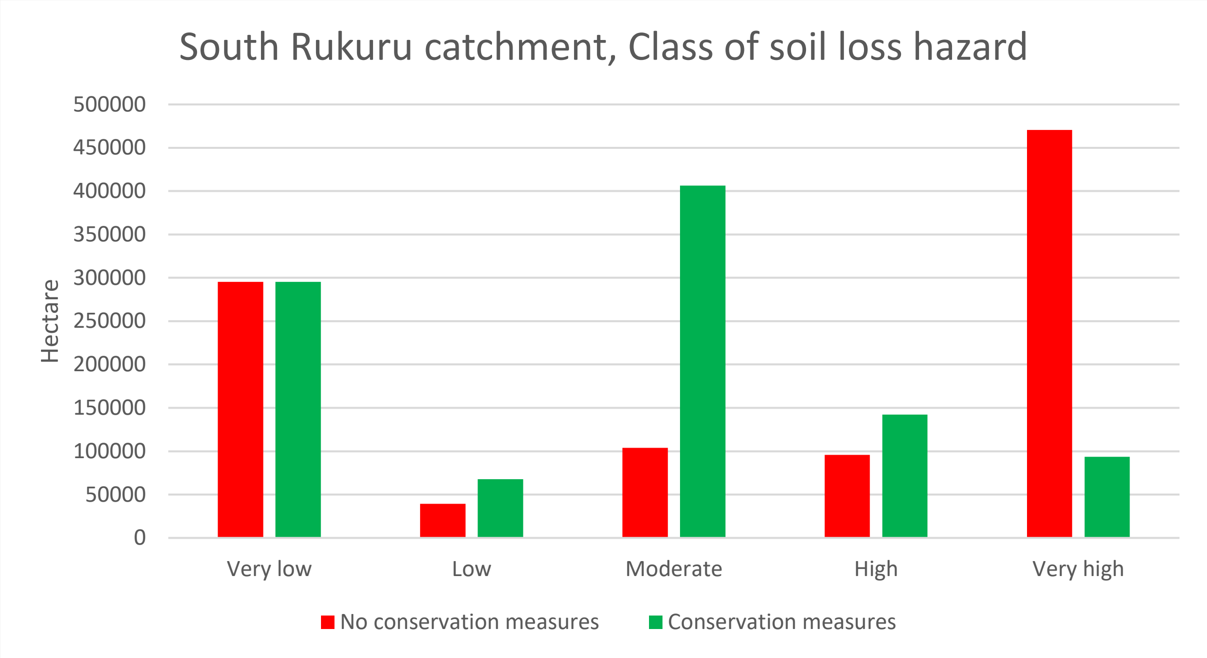

Figure 13: Comparison of areas in different classes of soil loss hazard in South Rukuru catchment

3.2 The Linthipe catchment

The Linthipe Catchment is the most densely populated catchment area in Malawi (~3 M inhabitants). A mix of urban and rural landscapes, with smallholder farms, forests, and wetlands dominate the landscape. According to the shape file provided by the Water Department its surface is 8,885 km² and its perimeter is 468 km.

Five geographical regions constitute the Linthipe catchment: i) The Dzalanyama Range, ii) Lilongwe Plain, iii) Dowa/Dedza Hills, iv) Rift Valley Scarp, and v) Lakeshore Plain. Elevation ranges from 500 m above mean sea level at the Lakeshore to 1500 m (Dzalanyama). The eastern and central parts of the catchment comprise the Lilongwe Plain, which is undulating with broad marshy valleys. Southwest of the Lilongwe Plain is the Dzalanyama Range with high and massive ridges covered by forest reserves. On the east of the Lilongwe Plain are the Dowa/Dedza Hills, with moderate to high relief extending north to south of the catchment. East of this region lies the Rift Valley Scarp, and Lakeshore Plain consecutively. Slope gradient is gentle (1–6%) in the Lilongwe and Lakeshore Plains, moderate to steep (6.1–50%) in the Scarp and Dowa regions.

The availability and quality of water from the river has a strong bearing on the survival of aquatic life in Lake Malawi. The river also serves as a breeding ground for endemic endangered species of Opsaridium microlepsis (Mpasa) and Labeo mesops (Ntchila). These fish species have high economic value because they fetch better prices on the market. Opsaridium microlepsisis are principally caught during seasonal breeding, with migration from Lake Malawi into the Linthipe River.

The land cover in the catchment is predominantly agricultural, with subsistence farming being the main economic activity in the area. The most common crops grown include maize, cassava, groundnuts, beans, and vegetables.

Apart from agriculture, the catchment area also includes some forest reserves and grasslands. The forest reserves are mostly located in the upper catchment and include the Dedza-Salima Forest Reserve and the Dowa Forest Reserve. These forests provide important ecosystem services, including water regulation and biodiversity conservation. Drastic deforestation appears to have taken place at the end of the 1990s (see the study on flooding). This deforestation seems to have halted nowadays.

