The shrinkage of Lake Manyara: causes and management options for lake protection

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Abstract

Lake Manyara is a terminal soda lake in the East African Rift System in Northern Tanzania, which provides an important habitat for flora and fauna in the area. Its size also reflects the water availability in the catchment, which is of great importance for local human inhabitants and wildlife. Lake levels naturally fluctuate over the year, but they have been following a shrinking trend in the past decades. The factors that contribute to the shrinkage of the lake have been researched in several studies, but the cause of the shrinkage remained unknown. The aim of this research was to unravel the causes of the shrinkage of Lake Manyara and to discuss management options that best guarantee a sustainable future for the lake. A literature review was carried out to determine which factors contribute to the shrinkage of Lake Manyara. Results strongly suggest that both the use of irrigation water and changes in land use and land cover have neglectable impacts on the shrinkage of the lake. The combination of precipitation and evapotranspiration seems to have a large impact on the size of Lake Manyara. Future rainfall is uncertain because of the East African Climate Paradox, but temperatures in the area will almost certainly increase in the coming decades. Increasing temperatures will lead to increased amounts of evapotranspiration and enhanced periods of droughts. This will almost certainly cause a decreasing size of Lake Manyara in the coming decades, mainly in the dry season. To determine the contribution of gully erosion to the shrinking lake levels, a remote sensing study based on images from *Google Earth Pro* was performed. Sedimentation in Lake Manyara does occur as a result of gully erosion, but the contribution of sediment load to the shrinkage of the lake is minor when compared to climatological changes. Management strategies that could enhance environmental rehabilitation help to adapt to drought conditions were discussed. It was shown that socioeconomical factors should be taken into account when selecting measures, since the success of proposed measures largely depends on them. The implementation of local measures will have a positive impact on the environment and the livelihoods of humans in the catchment. Local measures will however not prevent the shrinkage of Lake Manyara, since anthropogenic climate change is by far the largest contributor to its shrinkage.

Left cover photo by Micato Safaris (n.d.); right cover photo by Noud Egberts

Table of Contents

1. Introduction

1.1 Background information

Lake Manyara (LM) is a terminal soda lake located in the East African Rift System (EARS) in northern Tanzania. It is one of the core areas and the epicenter of the Lake Manyara National Park (LMNP) (Janssens de Bisthoven et al., 2020; UNESCO, 2019). The Lake Manyara Catchment (LMC) is a biodiversity hotspot which is of great ecological importance since it provides for terrestrial and aquatic habitat for wildlife (Janssens de Bisthoven et al., 2020; Munishi et al., 2017). The LMNP furthermore has a rich biosphere and entails a large variety of landforms and vegetation types (UNESCO, 2019). These characteristics create a diverse and ecologically complex landscape that provides for an exceptional diversity of living organisms and species (UNESCO, 2019). According to UNESCO (2019), the largest biomass density (weight per area) of mammals on Earth is probably present in the LMNP. In addition, the largest variety of biodiversity in the park can be found around Lake Manyara. The lake is home to over 380 species of birds, to approximately 4 million flamingoes and it is inhibited by endangered fish species (UNESCO, 2019; Keijzer, 2020). The lake is thus important for flora and fauna flourishment in the area.

Lake Manyara reflects the water availability in the area, because of its freshwater inflows (Janssens de Bisthoven et al., 2020; Nonga et al., 2011). It therefore indicates the water that is available for flora and fauna and the amount of water that can be used for example for agriculture in the catchment area (Janssens de Bisthoven et al. 2020; Keizer, 2020). In addition, the wetlands in the Lake Manyara Catchment are important for local human inhabitants since they provide ecosystem services to support their livelihoods (Nonga et al., 2010). The resources extracted in the wetlands are used, among others, for water, food, fuel wood, and materials for construction and handicrafts (Janssens de Bisthoven et al., 2020; Nonga et al., 2010). The Lake Manyara National Park furthermore thrives on tourism which supports the local economy (Ngana et al., 2004).

The area is undergoing rapid changes that lead to an unsustainable usage of the environment and of natural recourses (Wynants et al., 2018). Concerns have been raised regarding the policy of settlement programs that are implemented in the region (Homewood et al., 2009; Wynants et al., 2018). The Tanzanian government has instituted programs encouraging the Maasai, a group of indigenous Nilotic peoples who traditionally had a semi-nomadic lifestyle, to permanently settle in villages. These socio-economical changes had negative results regarding the environment. For example, they led to increased grazing pressure, to a less sustainable way of living for many people and they might have caused land use and land cover changes (LULC) (Nonga et al., 2010; Wynants et al., 2018). Lake Manyara is a shallow soda lake with an approximate average depth of 0.81 m at present. These characteristics create a unique aquatic ecosystem, but a change in factors influencing lake hydrology, e.g. human induced changes in input of water, sediment and pollutants, might therefore also have a large impact on the volume and area of the lake (Simonsson, 2000; Wynants, 2020).

Over the past thousands of years, Lake Manyara has fluctuated heavily in size (Simonsson, 2000). According to Hassani and Kendall (1994), Lake Manyara as it is today is a remnant of a lake that was once 300 meters deeper than it is at present. Other, sediment based, research shows that the maximum paleolake extent was approximately 140 meters above today's lake surface (Bachofer et al., 2014). Another study, based on a combination of field visits and remote sensing analysis, shows shorelines and terraces at approximately 80 meters above the present lake level (Deus et al., 2013). Lake levels nonetheless depend on variable factors and are thus fluctuating over the years, but they have been following a shrinking trend in the past decades. The reasons for this decrease in size have been researched in several studies, but it remains difficult to assign a causality to one or more natural or anthropological factors and the decreasing lake levels. The real causes for the shrinkage of Lake Manyara thus remain unknown.

1.2 Problem statement

The decreasing size of Lake Manyara, together with land and water use conflicts in the area cause environmental and socio-economic problems (Janssens de Bisthoven et al., 2020). It is therefore important to study the causes for the shrinkage of Lake Manyara and to determine how to manage the area to prevent the lake from disappearing. A large amount of research has already been performed on the shrinkage of Lake Manyara and on related challenges. Much can be learned from these studies, but a critical analysis of the published results is required in order to gain a better understanding of anthropogenic, bio-physical and climatological processes at play. Furthermore, erosion and sedimentation rates in the Lake Manyara Catchment (LMC) have increased in the previous centuries (Egberts et al., 2020; Schouten, 2020; Wynants et al., 2020) and the relationship between these factors and decreasing lake levels should be studied. In addition, it is important to put acquired knowledge into practice to improve the management of the area. This thesis research will therefore be divided into three parts:

1.2.1 Previous research on the shrinkage of Lake Manyara

Research on possible factors that might contribute to the shrinkage of lake Manyara has been done in several other master's theses, with each study having a different focus area. For example, research has been done on land use and land cover changes in the area (van den Berg, 2016; Verhoeve, 2019), on hydrological changes and local water extraction (Van Mens, 2016), on drought indicators and the impact of droughts on the dynamics of lake Manyara (Keijzer, 2020) and on gully erosion and local sediment dynamics (Egberts, 2020). In addition to knowledge obtained in previous master's theses, published research also contributes to the body of knowledge that exists on the Lake Manyara Catchment and on possible causes of the shrinkage of the lake (e.g. Deus et al., 2013; Wynants et al., 2020). The results obtained in all these studies contribute to the body of knowledge on possible factors contributing to the shrinkage and possible disappearance of Lake Manyara.

However, no single study has thus far determined the cause of the shrinkage of the lake. The various factors that might play a role in the shrinkage of Lake Manyara will therefore be analyzed based on a critical literature review. Based on this, it will be attempted to determine the importance of each factor.

1.2.2 Gully erosion and sedimentation rates

One of the changing factors in the LMC in the past decades relates to sedimentation; Lake Manyara has experienced an overall upward trend in sedimentation rates over the past 120 years (Schouten, 2020; Wynants et al., 2020). Enhanced sedimentation in Lake Manyara could therefore be an important contributor to the shrinkage of the lake. Research shows that gully erosion is one of the reasons for enhanced sedimentation rates in Lake Manyara (Egberts et al., 2020; Wynants et al., 2020). However, the contribution of gully erosion to the total amount of erosion and to the total amount of sedimentation in Lake Manyara remains unknown. It is still not determined what the gully growth rates are and how they connect to (the characteristics of) Lake Manyara. However, gullies have been shown to enhance the connectivity in landscapes and they are an important sediment source in many environments (Poesen et al., 2003). It is thus important to understand the role of gully erosion in the area as a possible cause or as a contributor to the shrinkage of Lake Manyara. In order to gain a better insight on the contribution gully erosion to the total amount of sediment in the lake, a remote sensing study will be performed to measure erosion rates in several gully systems in the catchment. This way, it can be determined whether or not gullies add much sediment to Lake Manyara or that their contribution is only minor.

1.2.3 Lake Manyara Catchment management

The Lake Manyara Catchment provides important means for wildlife and for livelihood of local inhabitants (Ngana et al., 2003; Nonga et al., 2010). It is therefore of great importance to sustain Lake Manyara and the ecology in the region. It is important to develop management strategies based on knowledge that is well founded. Management strategies should therefore be developed and/or adapted by taking into account the importance and weight of each factor that contributes to the shrinkage of Lake Manyara. For example, if droughts are the largest contributor to the shrinkage of Lake Manyara, a different management strategy should be implemented than when erosion would be the largest contributor. Management strategies that can be implemented in the LMC were discussed based on importance of each factor that contributes to the shrinkage of Lake Manyara.

1.3 Research Objective

The aim of this research is to unravel the causes of the Lake Manyara shrinkage and to discuss management strategies that can be implemented in the Lake Manyara Catchment to sustain the future of the lake. The threefold objectives of this study are defined as:

1. To critically evaluate the possible causes and factors that might be contributing to the shrinkage of Lake Manyara.

2. To estimate the amounts of gully erosion from three selected gully systems and their potential sediment delivery to Lake Manyara.

3. To discuss management strategies that best guarantee a sustainable future for Lake Manyara.

2. Materials and Methods

2.1 Study area: Lake Manyara Catchment

The study area of this thesis as a whole is the Lake Manyara Catchment. The catchment is the most southern catchment of the eastern segment of the East African Rift System (EARS) in northern Tanzania. It is approximately 18,763 km^2 in area (3°03′–5°90′ S, 35°26′–36°40′ E) and elevations in the catchment range between 885 m and 3618 m above sea level (figure 1) (Deus et al., 2013). The morphology in the region is strongly related to volcanism and tectonic activity during the Quaternary. This still exerts a strong control on the surface morphology (Bachofer et al., 2014; Deus et al., 2014; Ring et al., 2005).

Lake Manyara is located at 960 meters above sea level in the north-western part of the catchment, 126 km west of Arusha (3°25′–3°48′ S, 35°44′–35°53′ E) and contains an area of 410 to 480 km2 at present (figure 1) (Deus et al., 2013; Deus and Gloaguen, 2013). On the eastern side of the lake, an undulating plain with volcanic cones is superseded by a peneplain, while the western side is flanked by a deep escarpment (Deus and Gloaguen, 2013). The slopes surrounding Lake Manyara are reasonably lower than the slopes further east and west from the lake (Van Mens, 2016).

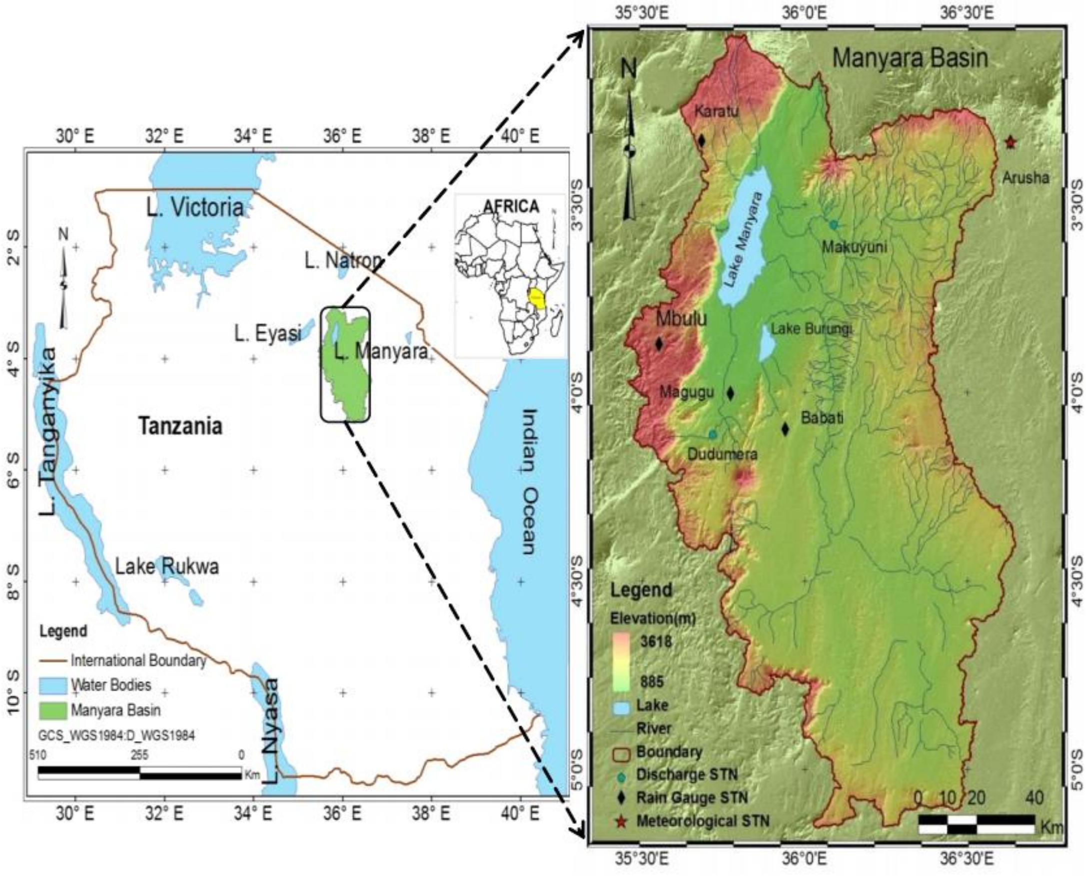

Figure 1: Location of the Lake Manyara Catchment. Source: Deus et al., 2013.

