Unravelling the hydrological dynamics of Lake Manyara in Tanzania

Lisa van Mens

Universiteit Utrecht

Unravelling the hydrological dynamics of Lake Manyara in Tanzania

MSc Thesis

November-2016

Author: Lisa van Mens

Student number: 5570301

E-mail: l.m.vanmens@students.uu.nl

First supervisor: Geert Sterk

Second supervisor: Patricia LopezLopez

MSc Programme: Earth Surface and Water

Faculty of Geosciences

Department of Physical Geography

Utrecht University

Abstract

The catchment of lake Manyara is part of the East African Rift System. It is sensitive to local hydrological changes since it is a closed basin. The Manyara catchment is very important for its inhabitants to provide a sustainable food source. The most dominant types of land use are pastures, rain-fed agriculture and savanna. The most dominant crop types that are cultivated in the area are: bananas, rice and maize. Problems arise since the lake seems to be shrinking during the past 40 years. In this paper possible drivers of the changes in surface area of lake Manyara are studied. The climatological impact on the lake area has been assessed by analysis temperature and precipitation data. In the past 40 years there has been a decrease in precipitation of about 100mm according to the Tanzanian National Parks. The temperature only increased during the dry season with 1.0-2.0°C. Land use changes have been analysed by using satellite imaginary. The images do not show a significant change in land use and are therefore excluded from further analysis. The expected increase in irrigation water abstraction was analysed using the Soil Water Assessment Tool (SWAT) and measurements taken during fieldwork (January-March 2016, Tanzania). It responds quickly to precipitation events. However, it is uncertain if the amount of irrigation water has increased due to a lack of in-situ datasets. The SWAT-model indicates that the event prior to the date of the satellite image is the main driver for the changes in surface area of lake Manyara. There is no reason to believe that Lake Manyara is disappearing. The shrinkage and expanding of the lake has a more cyclic nature. They do not occur on a regular base and the intervals between a small and a large lake seem to be getting longer.

Content

Introduction 1

Study area 3

Methodology 7

- Land cover change 7
- Climate change 7
- Irrigation 8
- Surface area lake Manyara 8
- SWAT model 8

Results 13

- Climatological changes 13
- Irrigation 15
- SWAT modelling 16
- El Niño/La Niña 22

Discussion & conclusion 25

- Conclusion 26
- Recommendations 26

Literature 27

    - Articles 27
    - Websites 30

Appendix I: CFSR meteostations 31

Appendix II: Measuring points 32

Appendix III: Multiple regression analysis - All data points 33

Appendix IV: Multiple regression analysis – A group 34

Appendix V: Mutiple regression – B group 35

Introduction

Lake Manyara is part of the Lake Manyara National Park, which is one of the smallest national parks in Tanzania. The catchment of Lake Manyara is situated in the East African Rift System (EARS) and besides attracting tourists it is also a transit to the better known Serengeti and Ngorongoro National Parks. During the dry season large herds of livestock from distant areas migrate to the Manyara catchment (Ngana et al., 2004). According to Fitzpatrick et al. (2015), the Manyara catchment hosts one of the highest densities of large mammals in the world. Ranging from elephants and hippos to giraffes and tree climbing lions. Furthermore, the area is also popular by immigrants due to the fertile soils and ample water resources for irrigated agriculture (Ngana et al., 2004).

Since the lake has a closed basin with no outlet to the sea or other lakes, it is very sensitive to local hydrology and water quality changes (UNEP, 2004). With recent developments such as population growth, the related intensification of agriculture and climate change the pressure on available water sources has increased (Legesse et al., 2003). Conflicts arise frequently, due to the increasing pressure on the limited natural resources (Ngana et al, 2004). It is therefore crucial to gain more understanding of the amount of irrigation water used from the lake and the land use change around it. A specific problem that seems to occur in the Manyara catchment is the shrinkage of the lake. According to Bachofe et al. (2014) there is evidence for a maximum paleo lake extent of approximately 140 m above today's lake surface. Other studies discovered evidence of beaches and lake terraces approximately 40 m above the current lake level either based on sediments or stromatolites (Uhlig and Jaeger, 1909; Keller et al., 1975; Casanova and Hillaire-Marcel, 1992; Dixit, 1984). More recent studies indicate that during the past 40 years the surface area of Lake Manyara fluctuated. Mainly variating between 410km^2 and 480km^2 (Yanda and Madulu, 2005). Other recent studies show that the fluctuations in lake level are influenced by climatic and environmental changes (Deus et al., 2013; Deus and Gloaugen, 2013; Maerker et al., 2014). In addition to these scientific findings, local people expressed their concerns regarding the shrinkage of the lake after a relatively dry season. Their main concern was the possibility of the disappearance of Lake Manyara.