In the Linthipe catchment, as in much of Central Malawi, urbanization has been increasing rapidly in recent years, particularly in and around the city of Lilongwe, the capital of Malawi. According to the

World Bank, the urban population in Malawi has been increasing at an average annual rate of 4.4% between 2010 and 2020, and is projected to continue to increase in the coming years.
Several factors contribute to soil erosion in the Linthipe Catchment, Figure 14 gives a map of soil loss classes assuming no conservation measures:

- Deforestation: Deforestation is a major contributor to soil erosion in the catchment. The clearing of forests for agriculture, timber extraction, and fuelwood collection encouraged by the presence of many urban centres, exposes the soil to erosion by removing the protective vegetation cover.
- Unsustainable agricultural practices: Inadequate terracing, inappropriate crop rotation, and the use of heavy machinery on steep slopes on industrial farms can exacerbate erosion.
- Climate change: Climate change impacts, such as altered rainfall patterns and increased intensity of rainfall events, can contribute to soil erosion. Heavy rainfall can lead to increased runoff and erosion, particularly on unprotected or poorly managed land.
- Streambank erosion: Erosion of streambanks within the catchment contributes to overall soil loss. High-velocity flows erode unprotected streambanks leading to sedimentation in rivers and streams.
- Roads and urban development typically involve the extensive use of impervious surfaces such as concrete and asphalt. These surfaces prevent water from infiltrating into the soil, leading to increased surface runoff. Urban areas generate significant amounts of stormwater runoff due to extensive continuously paved surfaces and reduced vegetation. This runoff accumulates and flows rapidly, leading to erosion in nearby areas, particularly because proper stormwater management (drainage) systems are often not in place. The construction and presence of roads and urban areas disrupts natural drainage patterns and increases the vulnerability of surrounding landscapes to erosion.
-

While Figure 15 takes into account conservation measures in the most fragile areas

Two thirds of the surface of this watershed are in the “high” and “very high” potential erosion class considering no conservation measures. This shows the influence of urban development on deforestation.

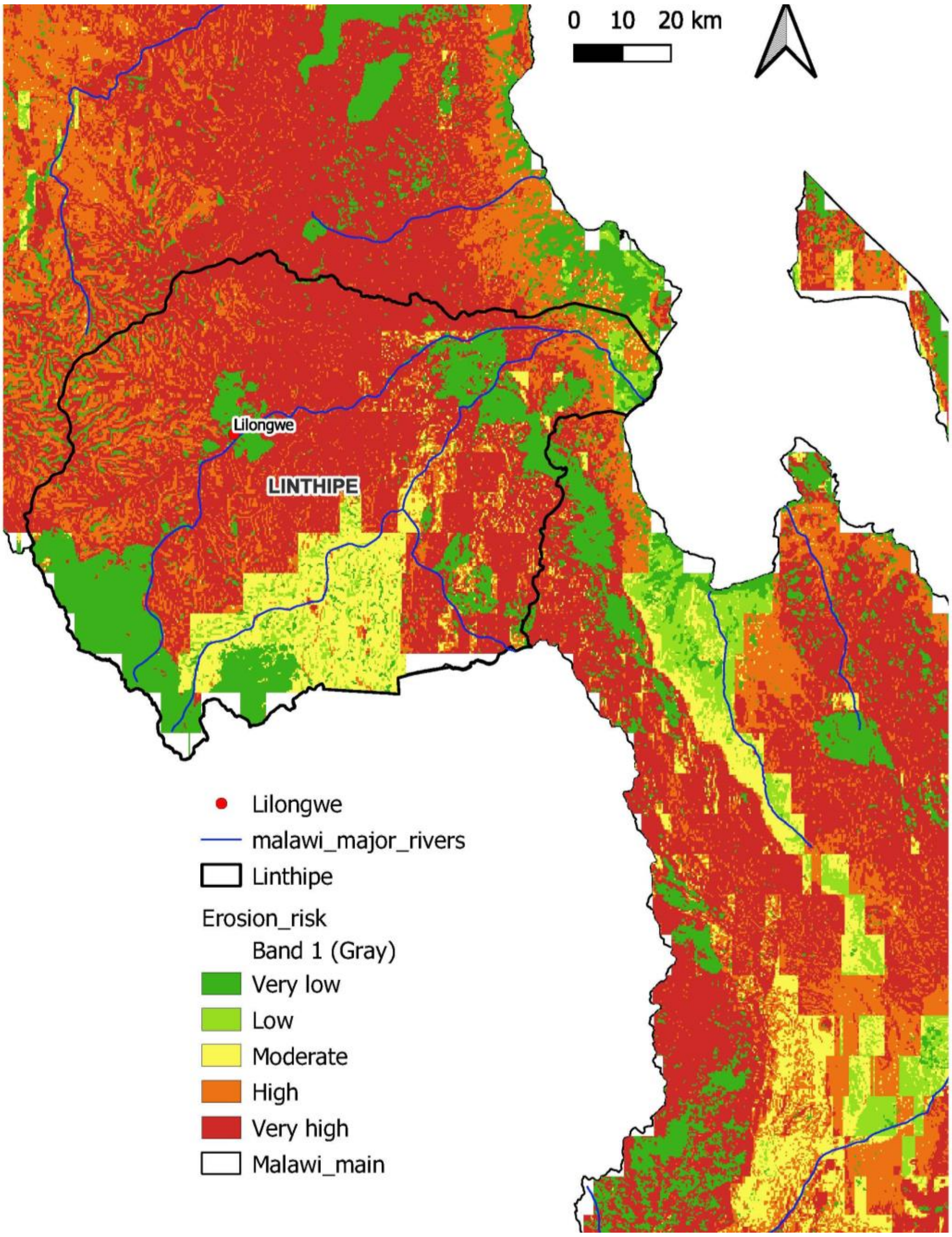

Figure 14: Map of soil losses in Linthipe according to the RUSLE equation with the same assumptions outlined at the country level.