In 2010, the average depth of Lake Manyara was 0.81 meters and the deepest part of the lake was approximately 1.18 meters deep (Deus et al., 2013). Both perennial and seasonal springs and streams drain into the lake (Yanda and Madulu, 2005). The westside of the LMC is drained by permanent and seasonal streams, while the eastern part is mainly drained by seasonal streams, which enter Lake Manyara on the north (Yanda and Madulu, 2005). The lake is an alkaline-saline soda lake with water temperatures between approximately 17.0 and 32.2 degrees Celsius and a pH between approximately 9.0 and 10.3 (Casanova and Hillaire-Marcel, 1992). Compared to other rift lakes in the area, Lake Manyara has a relative low salinity ranging between approximately 4.0 and 34.6‰ (Casanova and Hillaire-Marcel, 1992).

The LMC is located in dry sub-humid and semi-arid climate zones with high evaporation rates (Bachofer et al., 2014; Yanda and Madulu, 2005). The annual rain cycle consists of two wet seasons and two dry seasons, with an intense wet season from March until May and a moderate wet season from November to January (Bachofer et al., 2014). In addition to this intra-annual variability in precipitation rates, the region also experiences inter-annual variability as a result of the El Niño-Southern Oscillation, the Indian Ocean Dipole and the Madden-Julian Oscillation (Keijzer, 2020; Nicholson, 1996). Precipitation rates are different at various locations in the basin, with average annual precipitation ranging from approximately 1300 mm at the escarpment on the west side to 500 mm at the peneplain on the east side of the catchment (figure 2) (Bachofer et al., 2014; Wynants, 2020).

Because of the variable morphology and rainfall in the catchment, the environment and vegetation cover in the basin is also variable. In general, the main land covers in the catchment are agriculture, forest and semi open fields with shrubs and bushes (Van Mens, 2016). The elevated areas on the west side of Lake Manyara are covered by a tropical semi humid vegetation cover with highland forests and the flat areas on the east side of the lake are covered by semi-arid vegetation types such as bushed grassland (Bachofer et al., 2014). Soil types in the catchment are also variable in the catchment. The Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009) classified 12 soil types in the catchment. Van Mens (2016) revealed that there are two dominant soil types in the catchment: luvisols accounting for 23% and andosols accounting for 16% of the soil types. Eight different types of lithology have been classified in the catchment (figure 2) (Wynants, 2020).

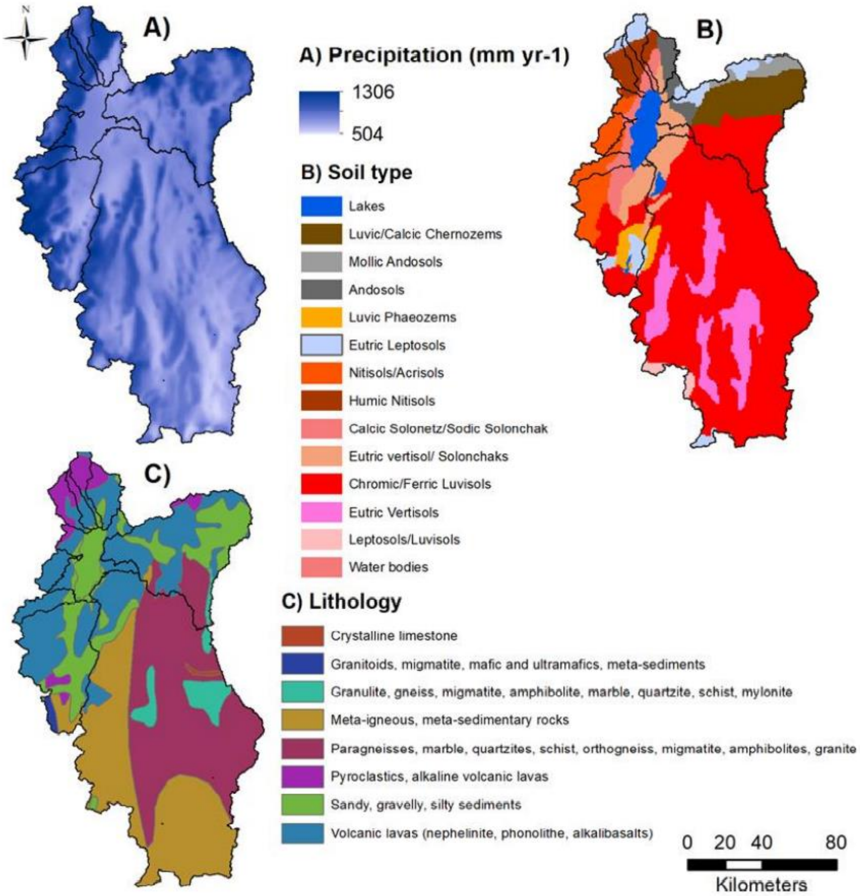

Figure 2: Spatial distribution of A) precipitation, B) soil types, and C) Lithology in the Lake Manyara Catchment. Source: Wynants, 2020.

2.2 Literature research: Causes of Lake Manyara shrinkage

Knowledge on several factors that might or might not contribute to the shrinkage of Lake Manyara was obtained in previous master's studies and in published research. To gain a better understanding of the possible causes for the shrinkage of Lake Manyara, this body of knowledge was examined so that it could be determined which factors are and are not contributing to or causing the shrinkage of the lake. It could also be determined what remained to be researched to obtain a comprehensive understanding on the factors that might be contributing to its shrinkage.

2.3 Gully erosion assessment

2.3.1. Available remote sensing imagery

First, it was explored which satellite images, that would be sufficient to study gully erosion in the LMC, were available for this research for free. *Google Earth Pro (GEP)* images (including historical imagery) were available from the beginning. Requests for imagery at the *European Space Agency* (ESA) and at *Planet* (Planet Team, 2018) resulted in obtaining respectively 8 SPOT 4 images and many RapidEye and PlanetScope images of areas within the LMC.

2.3.2 Gully erosion rates

To gain a better insight on gully growth rates in the LMC, three gully systems were mapped in detail using satellite imagery with a high spatial resolution. This way, information could be provided on the contribution of gullies to the total amount of sedimentation rates in the lake. Study sites were chosen based on the available data such as field measurements (Egberts, 2020; Maerker et al., 2015), availability of remote sensing imagery, erosion susceptibility and connectivity to Lake Manyara. The location of the three studied gully systems can be seen in figure 3.

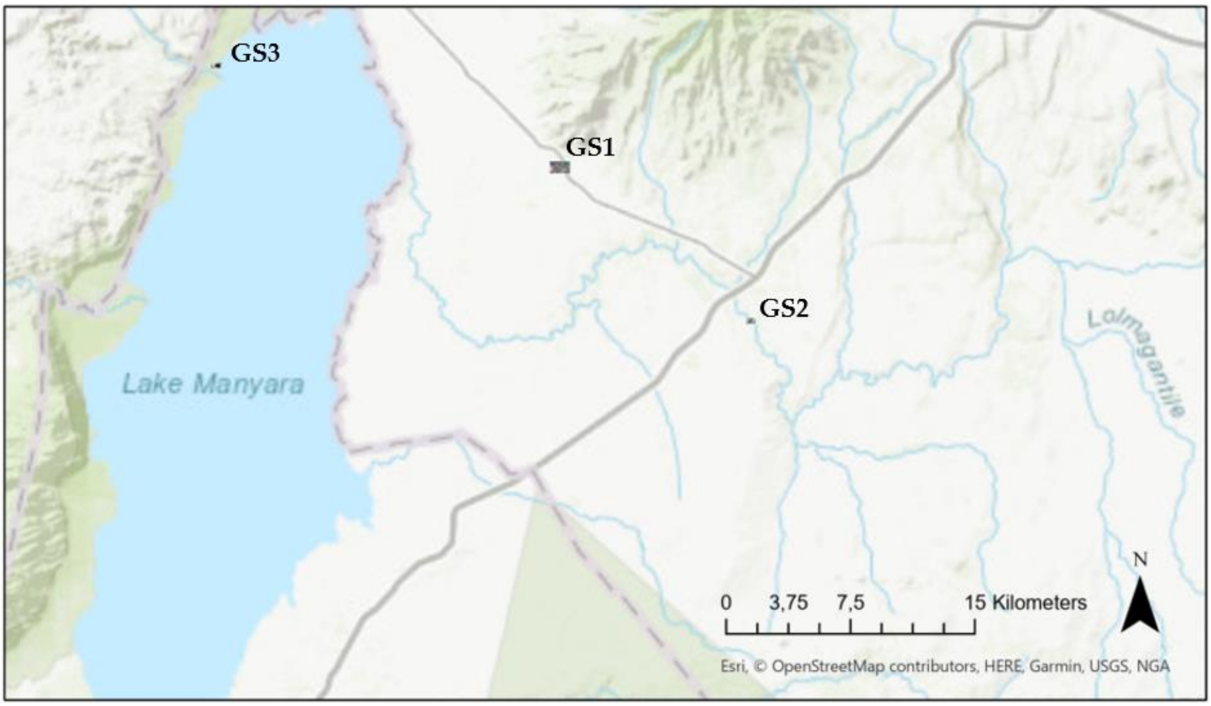

Figure 3: Overview of researched gully systems; GS 1-3

Available field data

For gully systems 1 and 3, cross sectional data was available from Egberts (2020). Egberts (2020) performed fieldwork to obtain measurements on GS1 and GS3 between 28-11-2019 and 27-01-2020. Measurements that were taken were dimension measuring, soil sampling and gully head monitoring. Gully head and channel bed erosion were monitored through the placement of erosion pins. This way, accurate measurements were obtained on erosional and depositional dynamics of the gully systems. The most accurate locations available of the cross sections were obtained as a Keyhole Markup language Zipped (.kmz) file, and imported in ArcGis Pro. All cross sections were digitized using GetData Graph Digitzier 2.26 to accurately obtain datapoints and the area of the cross sections.

For gully system 2, information from Maerker et al. (2015) was used. In that study, fieldwork was performed on gullies in September and October 2011 and field data such as gully length, average gully depth and average gully width were obtained. Based on these data and the obtained satellite images, an estimation was made on sediment loss in gully system 2.

GS 1-3: erosion amounts

To identify which characteristics of the gullies could be used to calculate the amounts of gully erosion, field data obtained by Egberts (2020; email) was compared to the available satellite images.

To determine the sediment loss in gully systems 1-3, differences between gully lengths over several years were calculated for each gully system. This was done by creating feature classes of the type 'line' in ArcGIS Pro and creating line features on top of gullies for several years. The differences between the lengths of these lines were calculated, so that the gully growth over time could be calculated. The calculated gully growths were then combined with field data obtained from Egberts (2020) and Maerker et al. (2015) for respectively GS1,3 and GS2 to best estimate sediment losses in these gully systems.

A range of possible amounts of sediment losses in GS1 and GS3 was determined based on the minimum, average and maximum cross sectional areas of these gully systems as measured by Egberts (2020). This was done by multiplying the minimum, average and maximum cross sectional areas with the amount of gully growth over time so that the range of possible volumes of sediment losses were calculated.

For GS2, the average cross sectional area was determined by multiplying the average gully depth and the average gully width as determined by Maerker et al. (2015). This estimated cross sectional area was then multiplied by the amount of gully growth, so that the approximate volume of sediment loss in GS2 was obtained.

Gully sediment delivery to Lake Manyara

Information on gully lengths at several points in time was obtained for 22 additional gullies (gully systems A-V) in the LMC from Metcalfe (2021). No field data were available for the gullies, but Metcalfe (2021) measured gully lengths at several points in time based on images in *Google Earth Pro*. Using these data on gully lengths at specific moments in time, the gully length growth rates (m/ year) were calculated for GS A-V.

Gully length growth rates that were derived from GS 1-3 were compared with the growth rates from gullies A-V to determine how GS 1-3 relate to other gully systems in the catchment. The average gully length growth rate of GS 1-3 was divided by the average gully length growth rate of all known gully systems (GS 1-3 and A-V) to determine how much more or less sediment (m^3/ year) was produced on average by GS 1-3 than by the average known gully system in the LMC. This way, the more detailed information that was obtained on GS 1-3 could be compared to information on a larger range of data to provide a more accurate representation of the average gully system in the LMC.