Table 10: Distribution of potential soil losses in Linthipe, without any conservation measure

Erosion / soil uses map 2020 / rainfall 1958 - 2021						
	Hazard					Av. soil loss t/ha/yr
Erosion class	Very low	Low	Moderate	High	Very high	
Hectares	164 538	20 952	104 553	132 093	427 437	44.06
%	19.4	2.5	12.3	15.4	50.3	

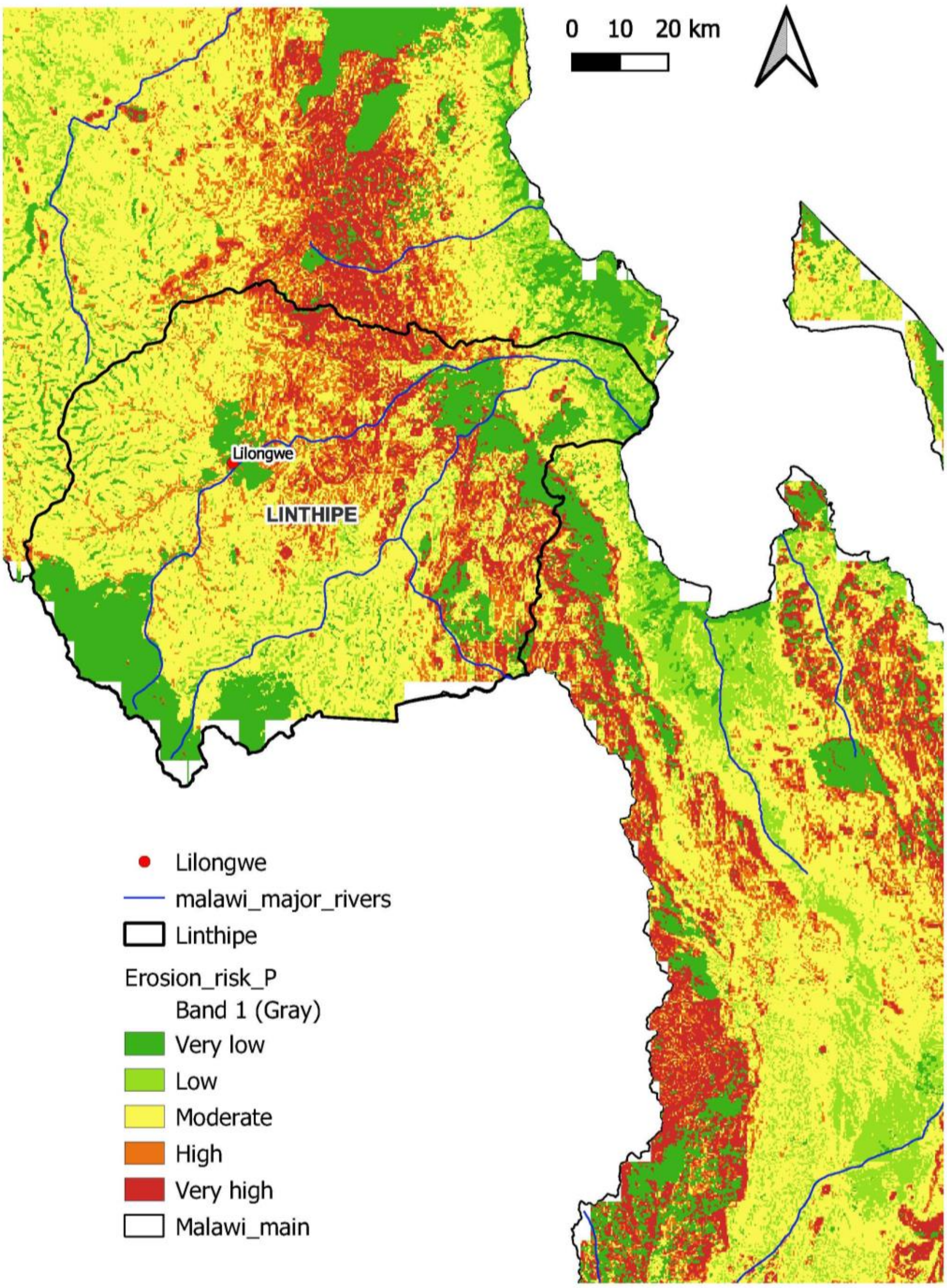

Figure 15: Map of soil losses in Linthipe catchment according to the RUSLE equation and P=0.4 on lands with a high or very high soil-loss potential

Table 11: Distribution of potential soil losses in Linthipe catchment, simulation with P=0.4 on lands with a high or very high soil-loss potential

Erosion control P=0.4 for classes "High and "very high" / soil uses map 2020 / rainfall 1958 - 2021						
	Hazard					Av. soil loss t/ha/yr
Erosion class	Very low	Low	Moderate	High	Very High	
Hectares	164 538	58 860	430 308	112 068	83 799	18.88
%	19.4	6.9	50.6	13.2	9.9	

These conservation measures drastically reduce the potential loss of land (Figure 16). Average soil loss decreases from 44 t/ha/yr to 19 t/ha/yr and the very-high erosion class drops from 427437 ha (50% of the total area catchment) to 83799 ha (10% of the total catchment area)!

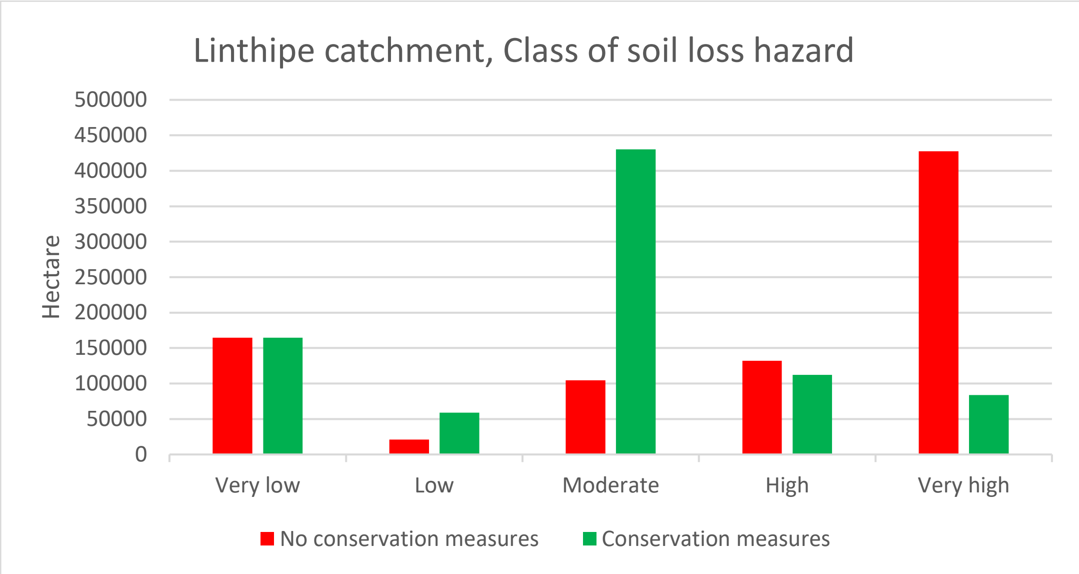

Figure 16: Comparison of areas in different classes of soil loss hazard in Linthipe catchment

3.3 The Dwangwa catchment

The Dwangwa River rises in the western portion of Malawi's central plateau and flows in an east-north-easterly direction for about 160 km until it enters Lake Malawi. The river's upper reaches exhibit ancient broad valleys and meanders, while the gorge cut for the river's descent to the lake is narrow and recent. Dwangwa's drainage into Lake Malawi occupies a flat swampy area 40 km north of Nkhotakota.

The Dwangwa River catchment shares its southern border with the Bua River catchment. To the west is the Kasungu National Park, which forms part of the Dwangwa catchment basin, a well-vegetated flat plain consisting mainly of indigenous woodlands and white sandy soils. The northern frontier of the basin is marked by the headwaters of numerous streams that drain the southern foothills of the Viphya Plateau. As the principle Dwangwa stream flows east-north-eastwards, it passes through a terrain of gentle slopes before abruptly falling over the Escarpment Zone on its way to the lake. Much of the middle and lower parts of this basin are well vegetated with indigenous forests.

Much of the upper basin of the Dwangwa lies in the aforementioned Kasungu National Park where the mean annual rainfall is less than 700mm. The majority of its major tributaries such as Liziwazi, Mpangala, and Mpasadzi have their sources in this part of the basin. However, despite being dry in the upper reaches, the Dwangwa River Basin still enjoys adequate rainfall as it flows eastwards towards the lake where the mean annual rainfall steeply increases sharply from 700 mm to over 1,300 mm per annum, recorded at Dwangwa Trading Centre on the Nkhotakota – Nkhata Bay Lakeshore Road.

The Dwangwa basin covers an area of 7750 km² according to the shape file provided by the Water Department, its perimeter is 486 km. Several factors contribute to soil erosion in the Dwangwa Catchment. Figure 17 gives a map of soil loss classes assuming no conservation measures and Figure 18 considers conservation measures in the most fragile areas.