Metcalfe (2021) studied the amount of gully systems that were available within an area of 760 km^2 on the eastern part of Lake Manyara. Since geomorphology and geology in the LMC are highly variable, the number of gullies within the studied area (760 km^2) could not be directly extrapolated to the total area of the Lake Manyara Catchment. To estimate the total amount of gullies that substantially contribute to sedimentation in the lake, information on relative amounts of sediment deposits per subcatchment were taken into account. The information on relative sediment deposits was obtained from Wynants et al. (2020), who studied sedimentation based on sediment cores in the lake. The assumption was made that 2/3th of all sediment was delivered to Lake Manyara. Based on this, the amount of sediment delivery to LM (m^3/ year) and the corresponding estimated lifetime of LM (years) were calculated.

2.4 Management strategies

Based on results of the literature review on possible causes for the shrinkage of Lake Manyara and on results on erosion and sedimentation rates, another literature research was carried out to discuss potential management strategies for the LMC. Socioeconomic factors that might affect the implementation of proposed techniques were also investigated.

3. Results

3.1 Shrinkage LM: possible causes

3.1.1 Irrigation water use

Local water extraction can be the cause of shrinkage of lakes (Mtahiko et al., 2006; Wine and Laronne, 2020). Excessive extraction of water in catchment areas reduces the amount of water that enters lakes. Since 1961, the population in Tanzania has been growing on average by approximately 3% each year (World Bank, 2019). This rapid population growth goes hand in hand with enhanced urbanization, settlements, industrial activities and other human activities that often change ecosystems and water bodies (Igoe, 2003; Msoffe et al., 2011). Since an increased population size can lead to an enhanced amount of water extraction, this could lead to excessive water extraction in the LMC.

Unguided river water extraction was found to be happening in at least some places in the LMC (Nonga et al., 2010). Research on local water extraction in combination with in situ data showed that the amount of water extraction, for example for irrigation, in the LMC did not significantly decrease the size of Lake Manyara (Van Mens, 2016). Discharge rates with and without irrigation showed minor differences, with differences being larger in dry years. In general, the discharge without irrigation was approximately 5-15 l/s lower than it would be with irrigation. On average, the discharge to Lake Manyara was shown to be approximately 150 l/s (Van Mens, 2016). These findings are in accordance with Deus and Gloaguen (2013), who showed that if a decrease in surface area of Lake Manyara was mainly caused by human activities like irrigation, the lake would be shrinking without following trends of precipitation and other climatic factors and yearly at a similar rate, which is not the case. It was shown that some of the increases in lake surface area would have been impossible if activities like irrigation would have a significant impact on the size of Lake Manyara (Deus and Gloaguen, 2013).

3.1.2 Hydrological changes

A number of studies have been undertaken to investigate the climatological impacts on the size of Lake Manyara. Projections for future rainfall patterns in Eastern Africa vary widely (e.g. Endris et al., 2019; Kent et al., 2015; Osima et al., 2018, Otieno and Anyah, 2013; Tierney et al., 2015; Zao and Dai, 2015). It is clear, however, that Eastern Africa often experiences severe droughts and that climate change will almost certainly lead to hydrological changes in the region (Nicholson, 2017). Large scale long term climate change will continue to affect the meteorological and physical geographical characteristics of the LMC, but the exact future changes remain unclear.

Causes of climate variability and droughts in Eastern Africa are variable in nature, since the region varies widely with respect to geographical features and is controlled by regional oceanic and atmospheric teleconnections (Lyon, 2014; Nicholson, 2017). It is important to note that the Lake Manyara Catchment is a closed catchment and the only natural outlet of water is evapotranspiration. This means that Lake Manyara is extremely responsive to water quality changes and local changes in hydrological patterns (Odada et al., 2006).

Yearly climatological factors such as overall yearly amount of droughts, precipitation (P) and potential evapotranspiration (PET) are no predictors for the Lake Manyara water volume (Keijzer, 2020). The size of the lake varies strongly and does not depend on the time of year. Water levels have been shown to vary largely for the same month from year to year. This has been shown by Keijzer (2020) and Deus and Gloaguen (2013), who investigated its size respectively based on the exploration of 83 images of the Surface Water Dataset from the Joint Research Centre (JRC) and on multi-temporal atmospherically corrected Moderate resolution Imaging Spectro-radiometer (MODIS) satellite images.

Seasonal lake levels largely depend on regional climatic factors and seasonal climatological changes (Deus and Gloaguen, 2013; Keijzer, 2020). Correlations between the surface area of Lake Manyara and regional in situ temperature, actual evaporation, land surface temperature (MODIS LST), evapotranspiration (MODIS ET) and precipitation exist (Deus and Gloaguen, 2013). When seasonal differences are being taking into account, the combination of precipitation and evapotranspiration seems to have a large impact on the size of Lake Manyara (Keijzer, 2020). Deus and Gloaguen (2013) strongly imply that the surface area of Lake Manyara is mainly a result of regional climate variability, but they leave room for the option that other factors might affect surface area dynamics.

Observed regional precipitation and temperature trends

Precipitation is an important factor that determines the size of Lake Manyara. Studies regarding trends in precipitation in the LMC are not conclusive. Some studies that used in-situ data in the LMC as well as over the whole of Tanzania showed downward trends with respect to rainfall during long rains in the past decades (e.g. Agrawala et al., 2003; Keijzer, 2020; Rowell et al., 2015) while other studies show no significant change in rainfall in the LMC in the past decades (e.g. Van Mens, 2016; Nyembo et al., 2021; Verhoeve et al., 2021). It should be noted that both Nyembo et al. (2021) and Verhoeve et al. (2021) observed overall non-significant decreasing trends in rainfall in the long rainy seasons in the past decades and that Van Mens (2016) found that years with a lower than average amount of rainfall are becoming more common at the end of the study period. Van Mens (2016) also showed a small increase in the percentage of long rains that contributes to the total amount of annual precipitation in the LMC. It was also shown that trends in annual rainfall in the past 30 years might be either non-significantly increasing or decreasing, depending on the location of the rainfall stations (Nyembo et al., 2021). This highlights the spatio-temporal rainfall variability in the area.

Significant increases in average temperatures and temperature extremes have been observed in the past decades for the whole of Tanzania as well as specifically for its semi-arid areas (e.g. Chang’a, et al., 2017; Kabote et al., 2012; Matata et al., 2019). On average, the mean annual minimum temperatures in the LMC have been shown to significantly increase in the past 30 years, while the maximum temperatures showed a non-significant decreasing trend (Nyembo et al., 2021). Annual minimum and maximum temperatures in the LMC have varied largely in the past 30 years, but average temperatures have increased significantly since the 1930s (Keijzer, 2020; Nyembo et al., 2021; Verhoeve et al., 2021) Positive trends in both seasonally and yearly averaged temperatures were observed for the period between 1940 and 2020. It was furthermore shown that the yearly average temperature between 1940 and 2020 increased by 1.04 °C (Verhoeve et al., 2021). Enhanced temperatures will almost certainly enhance evapotranspiration, causing more and enhanced periods of droughts in the coming decades (Verhoeve et al., 2021). An increased intensity of droughts was also observed for many parts of the LMC over the past decades (Nyembo et al., 2021).

Future projections

Conway et al., (2017a,b) analyzed 34 climate models on future rainfall and temperatures in Tanzania. The models all predicted that temperatures will rise in the whole of Tanzania in the coming decades. This means that evaporation is also expected to increase in the future. Predictions on precipitation in the future are less certain. Of the analyzed models, approximately 67% predicted increasing amounts of rainfall in northern Tanzania (Conway et al., 2017a,b). Approximately 59% of the models predicted changes to be smaller than 5% by the 2040s, be it increasing or decreasing amounts of rainfall (Conway et al., 2017a,b). For the LMC, models on average predict that precipitation in the short and long rainy season will increase by respectively 0-9% and 9% by 2090 (Conway et al., 2017a,b).

Most models predict increasing amounts of rainfall in the whole of Tanzania in the coming decades, while precipitation trends in the past decades seem to be decreasing (Conway et al., 2017a,b; Rowell et al., 2015). This apparent contradiction is called the East African Climate Paradox (Lyon and Vigaud, 2017). This paradox could either be a result of real, physical changing trends in climate or a result of flawed mechanisms on which the models are built (Rowell et al., 2015). Future precipitation rates in the LMC will more likely than not be increasing, but uncertainties are considerably large. Temperatures will almost certainly increase in the coming decades, therefore enhancing evapotranspiration. Hence, it is expected that there will be more and intensified periods of droughts in the coming decades (Verhoeve et al., 2021).

3.1.3 Land use/cover changes

Vegetation changes can occur as a result of three different causes (Teferi et al., 2015; Verbesset et al., 2010). The first one being a climatic driven change in seasonality which impacts plant phenology (e.g. Angert et al., 2005; de Jong et al., 2013; Slayback et al., 2003; Tucker et al., 2001). The second one being a gradual monotonic change over time, for example gradual land degradation or a gradational change in land management (e.g. de Jong et al., 2013; Verbesselt et al., 2010). Lastly, vegetation changes can occur as a result of abrupt changes that are caused by short-term events such as floods, fires and sudden changes in land use management (e.g. de Jong et al., 2013; Slayback et al., 2003; Tucker et al., 2001). All these factors in a way affect the LMC and could thus cause land cover changes in the area.

Many studies were done on land use and land cover changes (LULC) in the Lake Manyara Catchment and the obtained results vary largely. Some studies based on satellite imagery show large changes in LULC over the past decades (e.g. Kiunsi and Meadows, 2006; van den Bergh, 2016), while others show only minimal LULC changes (e.g. Verhoeve, 2019; Van Rosmalen, 2021).

All investigated studies in this thesis that show large changes in land use and land cover in the LMC in the past decades are based on a minimal amount of satellite images; oftentimes combined with field data (e.g. Kiunsi and Meadows, 2006; van den Bergh, 2016; Wynants et al., 2018) or have been performed mostly around villages and/or are based on interviews with local inhabitants (Blake et al., 2018). All of the above mentioned studies show increases in agricultural lands whereas other LULC changes largely differ per study. In some studies, land use and land cover types sometimes seem to fluctuate largely per year. Kiunsi and Meadows (2006) for example found that it was difficult to draw conclusions on LULC when comparing images of the created land cover maps with many types of land cover, since it generated an unrealistic amount of changes. Land cover types were then reclassified into more general groups, so that the comparison of maps only reflected changes in the amount of natural vegetation cover, agricultural land, gully- and bare land and water bodies. Even then, some changes in LULC seemed to be unrealistic (Kiunsi and Meadows, 2006).

The limited amount of datasets in the studies that show large changes in land use and land cover in the LMC could be biased by climatic factors and classification errors (Verhoeve, 2019). It has been shown that there is a large chance on producing classification errors in land cover classes, mainly when a small amount of images is used (Verhoeve, 2019). In many remote sensing studies on LULC, false classifications on vegetation changes also occur as a result of discrepancies that arise from noise in datasets (Slayback et al., 2003). Since the accuracy of image classification is largely influenced by training data and selected training properties, the initial classification of training sites is crucial for drawing the right conclusions on LULC change (Millard and Richardson, 2015). In addition, the LMC has two rainy seasons and two dry seasons, making the area susceptible to land cover changes throughout the year (Kalisa et al., 2019).

Verhoeve (2019) used 32 images from the Landsat TM, Landsat Enhanced Thematic Mapper plus (ETM+) and Landsat Operational Land Imager (OLI) to study LULC in the Monduli and Longido districts between 1982 and 2018. Monthly rainfall data were used in conjunction with the images to make sure that the obtained data was not biased, since precipitation is an important factor that limits the vegetation cover in semi-arid regions (Eigentler and Sherratt, 2020; Verhoeve, 2019). An accuracy assessments to the training data was performed and the extent of LULC classes was determined, which resulted in large differences in class sizes that were highly variable over time. These results were compared to classified maps that were made based on visual interpretation of satellite images and field observations. Based on this, Verhoeve (2019) showed that no conclusions could be drawn on LULC in the LMC based on a pixel based classification algorithm, despite the high accuracy of the classification method. This was confirmed by Van Rosmalen (2021), who did not discover large changes in LULC based on the use of several types of satellite imagery and comparisons between supervised and unsupervised classification methods. These results thus chiefly question the results of studies which concluded that many LULC have occurred.

Dry years are strongly related to lower vegetation covers and lower normalized difference vegetation index (NDVI) values (Eigentler and Sherrat, 2020, Moulin et al., 1997). The resilience of the vegetational system in the LMC is high when in dry conditions for one year, since the normalized difference vegetation index (NDVI) values are normal again two years after a dry year (Verhoeve, 2019). NDVI values of natural systems in the LMC were shown to be stable or increasing from 1982 to 2018 (Verhoeve, 2019). Vegetation shifts and/or desertification could however occur when periods of drought become larger and vegetation is under stress for a longer period of time (Rietkerk, 1998; Verhoeve, 2019).