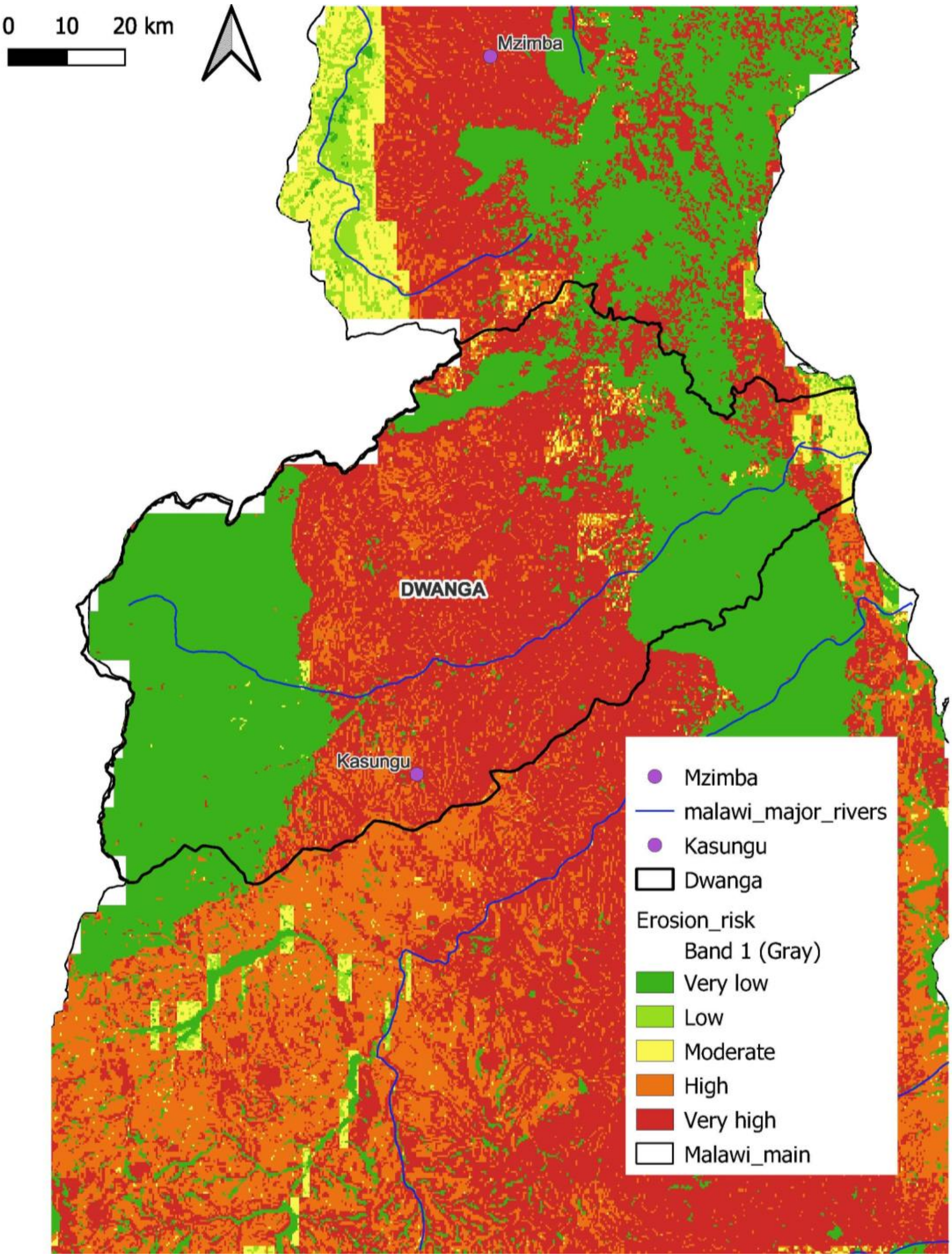

Figure 17: Map of soil losses in Dwangwa according to the RUSLE equation with the same assumptions outlined at the country level.

Table 12: Distribution of potential soil losses in Dwangwa, without any conservation measure

Erosion / soil uses map 2020 / rainfall 1958 - 2021						
	Hazard					Av. soil loss t/ha/yr
Erosion class	Very low	Low	Moderate	High	Very high	
Hectares	328 203	2 241	18 162	73 377	319 365	33.31
%	44.3	0.3	2.4	9.9	43.1	

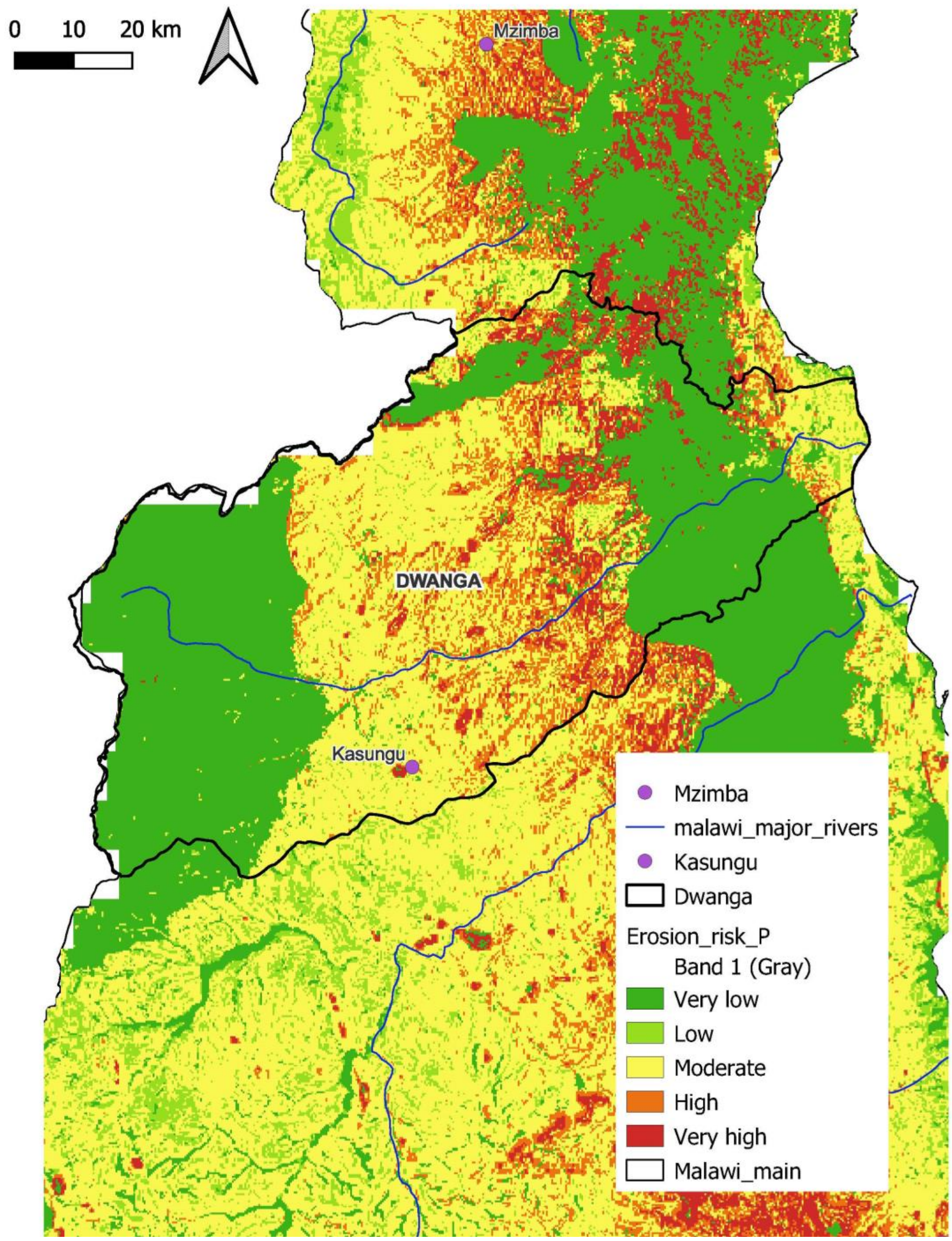

Figure 18: Map of soil losses in Dwangwa catchment according to the RUSLE equation and P=0.4 on lands with a high or very high soil-loss potential

Table 13: Distribution of potential soil losses in Dwangwa catchment, simulation with P=0.4 on lands with a high or very high soil-loss potential

Erosion control P=0.4 for classes "High and "very high" / soil uses map 2020 / rainfall 1958 - 2021						
	Hazard					Av. soil loss t/ha/yr
Erosion class	Very low	Low	Moderate	High	Very high	
Hectares	328203	17658	262728	82 404	50 355	13.61
%	44.3	2.4	35.4	11.1	6.80	

These conservation measures drastically reduce the potential loss of land (Figure 17). Average soil loss decreases from 33 t/ha/yr to 14 and the very high erosion class drops from 319 365 ha (43% of the total area catchment) to 50 355 ha (7% of the total catchment area)!

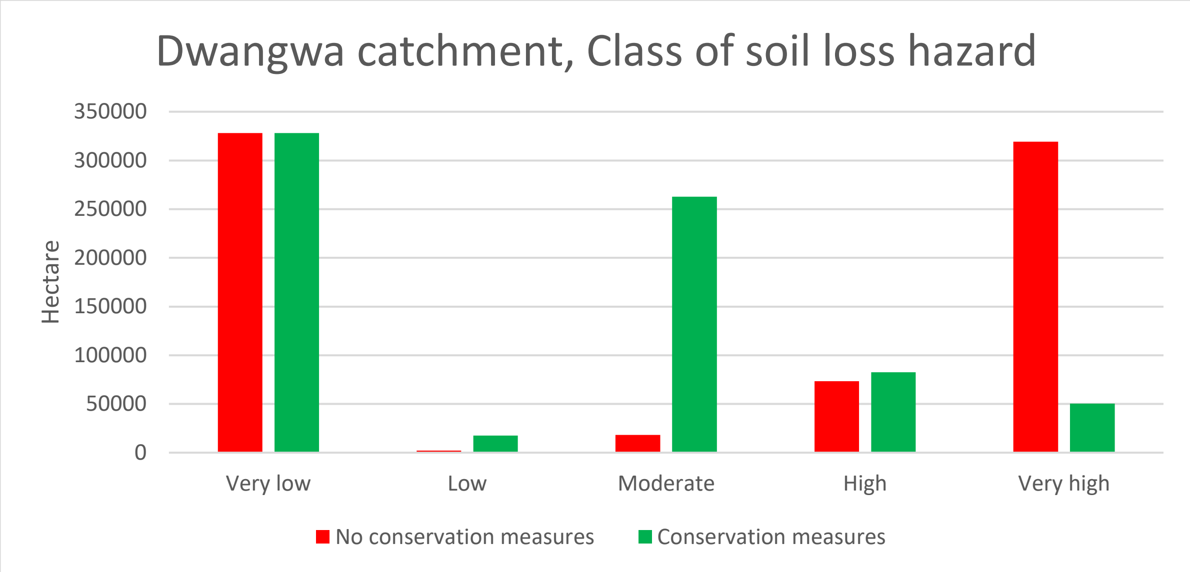

Figure 19: Comparison of areas in different classes of soil loss hazard in Dwangwa catchment

4. SOIL LOSS SIMULATIONS AND SCENARIO TO REDUCE EROSION HAZARD UNDER CLIMATE CHANGE CONSTRAINT

Agriculture is the backbone of Malawi's economy, and a large part of the population relies on subsistence farming for their livelihoods. Concomitantly, soil erosion, soil loss, and soil degradation are significant and growing environmental challenges that are impacting productivity in all parts of the country.