LULC: main findings

This study showed that there were many contradicting results regarding land use and land cover changes in the LMC (e.g. Van den Bergh, 2016; Verhoeve, 2019). A critical review on the studies related to land use and land cover changes in the LMC strongly indicated that no significant land use and land cover changes have appeared in the past decades. An increase in agricultural lands was observed to a greater or lesser extent in almost all studies that were performed (e.g. Blake et al., 2018; Kiunsi and Meadows, 2006; Van den Bergh, 2016; Van Rosmalen, 2021; Wynants et al., 2018). This type of change is therefore the most certain land use and land cover change that occurred in the past decades. The most reliable studies on land use and land cover changes however showed that these changes were only minor (an increase of approximately 2.5%) and/or that results that suggest otherwise could not be justified (Verhoeve, 2019; Van Rosmalen, 2021). The extent of these, and other type of land use and land cover changes, is too small to have a significant effect on the size of Lake Manyara.

This review also showed the importance of fieldwork, the scope of a research area, the use of multiple images and the use of multiple classification methods when studying land use and land cover changes. It was shown that apparent changes may occur as a result of many types of errors (e.g. false classifications on land use/land cover types due to a variety of reasons, the use of a singular image for a specific year while vegetation cover may vary during the year, etc.). When studying and drawing conclusions on land use and land cover changes, it is important to take all these aspects into account.

3.1.4 Soil erosion

Soil erosion has been occurring in catchments in the region for many decades (Rapp et al., 1972; Wynants, 2020). Four catchments near the LMC underwent very large rates of soil erosion and fast decreases of reservoir capacities in the decades before the 1970 (Rapp et al., 1972). The main sources of erosion were splash and sheet wash erosion, but gullies were considered to be very important ways for water and soil runoff from intergully slopes. Sheet wash has been shown to lead to a loss of topsoil and incision of drainage lines and flow paths in the upper Makuyuni subcatchment (Blake et al., 2018). There seems to have been a shift in erosion processes in the 1980s. Based on stratigraphy records from Lake Manyara, Blake et al. (2018) showed that there has been an increase in sheetwash erosion in the 1980's which was followed by an increase in rill and gully erosion at the end of the 1990s. Since the year 2000, an increase in gully erosion most probably occurred, at least in areas surrounding villages, in the LMC (Blake et al., 2018). Gully erosion is now the dominant erosion process contributing to land degradation in the LMC (Maerker et al., 2015). It leads to the delivery of sediment to the river network in many parts of the catchment, but predominantly in areas with volcanic soils (Kiunsi and Meadows, 2006; Maerker et al., 2015; Wynants, 2020).

New grazing regimes in Tanzania led to increased grazing in the Lake Manyara Catchment (Nonga et al., 2010; Wynants et al., 2018). The increased amount of grazing and a small increase in agricultural land resulted into more erosion and a higher availability of sediment in these areas (Schouten, 2020; Wynants, 2020). It is still unclear to what extent these changes may have caused enhanced sediment delivery to Lake Manyara. Natural vegetation was expected to decrease as a result of increasing agricultural areas in the coming decades (Wynants et al., 2018). Soil erosion and sedimentation are therefore also expected to increase in the coming decades. Again, the extent of the implications of these changes are still uncertain.

When studying soil erosion, it is important to note the importance of vegetation cover in conjunction with spatial and temporal variability of erosivity (Vrieling et al., 2014). The large spatial differences in soil type and vegetation cover and the seasonality of rainy and dry seasons in the LMC are therefore necessary to take into account when drawing conclusions on sedimentation and erosion in the catchment. This is also shown by Blake et al (2014), who showed the irregularity of soil erodibility in several environmental settings and different types of land management in the northern parts of the Makuyuni subcatchment in the LMC. Conclusions on erosion in the whole LMC can therefore not be made based on studies in only one part of the catchment, since it is a highly variable area with respect to many factors (e.g. soil type, LULC, climatic setting).

Research on high sediment yield areas within the Makuyuni tributary revealed that upstream hillslope connectivity, hillslope erosion and sediment yield have especially increased rapidly in the past decades (Wynants et al., 2020). Erosion and sedimentation rates in the LMC also showed an increasing trend in the previous centuries (Egberts et al., 2020; Schouten, 2020; Wynants et al., 2020). Sedimentation rates were shown to be especially large in the 1960's and in the year 2010 (Schouten, 2020; Wynants et al., 2020). Enhanced sediment deposits in Lake Manyara in the past decades were especially shown to be a result of sediment deposition from the Dudumera and Makuyuni subcatchments (Wynants, 2020; Wynants, et al., 2020). Depending on the core that has been researched, approximately 70-90% of sedimentation in Lake Manyara comes from these two subcatchments, with increasing contributions from the Makuyuni subcatchment. These conclusions should however be interpreted carefully and they may be an overestimation of the real number, since cores could not be taken in the entire lake (Wynants et al., 2020).

The influence of sedimentation on the subsurface hydrology of Lake Manyara should also be taken into account. On a large timescale, the groundwater table underneath Lake Manyara was shown to be determined by the lacustrine soil structure (Schouten, 2020). Infiltration into the subsoil of the lake was limited to the depth of the first impermeable layer. This layer is located at a relatively shallow depth, meaning that only a small amount of water infiltrates into the subsoil (Schouten, 2020). Future periods of increased drought may help to increase soil hardening of shallower soil layers on a smaller timescale. This may eventually lead to reduced infiltration rates and the preservation of more water within the lake throughout the dry seasons (Schouten, 2020). Altered sediment characteristics and sedimentation in the lake may therefore affect the size of Lake Manyara to some extent.

Gully erosion

Land degradation occurs in many regions along the East African Rift Valley (Kirui and Mirzabaev, 2016). In general, even though gully erosion only occupies a relatively small part of catchment areas (less than 5%), it is a major source of sediment in catchment areas (Ionita et al., 2015). It is often a large sediment source and it generates between 10 and 95% of the total sedimentation in catchment areas (Poesen et al., 2003). The connectivity of the landscape increases and sediment can be transferred more easily and faster when gullies develop. Gully development largely increases the risk for reservoir sedimentation and flooding, since it increases the runoff and sediment connectivity in catchment areas (Poesen et al., 2011). It has also been shown to increase the depletion rate of soil moisture and ground water in semi-arid regions and to negatively affect soil functions such as water infiltration, ecological productivity and biomass production both in gullies as well as in intergully slopes (Avni, 2005; Nyssen et al., 2006; Poesen et al., 2011).

Causes of gully erosion are manifold, including overgrazing, intensive rainfall events, poor vegetation cover, human activities, soil characteristics and more (Jahantigh and Pessarakli, 2011). Gully erosion and development occur when a threshold value regarding land use, land cover, topography, soil and subsurface characteristics, precipitation or flow hydraulics is being exceeded (Poesen et al. 2003). Topographic and climatic factors together with other factors that dominate the mechanisms of gully development have control over the threshold values that need to be exceeded for gully initiation to occur (Poesen et al., 2003). These threshold values differ for different topographic areas.

It is important to take into account where gullies end, since this impacts the connectivity and transport capacity of a stream system. Gullies usually end either where the erosivity of the topsoil layer decreases strongly or where the capacity for transporting concentrated runoff decreases (Poesen et al., 2003). In addition, instead of channel entrenchment, vegetation-controlled sediment deposition might occur when there is a sudden change of land use in catchment areas. Slope-controlled sediment deposition might occur when the transport capacity decreases as a result of a lowering slope gradient with an increasing drainage area, resulting into a decreasing gully depth (Poesen et al., 2003). In the LMC, there is an established well-connected and majorly incised drainage network that forms efficient conveyance routes from many upstream erosive areas to downstream ecosystems and the downstream channel network (Bracken et al., 2013; Blake et al., 2018; Nonga et al., 2010).

Egberts (2020) studied gully erosion in the Lake Manyara Catchment based on field measurements in the period between 28-11-2019 and 27-01-2020. Gully heads were monitored in two gully systems and the amounts of mobilized sediment was calculated based on differences in gully head volumes at the beginning and end of the fieldwork period. Sediment losses in gully heads in the two gully systems ranged from 0.01 to 0.06 m^3 per month in a gully system in the Lake Manyara National Park to 0.47 to 1.71 m^3 per month in a gully system in the Makuyuni subcatchment (Egberts, 2020). During the fieldwork period, precipitation was higher than the average precipitation in the catchment. When this was taken into account, the yearly gully head sediment mobilization was estimated to be in between 0.02 and 0.1 m^3 per year in the gully system in the LMNP and between 0.78 and 2.85 m^3 per year for the gully system in the Makuyuni subcatchment (Egberts, 2020). The Soil Water Assessment Tool (SWAT) was used to quantify sediment detachment in an area of 11.18 km^2 within the Makuyuni subcatchment. Based on this tool, Egberts (2020) estimated that between 4.5 and 15.7 tons of sediment per hectare was produced in that area on a yearly basis.

Thus far, it is unknown how much sediment per year ends up in Lake Manyara, either as a result of gully erosion or as a result of erosion in general. The most specific information on sediment production as a result of gully erosion was obtained by Egberts (2020), but this information was obtained in a small area of the highly variable LMC. Further research should therefore be done to determine the contribution of (gully) erosion to the shrinkage of Lake Manyara.

3.1.5 Literature study: main findings

The possible causes and factors that might be contributing to the shrinkage of Lake Manyara were evaluated.

Research on irrigation water use in the LMC showed that differences in discharge rates with and without irrigation are minor (Van Mens, 2016). It was also shown that some changes that occurred with regard to the size of Lake Manyara (e.g. large increases in lake surface area) would have been impossible if activities such as irrigation would have a significant impact on its size (Deus and Gloaguen, 2013). Based on this, it can be concluded that the use of irrigation water is not a factor that contributes to the shrinkage of the lake.

There are many contradicting results on to what extent land use land and cover changes appear in the LMC and whether or not this may lead to the shrinkage of Lake Manyara. A critical review on the studies that were performed however strongly indicates that LULC in the LMC is not a significant contributor to the shrinkage of Lake Manyara, since studies that do suggest otherwise most probably used false classifications or are only based on a small area in the catchment (e.g. van den Bergh, 2016; Blake et al., 2018). It is important to consider the scope of the areas where studies have been performed. For example, Nonga et al. (2010) observed that local changes had impacted the local catchment hydrology and that desertification and large gullies occurred as a result of these changes around villages. These and other changes occurred on a relatively small scale (e.g. Blake et al., 2018, Kiunsi and Meadows, 2006) and cannot be extrapolated to the whole LMC. The most certain change in LULC is an increase in agricultural lands, since this is observed in almost all studies that have been performed. The extent of the possible changes in land use and land cover is almost certainly small and irrelevant for the size of Lake Manyara. When vegetation is under stress for a longer period of time however, land cover changes and desertification of the area may occur in the whole LMC (Rietkerk, 1998; Verhoeve, 2019). This is important to recognize, since vegetation might come under increasing stress in the coming decades as a result of a changing climate.

Climatological factors, most importantly precipitation and evapotranspiration, have a large impact the size of Lake Manyara. Potential future changes in rainfall and temperature will therefore affect the size of the lake. Future precipitation is still uncertain, since precipitation trends show decreasing rates in rainfall in the long rainy season, whereas most models predict increasing rainfall patterns in the coming decades. Hard conclusions on future rainfall patterns could therefore not be made. Future temperatures in the LMC will almost certainly increase in the near future. These increasing temperatures will lead to enhanced evapotranspiration rates and enhanced periods of droughts. It is therefore predicted that the size of Lake Manyara will decrease, mainly in the dry seasons, as a result of anthropogenic climate change.

The last factor that might cause a shrinkage of Lake Manyara is sedimentation. Sedimentation may affect the size of the lake by decreasing lake levels and by altering the subsurface hydrology. Gully erosion was shown to be a large contributor of land degradation in the LMC and it most probably increases the runoff and sediment connectivity in the catchment (Maerker et al., 2015; Poesen et al., 2011). Most sedimentation in Lake Manyara is probably a result of erosional processes in the Makuyuni and Dudumera subcatchments, but this might be slightly biased since data on sediment deposition was not available for the whole lake (Wynants et al., 2020). It was shown that gully erosion has been increasing in the past decades and that this could lead to a shrinkage of Lake Manyara. The amount of sedimentation that occurs, mainly as a result of gully erosion, is unclear yet. The contribution of gully erosion to the shrinkage of Lake Manyara should be studied in more detail to provide information of the importance of this factor to the shrinkage of the lake.

3.2 Gully erosion

3.2.1 Selection of satellite images

A request for imagery at *ESA* resulted in obtaining 8 SPOT 4 images of areas within the LMC with variable spatial resolutions of 10 meters in panchromatic mode and of 20 meters in multispectral mode. Many images were available for usage from *Planet.* These images were of better quality, had a higher spatial resolution and a lower cloud coverage than the SPOT 4 images and they were available for the whole LMC. The best images from *Planet* that were available for this research were RapidEye (5m spatial resolution) and PlanetScope (3.125m spatial resolution), which were available from the end of 2009 onwards. These images were compared with images that were available at *Google Earth Pro* (including historical imagery), which were five CNES/Airbus images (50cm spatial resolution), and one IKONOS image of 2005 (80cm spatial resolution). It was concluded that the latter images were of the best quality for studying gully erosion in the LMC. Therefore, gully systems were analyzed based on images from *Google Earth Pro*. These images were georeferenced and imported in ArcGis Pro to further study gully erosion in the LMC.

3.2.2 Gully erosion sediment loss

Comparing field data with satellite images

Between 20/11/2019 and 27/01/2020, Egberts (2020) measured nine cross sections of several parts of GS1. These measurements are shown in figure 4 and cross section locations are shown in figure 5.

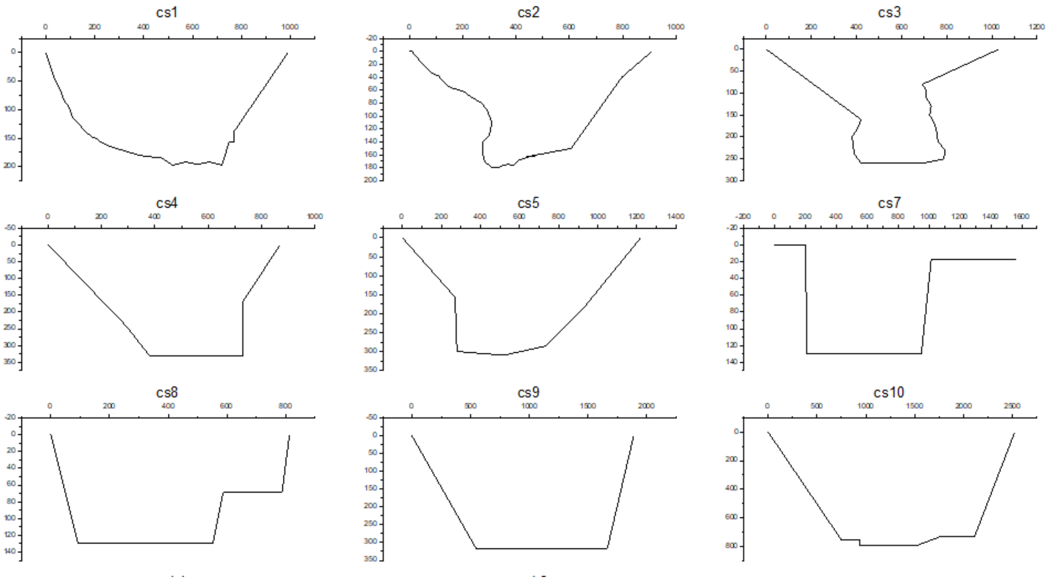

Figure 4: Cross-sections that were taken in Gully System 1; units are in centimeters. Source: Egberts (2020).

Figure 5: Overview of cross section locations from Egberts (2020)

All cross sectional measurements were digitized to accurately obtain datapoints and the area of the cross sections. The obtained width of the top view of the gully, maximum depth of the gully and the approximate cross sectional areas are shown in table 1.

Table 1: Cross sectional data of GS1, units in meters (width and depth) and square meters (area).

Cross section	Width top view gully (m)	Maximum depth gully (m)	Approximate cross sectional area (m^2)
1	10.0	2.2	14.8
2	9.1	1.8	8.4
3	10.2	2.6	12.4
4	8.8	3.6	19.7
5	12.1	3.1	22.5
7	15.6	1.3	9.3
8	8.1	1.3	8.2
9	18.8	3.2	45.5
10	25.1	8.9	157.8

Using these data, the average area of a cross section in GS1 would approximately be 33.2m^2. The minimum cross sectional area would approximately 8.2 m^2 and the maximum cross sectional area would be approximately 157.8 m^2.

When observing the locations of the cross sections in combination with the field data, it was difficult to identify a relationship between the two. When detailed field measurements in gully systems (measured by Egberts (2020) between 20-11-2019 and 27-01-2020) were compared with the best available satellite imagery, it became clear that the width, depth and cross sectional area of gullies could not be derived accurately from the images. For example, field measurements show that cross section 10 (CS10) was approximately 25.1 meters in width, but when measuring the width on the *GEP* imagery, it was estimated at 16.7 meters. Another example is CS7: field measurements show that the width of the gully was approximately 18 meters and that it was only deeply incised for a width of approximately 8 meters (see fig. 4), whereas the width at the *GEP* imagery would be estimated at approximately 22.0 meters. These are only a few of many examples of dissimilarities between measurements on the apparent width of gullies on satellite images and the gully widths as measured precisely in the field. The use of the apparent width of the gullies on satellite imagery could therefore not be used.

The length of gullies could be observed more accurately on satellite imagery. Therefore, differences between gully lengths over several years were calculated and combined with field data obtained from Egberts (2020) and Maerker et al. (2015) to best estimate sediment loss in gully systems in the LMC.

Sediment loss in GS 1-3

- *Gully system 1*

Based on Google Earth Pro images from 25-01-2010 and 13-03-2017 (see figures 6 and 7), the difference in gully length was determined to be 2154.9m (2017) -1706.9m (2010) =448.0 m

Figure 6: Google Earth Pro image (CNES/Airbus) of 25-01-2010 adapted with line segments in ArcGis Pro. Length of this part of the gully is 1706.9 meters

Figure 7: Google Earth Pro image (CNES/Airbus) of 13-03-2017 adapted with line segments in ArcGis Pro. Length of this part of the gully is 2154.9 meters

Sediment loss in gully system 1 was calculated based on cross sectional areas that were obtained from field data by Egberts (2020):

- Sediment loss based on the minimum cross sectional area: 448 m*8.2m^2=3673.6 m^3 in 85.5 months
  → 515.6 m^3 per year
- Sediment loss based on the average cross sectional area: 448 m*33.2m^2=14873.6 m3 in 85.5 months
  → 2087.5 m^3 per year
- Sediment loss based on the maximum cross sectional area: 448 m*157.8 m^2 =70770.6 m^3 in 85.5 months
  → 9932.7 m^3 per year

❖ *Gully System 2*

Based on Google Earth Pro images from 12-09-2005 and 23-09-2019 (see figures 8 and 9), the difference of gully length was determined to be 666.0 m (2019) - 302.4 m (2005) = 363.6 m

Figure 8: Google Earth Pro image (IKONOS) of 12-09-2005 adapted with line segments in ArcGis Pro. Length of this part of the gully is approximately 302.4 meters

Figure 9: Google Earth Pro image (CNES/Airbus) of 23-09-2019 adapted with line segments in ArcGis Pro. Length of this part of the gully is approximately 666.0 meters

Maerker et al. (2015) found that the average depth of gully system 2 was 1.658m and the average width was 13.6m in 2011. Therefore, it was assumed that the average cross sectional area of gully system 2 is: average depth*average width 2011= 22.549m^2

Sediment loss in gully system 2 was calculated based on the estimated cross sectional area of the gully in 2011 (data obtained by Maerker et al., 2015):

- 363.6m*22.549m^2= approximately 8199 m^3 in 167.5 months
  → 587.4 m^3 per year

- *Gully System 3*

Based on Google Earth Pro images from 04-01-2014 and 26-08-2019 (see figures 10 and 11), the difference of gully length was determined to be 302.4 m (2019) - 188.4 m (2014) =114.0 m

Figure 10: Google Earth Pro image (CNES/Airbus) of 04-01-2014 adapted with line segments in ArcGis Pro. Length of this part of the gully is approximately 188.4 meters

Figure 11: Google Earth Pro image (CNES/Airbus) of 26-08-2019 adapted with line segments in ArcGis Pro. Length of this part of the gully is approximately 302.4 meters

Based on field data from Egberts (2020), it was determined that one cross sectional area in gully system 3 was 2.1 m^2 and the other one was 3.3 m^2

Sediment loss in gully system 3 was calculated based on cross sectional areas that were obtained from field data by Egberts (2020):

- Sediment loss based on the minimum cross sectional area: 114.0 m*2.1m^2 =237.1 m^3 in 68 months
  → 41.8 m^3 per year
- Sediment loss based on the average cross sectional area: 114.0 m*2.7 m^2=305.5 m^3 in 68 months
  → 53.9 m^3 per year
- Sediment loss based on the maximum cross sectional area: 114.0 m*3.3 m^2 =373.9 m^3 in 68 months
  → 66.0 m^3 per year

Table 2 shows the estimated amounts of sediment loss as a result of gully erosion in gully systems 1-3.

Table 2: Estimated amount of sediment loss in gully systems 1-3

	Sediment loss based on minimum cross sectional area (m^3/year)	Sediment loss based on average cross sectional area (m^3/year)	Sediment loss based on maximum cross (m^3/year)
Gully System 1	515.6	2087.5	9932.7
Gully System 2	n/a	587.4	n/a
Gully System 3 (LMNP)	41.8	53.9	66.0
Total	557.4 (GS 1&3)	2718.0 (GS 1-3)	9998.7 (GS 1&3)
Average GS 1-3	278.7 (based on GS1 and GS3)	906.0	4999.4 (based on GS1 and GS3)

Average gully system LMC

In addition to the estimations on sediment losses based on data related to GS 1-3, supplementary information on gully systems in the LMC was obtained. Metcalfe (2021) analyzed 22 gully systems (GS A-V) in the LMC based on measurements in Google Earth Pro. No field data were available for these gully systems, but information on gully length growth rates could be derived from the measurements. Appendix A shows the gully length growth rates that were derived from data obtained by Metcalfe (2021). It also shows the gully length growth rates that were derived from GS 1-3 to compare data and to be able to generate a broader view on gully system growth rates and sediment losses in the whole LMC.

These additional measurements provided information on how GS 1-3 relate to other gully systems in the catchment. Gully length growth rates of GS A-V were compared to those of GS 1-3. The average gully length growth rate of GS 1-3 was divided by the average gully length growth rate of all measured gully systems (GS 1-3 and GS A-V). Based on this, it was estimated that GS 1-3 on average generate approximately 2.33 times more sediment than the average gully system in the LMC. This would mean that the average gully in the LMC produces 388.9 m^3 sediment per year (= best estimate average GS).

Expected lifetime LM

The surface area of Lake Manyara fluctuates heavily. For example, it has had values between 30.5km^2 and 520.25km^2 (Deus and Gloaguen, 2013). The average area of Lake Manyara has been approximately 370km^2 since 1974 (Van Mens, 2016). The average depth of Lake Manyara was 0.81m in 2010 (Deus et al., 2013). Considering these values for area and depth, Lake Manyara would contain an approximate volume of 299,700,000m^3 (= approximately 0.300km^3). Based on these values, it was calculated how many years it would take for Lake Manyara to be completely filled with sediment (= expected lifetime of LM) as a result of gully erosion. This was done based on a range of values, namely: the absolute minimum amount of sediment loss in GS 3 (41.8 m^3/year), average minimum amount of sediment loss of GS 1-3 (278.7 m^3/year), the average sediment loss of GS 1-3 (906.0 m^3/year), average maximum amount of sediment loss of GS 1-3 (4999.4 m^3/year), the absolute maximum amount of sediment loss in GS 1 (9932.7 m^3/year) and the best estimated amount of sediment loss based on all available information on GS 1-3 and GS A-V (388.9 m^3/year). The amounts of sediment load and the expected lifetime of Lake Manyara are shown in figures 12-14. Figure 12, 13 and 14 respectively show this in case all sediment, 2/3th of the sediment and 1/3th of the sediment is delivered to Lake Manyara.