Soil erosion is a prevalent problem, particularly in areas with steep slopes, heavy rainfall, and unsustainable land management practices. Erosion rates vary across the country, with higher rates typically observed in the southern and central regions. The loss of topsoil due to erosion reduces soil fertility and the capacity to retain water, negatively affecting agricultural yields.

The annual average soil-loss rate is estimated to be around 30-50 tons per hectare, far exceeding the tolerable soil loss limit for sustainable agriculture (10-20 tons). This soil loss not only depletes valuable nutrients but also leads to sedimentation in rivers in their lower flatter courses and lakes via tributary outflows, affecting water quality and aquatic ecosystems.

Considering the parameters of the Universal Soil loss equation, we can do these realistic assumptions:

1. K, the soil erodibility factor is unlikely to change under climate change. Soils evolve very slowly and over geological timescales that are much longer than those predicted by climate change are.
2. LS, slope length and slope steepness factor does not change on the time steps of the climate change models either.
3. C the cover and management factor: I have assumed that deforestation will stabilise. The temporal analysis confirmed that deforestation had stopped in the 2000s and Malawi shows strong policy to protect the forest cover. An increase in urban areas and the surface areas occupied by communications infrastructures and mines are likely to grow significantly. Although, they will remain marginal in terms of soil loss on a national scale. They could have a significant impact on the scale of catchment areas. Cultivation management may change under

climate change constraints, depending on which crops are better adapted to the new climate. An average value for tropical crops is still plausible, however.

4. R, the rainfall-runoff factor is very impacted by climate change. The more intense the rainfall and the longer it lasts, the greater the risk of erosion. Average rainfall is likely to fall, as most climate models predict; on the other hand, heavy and very heavy rainfall and cyclones should increase. A 10% increase in R, is a realistic scenario as rainfall intensity is more important than average rainfall when computing rainfall energy.
5. P, the support practice factor depends on the different soil conservation measures.

Table 14 summarises, for Malawi, the 4 simulations with the RUSLE model taking into account a 10% higher erodibility due to climate change with or without conservation measures on the most fragile areas (classes “high” and “very high”).
Simulations of soil loss in actual climate show that soil conservation management of the most erosion-sensitive parts of the land leads to significant reductions in soil loss and drastically reduces the extent of areas in the "very high" category of soil erosion. Comparing the soil loss in future climate with and without soil conservation measures show that soil conservation measures (P =0.4) are very resilient to climate change.

The table shows that climate change leads to an increase in soil loss of about 5t/ha/year without conservation measures but only 0.7 t/ha/year when the "High" or "Very High" class areas are treated (Figure 20). Figure 21shows little change in the "High" and "Very High" classes to climate change in the "High" and "Very High" class areas and even an increase in the "very low" class when fragile areas are treated (class pixels “high” and “very high” are divided into “moderate”, “low” et “very low”).

Table 14: RUSLE model simulations

	Very low	Low	Modera-te	High	Very high	Soil-Loss t/ha/yr
No erosion control + historical R factor (ERA rainfall data)	27 651	39 86	8 827	14 577	35 060	46.84
No erosion control + R factor * 1.1	27 650	2 580	9 114	11 785	38 973	51.52
Erosion control on zones "High" or "Very high" + historical R factor	27 651	9 110	35 040	8 236	10 065	19.92
Erosion control on zones "High" or "Very high" + R factor*1.10	36 457	61 38	26 413	97 59	11 335	20.61

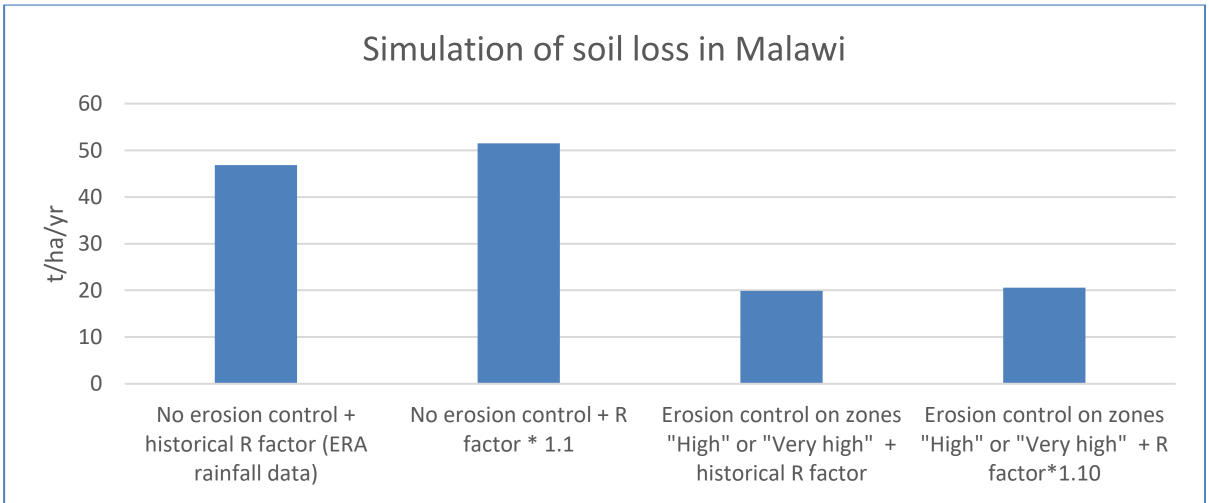

Figure 20: Soil loss in Malawi considering climate change without and with conservation measures