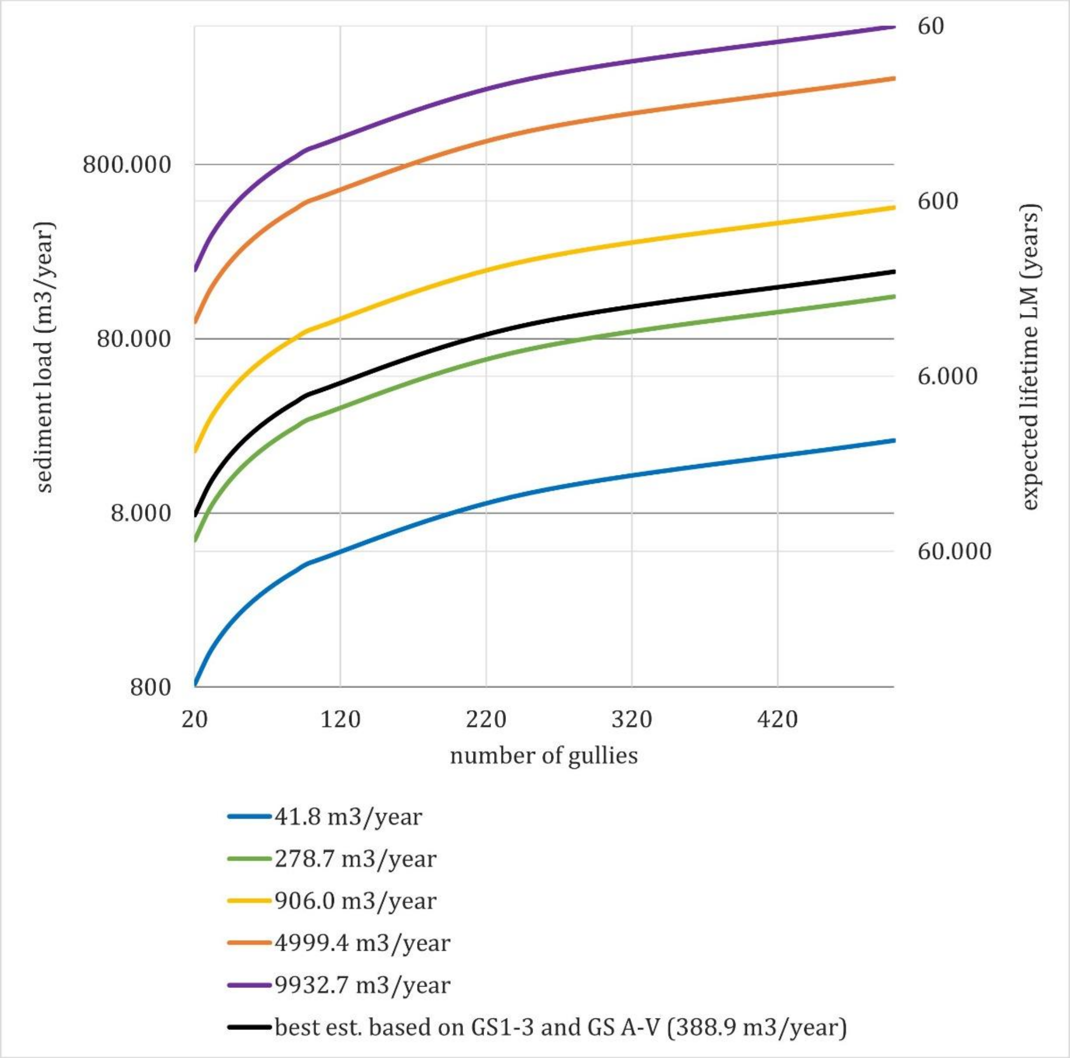

Figure 12: Estimated amounts of sediment load and the expected lifetime of LM in case all sediment ends up in the lake based on the range of production rates

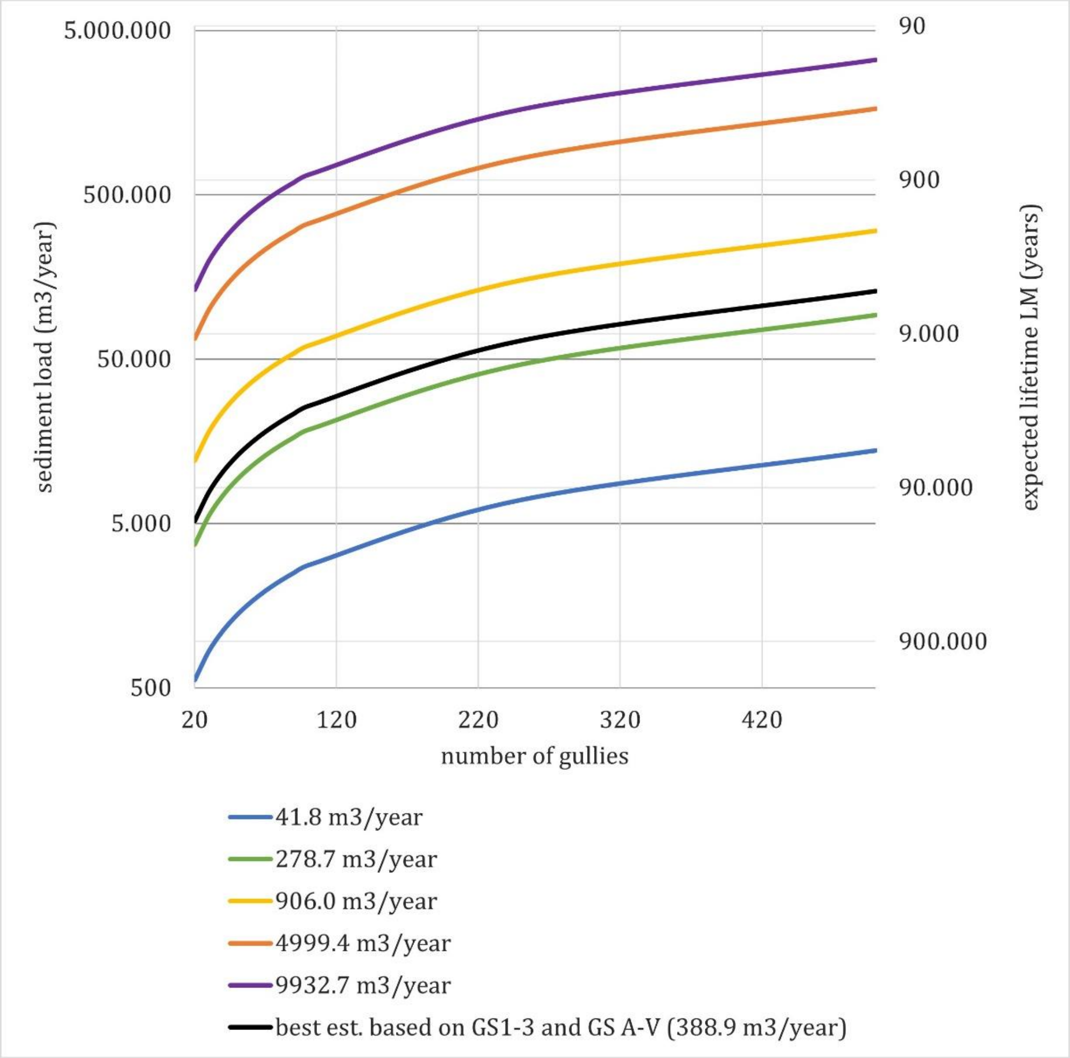

Figure 13: Estimated amounts of sediment load and the expected lifetime of LM in case 2/3th of the sediment ends up in the lake based on the range of production rates

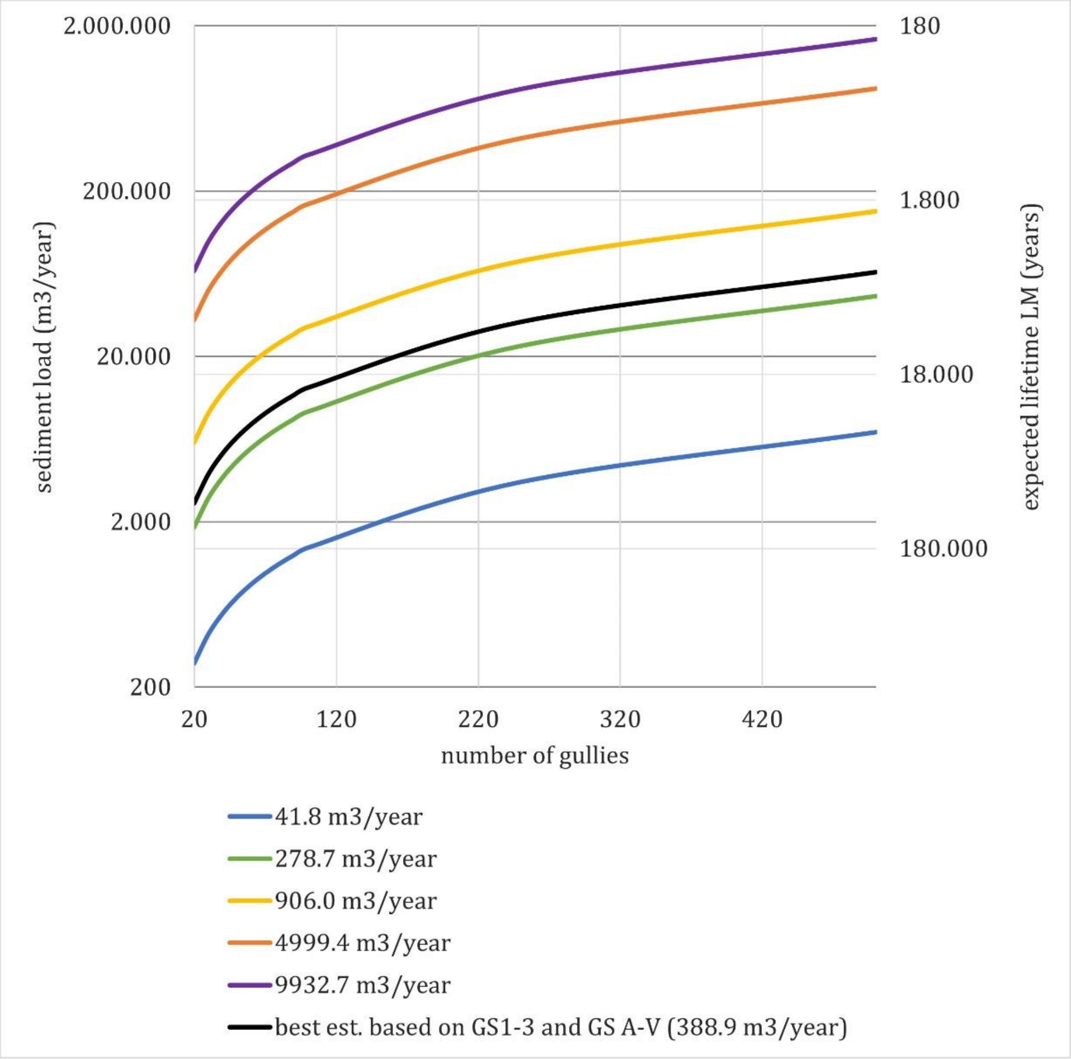

Figure 14: Estimated amounts of sediment load and the expected lifetime of LM in case 1/3th of the sediment ends up in the lake based on the range of production rates

The best estimations on sediment production (388.9 m^3/year per gully system) suggested that 7777 to 202,228 m^3 sediment per year ends up in LM in case respectively 20-520 gully systems are present in the LMC and in case all sediment ends up in the lake. This corresponds with a LM lifetime of 38,538 to 1482 years. In case 2/3th and 1/3th of sediment would enter the lake for 20-520 gully systems, the LM lifetime would be respectively 57,807 to 2223 years and 115,614 to 4446 years.

Estimations on sediment load and the lifetime of Lake Manyara became much more accurate when additional information on sedimentation and gully erosion in the LMC were taken into account. Metcalfe (2021) thus far found 36 gully systems within an erosion prone area of 760 km^2 within 13 kilometres east of Lake Manyara, but estimated that some more gullies were present within this area (J. Metcalfe, personal communication, June 18, 2021). It was therefore estimated that 45 gully systems were present within the area of 760 km^2 as researched by Metcalfe (2021). Most of these gully systems were located in the Makuyuni subcatchment. The information on gullies in the studied area could not be extrapolated directly to the whole LMC, since the geology and geomorphology in the area is highly variable. Research has shown that 70-90% of sediment input in Lake Manyara was a result of gully erosion in the Makuyuni and Dudumera subcatchments (Maerker et al., 2015; Wynants et al., 2020). Because of data limitations, this number might be an overestimation of the actual amount of sediment delivery to Lake Manyara. It was therefore estimated that approximately 70% of all sediment that is delivered to the lake is a result of gully erosion in the Makuyuni and Dudumera subcatchments. The area of these two subcatchments together (respectively 2915 km^2 and 2066 km^2 (Wynants, 2020)) is approximately 6.55 times the size of the area researched by Metcalfe (2021). Multiplication of this number by the 45 gully systems that were estimated to be present within the area studied by Metcalfe (2021), led to the estimation that approximately 295 gully systems in total were present in the Dudumera and Makuyuni subcatchments. Assuming that these gullies account for a total of 70% of gully sediment delivery to Lake Manyara, the total amount of gullies in the LMC would be 295/70*100 = 422.

Research has shown that there in an established well-connected drainage network that forms efficient conveyance routes from many upstream erosive areas to downstream ecosystems and the downstream channel network (Bracken et al., 2013; Blake et al., 2018; Nonga et al., 2010), but chances are small that all sediment ends up in the lake. Sedimentation most probably also occurs on other locations in the catchment, where the steepness of the area becomes shallower or where LULC changes occur (Betts et al., 2003). Based on this information, it was estimated that 2/3th of all sediment that was lost from gully systems in the LMC will end up in Lake Manyara. The most accurate calculations on sediment load per year in Lake Manyara could be made by multiplying the estimated amount of gullies in the LMC, the best estimation on the amount of sediment production per gully and the estimation on the percentage of sediment loss that would end up in Lake Manyara: 422 * 388.9 m^3/year * 2/3 = 109,411 m^3/year. By dividing the approximate volume of Lake Manyara (299,700,000m^3) by the estimated sediment load (109,411 m^3/year), it was estimated that the lifetime of Lake Manyara would be 2739 years if gully erosion was the main factor that determines the size of the lake.

3.2.3 Gully erosion: main findings

The estimated amounts of gully erosion from gully systems 1-3 were calculated based on satellite imagery from *Google Earth Pro* in combination with field data. Images from *Google Earth Pro* were selected since these were the ones with the best quality for this research that were available for free. A comparison between field measurements and the images led to the conclusion that the width, depth and cross sectional areas of the gullies could not be derived in high detail from the images. Gully growth rates in width and depth could therefore not be taken into account. Gully length growth rates in combination with field data were studied to estimate the amount of sediment loss in each gully system. This caused that estimates related to sediment loss are less accurate than would be optimal, but are still useful to answer the research question.

Estimated sediment losses in GS 1-3 range from 41.8m^3/year to 9932.7m^3/year (see table 2). Based on the gully length growth rates and the average cross sectional areas of gully systems 1-3, it was estimated that a total amount of 2718.0 m^3 sediment per year was lost from these three gully systems.

Supplementary information on 22 other gully systems (GS A-V) was obtained from Metcalfe (2021) and gully length growth rates of GS A-V were calculated and compared to those of GS 1-3. This led to the estimation that GS 1-3 on average generate 2.33 times more sediment than the average gully system in LMC and that the average gully produces 388.9 m^3 sediment per year. A range of numbers on sediment load in LM and the amounts of years that it would take for LM to fill up with sediment was found. This was done for a range of 20-520 gully systems and in case all, 2/3th and 1/3th of sediment enters the lake (see figures 12-15). The broadest estimates range from a sediment load of 836 to 4,966,350 m^3/year and respectively a LM lifetime of 358,493 to 60 years.

More accurate estimations on the total amount of gullies in the LMC, the yearly sediment load in Lake Manyara and the expected lifetime of the lake could be made by incorporating additional information with regard to erosion in the LMC (e.g. information on relative amounts of sediment deposits per subcatchment and a quantitative analysis on the amount of gullies in a specific area within the LMC). It was determined that there are approximately 422 gullies that substantially contribute to sedimentation in the LMC. When incorporating this with the estimation that 2/3th of all sediment lost from gullies ends up in Lake Manyara, it was estimated that 109,411 m^3 sediment per year ends up in the lake. This corresponds to a Lake Manyara lifetime of 2739 years.

4. Discussion

4.1 Causes shrinkage LM

One of the objectives of this study was to critically evaluate the possible causes and factors that might be contributing to the shrinkage of Lake Manyara. Results obtained based on a critical literature review strongly suggest that irrigation water use cannot be an important factor in the shrinkage of Lake Manyara. Some of the changes in the size of Lake Manyara could not have occurred if activities such as irrigation would significantly impact the size of the lake (Deus and Gloaguen, 2013). Discharge rates with and without irrigation also show minor differences (Van Mens, 2016). Many studies on land use and land cover changes in the LMC present contradicting results (e.g. Kiunsi and Meadows, 2006; Verhoeve, 2019). A critical review on the results and methods and used in the studies related to LULC changes strongly indicates that no significant land use and land cover changes have occurred in the past decades. It can therefore be concluded with a large certainty that land use and land cover changes are not a large factor in the shrinkage of Lake Manyara. Climatological changes, most importantly precipitation and evapotranspiration, do impact the size of Lake Manyara. Future projections on precipitation in the LMC are uncertain, but most models predict a precipitation increase in the coming decades. Precipitation trends of the past decades are however decreasing. This East African Climate Paradox is still an uncertainty and hard conclusions on future rainfall patterns cannot be made. Temperatures in the LMC will almost certainly increase in the future. These increased temperatures will lead to enhanced evapotranspiration rates, therefore leading to more and enhanced periods of droughts. This will most probably cause a decreasing size of Lake Manyara in the coming decades, mainly in the dry seasons (Keijzer, 2020; Verhoeve et al., 2021).

The impact of (gully) erosion on the shrinkage of Lake Manyara could not be fully researched based on only literature. A remote sensing study was performed to estimate the amount of sediment load that ends up in Lake Manyara as a result of gully erosion. For that study, images available at *Google Earth Pro* (CNES/Airbus and IKONOS) were preferred over SPOT 4, RapidEye and PlanetScope images because of the higher spatial resolution, the available time range and the low cloud coverage of the images. A comparison of GS 1-3 with GS A-V led to the conclusion that the amount of sediment loss from GS 1-3 was most probably a large overestimation for the average sediment loss from gullies in the LMC. Based on the additional information on GS A-V, it was estimated that the average gully in the LMC loses 388.9 m^3 per year.

A quantitative analysis on the amount of gullies in a specific area ($760km^2$) in the LMC was combined with information on the amount of relative sediment deposits per subcatchment. This information was used to determine the total amount of gullies in the LMC. It was estimated that there are approximately 422 gully systems in the LMC. Not all sediment lost from the gullies ends up in the lake, since sedimentation also occurs in other parts of the LMC (Betts et al., 2003). To best estimate the yearly sediment load in Lake Manyara and the corresponding expected lifetime of the lake, it was estimated that 2/3th of all sediment lost from gullies ends up in the lake. Based on calculations including the estimated average sediment loss per gully system in the LMC (388.9 m^3/ year), the approximate amount of gullies (422) and the estimated fraction of sediment lost from gully systems that ends up in Lake Manyara (2/3th), it was determined that approximately 109,411 m^3 sediment per year ends up in the lake. This means that if gully erosion was the main factor that determines the size of Lake Manyara, the expected lifetime of the lake is 2739 years.

The additional information on sediment load in Lake Manyara as a result of gully erosion suggests that gully erosion is also not a large factor that contributes to the shrinkage of Lake Manyara. If sedimentation was the main factor that determines lake levels, it would take at least centuries before substantial decreases of lake levels would be noticed. Since rising temperatures – enhanced periods of droughts in particular - will increasingly affect the size of Lake Manyara in the coming decades, it can only be concluded that anthropogenic climate change is the main cause of the shrinkage of Lake Manyara.

4.2 Management strategies LMC

The third objective of this thesis was to discuss management strategies that best guarantee a sustainable future for Lake Manyara. Since increasing temperatures, enhanced periods of droughts in particular, are by far the largest contributor to the shrinkage of Lake Manyara, local management strategies will not be able to ensure the sustainability of the lake. They may however increase land rehabilitation and help to adapt to drought conditions.

4.2.1 Increasing land rehabilitation

The Lake Manyara Catchment has been undergoing rapid changes that led to degradation of the soil (Wynants et al., 2018). In this thesis it was shown that land use and land cover changes most probably did not occur on a large scale. Erosional processes on the other hand did occur and caused degradation of the soil (Wynants, 2020). Gully erosion rates have increased in the past decades and it is now the largest type of erosion that contributes to land degradation in the LMC (Maerker et al., 2015; Schouten, 2020). To increase land rehabilitation, it is therefore important to mitigate gully erosion in the LMC.

If measures are to be taken to prevent land degradation and sedimentation, it is important to do this in the early stages of gully incision (Betts et al., 2003). Soil conservation strategies are most effective in the early stages of gullying, before gullies deepen and mass movement processes start to occur. When mass movement has already begun, as is the case in many gullies in the LMC, erosion rates increase rapidly (Betts et al., 2003; Egberts, personal contact). At this stage of gullying, attempts to decrease further gully incision are often much less successful then when measures are taken at earlier stages of gully erosion (Betts et al., 2003). If measures against gully erosion are desired in the LMC, the most successful strategy would be to prevent small gullies from becoming large gully complexes.

Several measures can be implemented to mitigate gully erosion in the LMC. Vegetation restoration has been shown to be an effective tool to protect soil against erosion (Descheemaeker et al., 2006; Wang et al., 2020). Vegetation cover can help to control gully retreat and mitigate concentrated overland flow erosion by decreasing runoff discharge and increasing water infiltration rates (Chen et al., 2018).

In semi-arid regions, grasslands have been shown to be the most effective type of land cover to reduce erosional processes on slopes of 0°–25° (Wu et al., 2020). On slopes of 10°–25° and 20°–30°, scrublands and forests are respectively the most effective vegetation type in controlling erosional processes in semi-arid regions (Wu et al., 2020). When deciding on whether to use scrublands or forests to control soil erosion, soil type should also be taken into account. Scrublands are most often the better choice on moderately coarse soils, whereas forest are generally more effective on medium-textured to moderately fine soils (Wu et al., 2020).

Bare lands can be reseeded with grass and other types of vegetation to stabilize the soil to prevent gullying (Rapp et al., 1972). Grasses and herbs can be planted in existing gully bottoms to stabilize gullies and to stop further gully erosion (van Rensburg, 1958). To reduce the risk of soil collapse at the edge of the gullies and to prevent depletion of soil water by shrubs, the most suitable choice for revegetating gully banks is the use of grass types (Wang et al., 2020). Some types of grasses (e.g. star grass and elephant grass) have been shown to become readily established in the system when they are planted in semi-arid regions (van Rensburg, 1955). Star grass for example spreads sidewards, holds back soil particles and stabilizes gullies that were bare and unstable before. Other species then infiltrate and help to stabilize the soil as a result of an enhanced ground cover (van Rensburg, 1958). When different types of grass increase the root density in the area, an exponential decrease of concentrated flow erosion rates could occur (Gyssels and Poesen, 2003).

When the vegetation cover is increased, the last vegetation layer that intercepts rainfall should be near the soil surface to be an effective tool to protect the soil from (gully) erosion (Valentin et al., 2005). The characteristics of plant roots determine the effectiveness of the vegetation layer as a measure against erosion, since they improve the physical properties of soil (e.g. stability and infiltrability) and hence reduce gully erosion (Valentin et al., 2005). In hillslope areas, the placement of terraces and perennial vegetation could also reduce gullying (Valentin et al., 2005).

These measures may help to reduce gully erosion and sediment delivery to Lake Manyara in the future. It may however take decades before gullied land is rehabilitated, even if vegetation cover would increase largely (Gomez et al., 2003a; Gomez et al., 2003b). Sedimentation areas along channels in the LMC were probably established in the past decades as a result of active gullying. These sediment stores could be expected to cause sediment yields in lake Manyara even decades after the catchment would be stabilized (Betts et al., 2003).

4.2.2 Adapting to drought conditions

Management strategies that can be implemented on a local catchment scale will have a positive impact on the preservation of the LMC, but they will not prevent Lake Manyara from shrinking. Since anthropogenic climate change will almost certainly lead to increased temperatures and droughts in the LMC, local management strategies should be focused on adapting to drought conditions.

Water resources other than Lake Manyara are important for humans and terrestrial wildlife in the LMC. They mainly use water from rivers, streams and dams as a source of drinking water rather than using water from the lake (Nonga et al., 2010). Water productivity should be increased to efficiently use the available water in the catchment. While this does not have a direct impact on the sustainability of Lake Manyara, it does positively impact the use of water for irrigation and consumption in the catchment.

Harvested rainwater is an alternative and supplemental source of water in semi-arid regions (Adham et al., 2016). Rainwater harvesting is used to collect, store, induce and conserve surface runoff for agricultural purposes in these types of regions, where runoff has an infrequent character (Boers and Ben-Asher, 1982). Rainwater harvesting practices that can be implemented in sub-Saharan Africa can be categorized into four groups: (1) rainwater harvesting techniques that collect surface runoff at a micro-catchment scale to store rainwater in the soil to mitigate dry-spells in periods of droughts, (2) rainwater harvesting techniques that collect surface runoff at a macro-catchment scale to collect water for supplementary irrigation, (3) in-situ rainwater harvesting techniques to enhance infiltration, improve soil water availability and reduce surface runoff and soil evaporation and, (4) the selection of well-adapted crop types and response farming (Biazin et al., 2011).

Micro-catchment rainwater harvesting

Micro-catchment rainwater harvesting techniques are ways to enhance agricultural production by guiding runoff into an infiltration enhancement structure on a relatively small scale (often 10-500 m^2) (Biazin et al., 2011; Hatibu and Mahoo, 1999). These techniques are a useful tool to prevent dry-spells in periods of droughts. Since enhanced periods of droughts are expected in the LMC in the near future, the implementation of these types of rainwater harvesting might be of vital importance in the coming decades. Many types of micro-catchment rainwater harvesting exist, but the most common types that could be implemented in semi-arid regions are pitting, contouring, terracing and the creation of micro-basins. These techniques have been widely used and are part of the traditional practices in sub-Saharan Africa (Biazin et al., 2011; Hatibu and Mahoo, 1999). Because of socioeconomic reasons, the development of these kinds of traditional techniques have been shown to be more effective than the introduction of new rainwater harvesting systems (Biazin et al., 2011; Reij et al., 2009). They may therefore be the most adequate techniques that can be implemented in the LMC in the coming decades.

Macro-catchment rainwater harvesting

Macro-catchment rainwater harvesting techniques are used to collect water from external catchments to divert it into well designed storage structures for usage in a target area (Biazin et al., 2011). The collection of rainwater is almost always done via natural slopes and existing paved surfaces. The collected water is used for consumption or for supplementary irrigation during periods of droughts. Macro-catchment rainwater harvesting techniques that are most often applied in East Africa include collecting rainwater in traditional open ponds, the use of cisterns, micro-dams and sand dams and the direct irrigation of crops via diversion streams (Biazin et al., 2011).

In-situ rainwater harvesting

In-situ rainwater harvesting systems are water conservation methods that store rainwater within the soil by capturing the water where it falls (Yosef and Asmamaw, 2015). These types of methods increase the water holding capacity of the soil, enhance infiltration rates and reduce runoff and evaporation (Biazin et al., 2011; Yosef and Asmamaw, 2015). Types of In-situ rainwater harvesting techniques that are currently applied in Eastern Africa include ridging, mulchin, furrowing and hoeing and conservation tillage (Biazin et al., 2011). These types of techniques have been shown to largely improve the smallholder livelihood and income in semi-arid regions in sub-Saharan Africa (e.g. Rockstöm et al., 2009; Vohland and Barry, 2009).