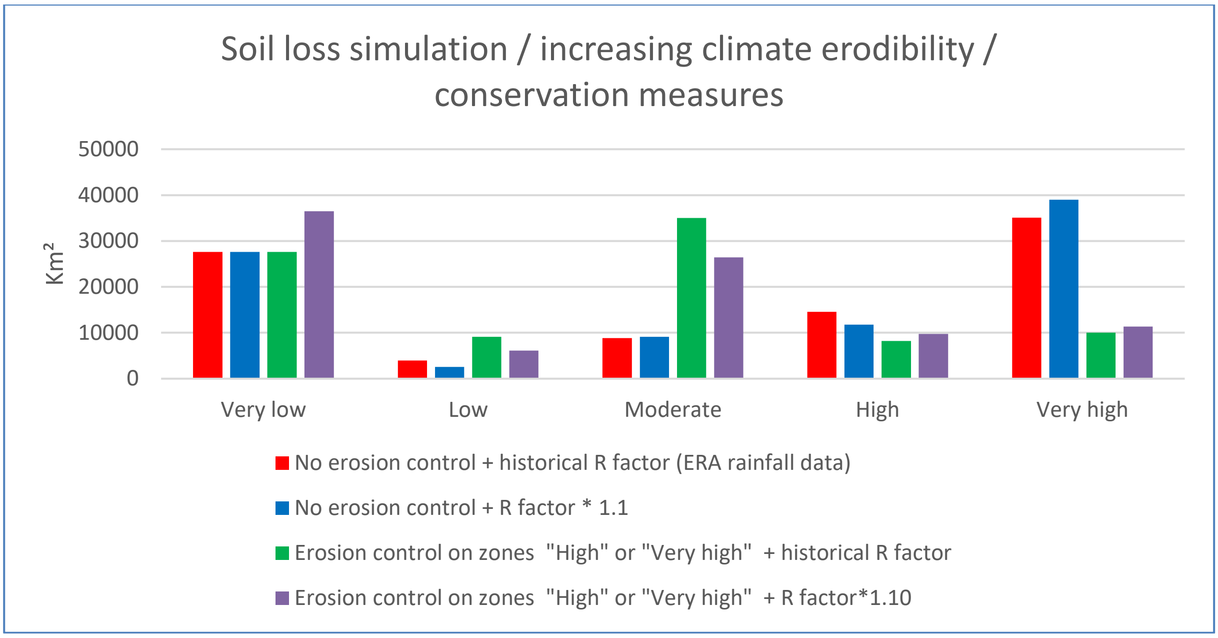

Figure 21: Soil loss classes simulated by RUSLE in different scenarios

The P factor reflects the effects of practices that will reduce the amount and rate of the runoff water by modifying the flow pattern, gradient or direction of surface runoff and thus reduce the amount of erosion. The most commonly used supporting cropland practices are:

- Cross slope farming.
- Contour farming
- Strip cropping
- Terracing

The FAO and the USDA's National Resources Natural Service described and explained extensively these conservation measures. [43][44] The latter has published online fact sheets describing their implementation and advice on how to combine them with cropping practices to minimise erosion. Table 15 gives the main characteristics and effectiveness of these measures.

43 https://www.fao.org/family-farming/detail/fr/c/1618032/
44 https://www.nrcs.usda.gov/

Table 15: Soil conservation measures to limit erosion

	Cross slope farming	Contour farming	Strip cropping	Terracing
Definition	Aligning rows so that tillage, planting, and other crop management operations are performed across the field slope, as closely as practical to the contour.	Practice of tillage, planting, and other farming operations performed on or near the contour of the field slope. This method is most effective on slopes of between 2% and 10 %	Planting several cultures in strips alternated in crop rotation, across slope or on contour.	Rearranging farmlands or turning hills into farmlands by constructing specific ridged platforms
Use	Tillage, crop rows create ridges which act as small dams across slope - ridges redirect runoff, modify downslope flow pattern, reduce erosive capacity of runoff	Reduce sheet & rill erosion. Reduce sediment transport to surface waters. Increased water infiltration.	Least costly measures to reduce sheet and rill erosion. Improve crop yields by encouraging infiltration and thereby increasing soil moisture.	Benefits of terrace farming include the control of runoff water and the conservation of soil. The primary disadvantage of terrace farming is that their construction requires a high level of skill and labour
Maintenance	Establish and maintain row markers, as needed, or leave marker rows for operation of the system the next cropping year. Inspect and maintain other practices (grassed waterways, diversions, terraces, field borders, etc.) that support the system.	Inspect and maintain after important storms	Same as Cross slope farming.	Inspect and maintain after important storms
Resilience to Climate changes	Almost complete protection from storms of low to moderate intensity	Almost complete protection from storms of low to moderate intensity, more effective than cross slope farming	Almost complete protection from storms of low to moderate intensity	Very resilient
Erosion reduction	up to 25%	Erosion reduction - 10% to 50 %	Erosion reduction - 10% to 75 %	Erosion reduction - 10% to 90 %
P Value	Range 0.75-1.0	range 0.50-0.90	range 0.25 - 0.90	Range 0.10-0.90