Maximizing plant water uptake and response farming

Agricultural water productivity can be increased by maximizing plant water uptake and response farming. Plant water uptake can be increased by selecting the right plants based on their genetic traits. Genetic traits that should be taken into consideration are ability to: (1) reduce transpiration without affecting productivity, (2) increase production without increasing transpiration, (3) decrease the non-transpiration water usage and, (4) the ability to tolerate water stress (Biazin et al., 2011). Another way to increase the water uptake ability of plants is the use of fertilizers. The possible effects on the chemical composition of Lake Manyara should however be considered if the use of fertilizers is preferred. The agricultural yield can also be improved when response farming is implemented. This type of farming consists of the prediction of expected rainfall behaviour at the beginning of each rainy season and accordingly selecting the preferred cropping systems (Stewart, 1988).

Critical notes

Rainwater harvesting techniques are useful ways for local human inhabitants to adapt to drought conditions and to enhance water productivity in the LMC. What these techniques will not do, is combating the shrinkage of Lake Manyara. Many species, including endangered ones, are dependent on the existence of the lake. Lake Manyara is also an important feature within the Lake Manyara National Park, which provides for a booming tourism industry in the region and which is an important biodiversity hotspot that is of great ecological importance in the area (Janssens de Bisthoven et al., 2020; Munishi et al., 2017). It should thus be noted that important aspects of the Lake Manyara shrinkage are not being tackled by adapting to drought conditions.

The selection of suitable sites and the most suitable techniques are critical criteria for the success of rainwater harvesting (Adham et al., 2016). Earth scientific properties that should be taken into account when selecting rainwater harvesting techniques include slope, land use and land cover, distance to settlements and streams, soil type, and rainfall (Adham et al., 2016). In addition to these properties, it is important to investigate the consequences of the proposed water harvesting methods on public health. Studies have shown that an increase in open water surfaces may increase the transmission of water related diseases, especially in sub-Saharan Africa (Boelee et al., 2013). Other important aspects that should be taken into consideration when selecting water harvesting techniques are related to socioeconomics. It was shown that the success rate of the selected methods are considerably larger when socioeconomical needs, such as the recognition of indigenous knowledge and cultural traditions, are met (Hatibu and Mahoo, 1999).

4.2.3 Socioeconomics and multi-stakeholder cooperation

Many techniques to enhance environmental rehabilitation and to adapt to drought conditions could potentially be implemented in the Lake Manyara Catchment. Before selecting techniques that would be best suitable in the catchment, it is important to consider cultural and socioeconomic and aspects that play a role in the area. The success or failure of the selected techniques depends for a large part on these aspects (Hatibu and Mahoo, 1999). Techniques that are suitable from an earth scientific perspective could otherwise fail for many reasons.

Many environmental problems in the LMC are a result of complex socioeconomical problems, such as an underdeveloped regulatory framework on a local scale and the implementation of programs that encourage the Maasai to permanently settle in villages (Homewood et al., 2009; Nonga et al., 2010). Many inhabitants in semi-arid Africa have experienced subsistence regimes that led to the increased need for direct survival. Techniques to enhance environmental rehabilitation and, more importantly, to adapt to drought conditions most probably will only be implemented when the urgent need for these techniques is understood (Hatibu and Mahoo, 1999). Thus far, the causes for the shrinkage of Lake Manyara and for decreased amounts of water in rivers and streams are unclear to local inhabitants in the catchment. Inhabitants give a variety of reasons for the decreased amounts of water, including but not limited to: increased local human activities, sedimentation, decreased rainfall and sedimentation (Nonga et al., 2010). The urgent need for adaptation strategies to mitigate the effects of increased temperatures and enhanced droughts should become clear to local inhabitants before coming up with management strategies that should be implemented in the area.

Socioeconomic reasons also limit the development of suitable water harvesting techniques. At present, traditional water harvesting techniques will most probably be more effective than introducing new rainwater harvesting systems (Reij et al., 2009). For the appropriate technical development indigenous techniques, institutional and technical support is needed (Biazin et al., 2011). Development projects and resource-conservation programmes should be made to enhance ability to adapt to the consequences of anthropogenic climate change. It is recommended that indigenous knowledge and practices are incorporated in these programmes, because traditional systems have been suitable for centuries and cultural knowledge and practices are of great importance to local people (Mbilinyi et al., 2005).

When developing adaptation plans, it is important that the plans will also be implemented. Rapp et al. (1972) found already in the 1970’s that there was an urgent need for water and soil conservation measures. Since then, programmes for environmental conservation in the LMC were created, but they have not been widely implemented (Nonga et al., 2010). It was also shown that people living in the LMC often know what can be done against environmental degradation, but that they were often not able to implement the suggested measures. These are examples of failing management systems, since plans are not being implemented. A more intense collaboration between scientists, policy makers and local human inhabitants could increase the implementation of existing management strategies. This could also lead to the creation of adaptation strategies and hence enhanced ability to adapt to drought conditions and other environmental challenges.

4.3 Accompanying challenges

Increasing temperatures in the area will lead to other environmental and lake related problems besides decreasing lake levels. Potential impacts of changes in lake productivity, salinity and fish predation as a result of rising temperatures may even be larger than the impacts of rising temperatures in itself (Meerhoff et al., 2012). Increased temperatures will probably alter nutrient compositions in shallow lakes such as Lake Manyara. Higher chlorophyll-a concentrations, a larger dominance of cyanobacteria and reduced amounts of zooplankton are predicted to occur when temperatures rise (Mooij et al., 2007). In July and August 2004 for example, a mass mortality of Lesser Flamingoes occurred in three alkaline lakes, including Lake Manyara. The unusual large amount of the cyanobacterium *Arthrospira fusiformis* in the lakes was found to be toxic to Lesser Flamingoes (Lugomela et al., 2006). These kinds of problems are expected to occur more often when temperatures rise. More research should be done on other potential impacts of rising temperatures in the LMC, since these problems may be crucial for wildlife in the area, but may easily be overlooked.

4.4 Combating anthropogenic climate change

Inhabitants of the LMC are victims of anthropogenic climate change and this cannot be prevented by taking measures on a small scale. Local measures to enhance environmental rehabilitation and to adapt to drought conditions may be taken, but they will not prevent Lake Manyara from shrinking. Global action thus needs to be taken to combat climate change and this study is only one of many (e.g. Doulton and Brown, 2009; IPCC, 2014) that shows the urgent need for immediate global action.

4.5 Limitations study

Limitations of this study mainly occur with respect to the study on gully erosion. Accurate field measurements were obtained for gully systems 1-3. These field measurements were compared to satellite images to estimate the amount of sediment that was lost from GS 1-3. Satellite imagery provided information on the growth of gully lengths, but no information could be obtained on gully depths and gully widths. In addition, literature suggests that gully erosion has accelerated since the year 2000, but no images with a high spatial resolution were available from before the year 2005. The rate at which gully erosion accelerates or decelerates could therefore not be determined. The results on gully erosion are accurate enough to conclude that gully erosion is not a large factor that causes the shrinkage of Lake Manyara, but precise numbers on sediment load in Lake Manyara could not be provided.

Future rainfall is another uncertainty that might affect the future of Lake Manyara. Precipitation rates over the past decades show a decreasing trend in rainfall, but most models predict increasing amounts of precipitation in the coming decades. If precipitation does increase in the future, the consequences on the size of Lake Manyara could be better than expected. Future temperatures however almost certainly increase and even if rainfall increases, the question remains if the increased amounts of rainfall outweighs the effects of rising temperatures and droughts.

5. Conclusion

The aim of this research was to unravel the causes of the Lake Manyara shrinkage and to discuss recommendations for the management of the Lake Manyara Catchment to sustain the future of the lake. The possible causes and factors that might be contributing to the shrinkage of Lake Manyara were studied.

Based on a literature review, it was concluded that both the use of irrigation water and changes in land use and land cover have neglectable impacts on the shrinkage of Lake Manyara. Regional in situ temperature, land surface temperature, actual evaporation, evapotranspiration and precipitation all show correlations with the surface area of Lake Manyara. The combination of precipitation and evapotranspiration seems to have a large impact on the size of the lake. Future rainfall is still uncertain because of the East African Climate Paradox, which means that the exact changes in the size of Lake Manyara cannot be predicted. However, it is almost certain that temperatures will rise in the coming decades. This will result into a large increase in evapotranspiration and hence an increase in periods of droughts; therefore enhancing the shrinkage of Lake Manyara. In terms of sedimentation, findings showed that gully erosion is by far the largest source of sedimentation in Lake Manyara. Absolute amounts of yearly sedimentation rates in Lake Manyara were not available, which meant that the impact of (gully) erosion on the size of the lake could not be determined based on literature only.

A remote sensing study was performed to determine the contribution of gully erosion to the shrinkage of Lake Manyara. Gully length growth rates of three gully systems (GS 1-3) were studied based on high resolution imagery available from *Google Earth Pro.* These growth rates were combined with obtained field data (e.g. gully dimensions) to determine the amounts of sediment that were lost from each system. It was determined that gully systems 1-3 together lose approximately 2718.0 m^3 sediment per year. Additional information on gully lengths of 22 other gully systems (GS A-V) in the LMC was obtained for several periods in time. Gully length growth rates of these extra gully systems were calculated and compared to the ones of GS 1-3. Calculations revealed that GS 1-3 generate approximately 2.33 times more sediment than the average significant gully system in the LMC (based on GS 1-3 and GS A-V). It was therefore estimated that the average gully in erosion prone areas loses 388.9 m^3 sediment per year. A study on relative sedimentation rates per subcatchment was combined with an analysis on the amount of gullies in a specific part of the LMC. This revealed that there are approximately 422 gully systems in the LMC that together produce approximately 164,116 m^3 sediment per year. It was assumed that 2/3th of the produced sediment ends up in Lake Manyara, leading to a sediment load of 109,411 m^3 per year in the lake. This means that Lake Manyara would have an approximate lifetime of 2739 years if gully erosion was the main factor that determines the size of Lake Manyara. When comparing these numbers with the data on climatological factors, it can be concluded that erosional processes are not a large factor causing the shrinkage of Lake Manyara. It can therefore be concluded that anthropogenic climate change – increased temperatures and enhanced periods of droughts in particular - is the main factor in the shrinkage of Lake Manyara.

Management strategies that could be implemented in the Lake Manyara Catchment to enhance environmental rehabilitation and to adapt to drought conditions were discussed. In terms of the environmental rehabilitation, the most important measures that can be taken are measures to prevent gully erosion, since this is the largest contributor of land degradation in the catchment. Soil conservation strategies were shown to be most effective in the early stages of gullying, so that mass movements of sediment can be prevented. Measures that can be implemented to mitigate gully erosion include, but are not limited to, vegetation restoration, the reseeding of bare lands and the placement of terraces. If soil conservation measures were to be taken now, it could however take decades before sediment yields in the catchment were stabilized.

Since anthropogenic climate change will almost certainly lead to increased temperatures and droughts in the LMC, local management strategies should be focused on adapting to drought conditions. Increasing water productivity is an important tool to efficiently make use of the available water in the catchment. Four types of water harvesting techniques that can increase water productivity in sub-Saharan Africa include: (1) micro-catchment rainwater harvesting, (2) macro-catchment rainwater harvesting, (3) in-situ rainwater harvesting and (4) maximizing plant water uptake and response farming. Before being able to select the best suitable methods to increase land rehabilitation and adapt to drought conditions, socioeconomic factors should be taken into account. These factors largely contribute to the success or failure of the selected techniques. It is recommended to incorporate indigenous knowledge and practises in adaptation programmes, because this is of great importance for local human inhabitants and traditional systems have been shown to be suitable for centuries. Intensifying the collaboration between policy makers, scientists and local human inhabitants can help to create and implement strategies in the LMC.

The implementation of management strategies within the LMC will have a positive impact on environmental rehabilitation. Gully erosion can be mitigated, biodiversity and ecosystem services may be enhanced and the creation and implementation of strategies for soil and water conservation can help to adapt to drought conditions. Since anthropogenic climate change is by far the largest contributor to the shrinkage of Lake Manyara, local measures will however not be able to prevent the lake from shrinking.

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Appendices

Appendix A: Comparison of GS 1-3 and A-V

Table 3: gully length growth rates of GS A-V and GS 1-3 and their average growth rates

Gully Systems A-V (Metcalfe, 2021) and GS 1-3	Gully length growth rate (m/year)
GS A	0.1
GS B	15.2
GS C	3.3
GS D	1.5
GS E	4.4
GS F	25.4
GS G	9.5
GS H	10.1
GS I	6.3
GS J	4.9
GS K	6.9
GS L	27.0
GS M	21.6
GS N	8.9
GS O	7.4
GS P	5.8
GS Q	16.3
GS R	55.9
GS S	9.7
GS T	4.8
GS U	32.8
GS V	3.0
Average GS A-V	**12.8**
GS 1	62.9
GS2	26.1
GS3	20.1
Average GS 1-3	**36.4**
Average all GS	**15.6**