Resulting from the previously mentioned articles several possible causes for the changes in surface area can be derived. Namely land use changes, an increasing water demand for irrigation or other purposes and climate change. The main driver of land use change in the Manyara catchment is the intensification of agriculture, which has its impact on the hydrology of the lake (Legesse et al., 2003). Especially because lake Manyara is the central element of the hydrological system of the area and is therefore mainly controlled by processes in its catchment (Legesse et al., 2003). Sechambo (2001) used aerial photographs and satellite imagery of the Manyara catchment to observe the changes in land use. The results showed that the amount of farmland has increased by 150%, while the amount of wood land, forest and savanna, has decreased by 77%. Deus et al. (2011) used remote sensing to assess the land use changes in the Lake Manyara catchment. Modis imaginary was used to divide all the land uses into 13 different land cover classes: Water, evergreen broadleaf forest, deciduous broadleaf forest, mixed forests, closed shrub land, open shrub land, woody savannahs, savannahs, grasslands, permanent wetlands, urban and built-up, cropland-natural vegetation mosaic, and barren or sparsely vegetated. The availability of aerial photographs and satellite images is important since there is a lack of in-situ data of the area (Andersen, 2008). For each land cover class the evapotranspiration and runoff were calculated in order to model the water balance of the area. The results showed that 93% of the inflow was lost through evapotranspiration, with a potential evapotranspiration ranging between 1004 and 1221 mm per year for the different classes. The runoff responds to precipitation events across the catchment, with high runoff values during the wet periods and low runoff values during the dry periods.

Climate change can result in higher temperatures (+0.5-1.0°C) and an increase in precipitation for the Manyara catchment (+5-10%) and can therefore cause changes in the hydrology (IPCC, 2014). An example of how climate change can affect the hydrology of a lake is given by Girons Lopez (2011). The response of lake Babati, which is located approximately 120km south of lake Manyara, was modelled for four different climate scenarios. For lake Babati the threat is not particularly the decrease of water level but the risk of an overflow. There were two scenarios with an increase of 15% in precipitation which caused lake Babati to overflow in 11 years and the two scenarios with an increase in precipitation of 10% took 15 years to cause an overflow. For the two scenarios with the lower temperature increase (2.5 vs 3.0 °C) the lake level evolved faster compared to the two scenarios with the higher temperature increase. The model used by Girons Lopez (2011) however had a high sensitivity for temperature and precipitation. Legesse et al. (2009) modelled the response of the Ketar basin to climatological changes. This research shows that an increase in temperature would result in less runoff and more evapotranspiration. Other feedback mechanisms affected by an increase of precipitation and/or temperature are the vegetation cover, rainfall pattern and solar radiation. This is also confirmed by Ficklin et al. (2009).

The third possible cause for changes in the Lake Manyara hydrology is the increase of water used for irrigation or other purposes. With the population growth and the increase of farmland the water demand exceed the water availability. The seasonal and climatic variability cause large variations between the supply and demand for the water. Often there is no investment in storage capacity, therefore in the case of a relatively wet year the farmer simply extends his cropping area (Lankford, 2004). According to Machibya (2003), the efficiency drops when water is abundant and increases when water becomes scarce. There is not much data available considering irrigation schemes for the Lake Manyara catchment, therefore it is compared to a similar surrounding area. According to Adams et al. (1994), the type of irrigation used in the Manyara catchment is similar to that in the Sonja, near lake Natron, and consists mainly of hill furrow irrigation. Irrigation channels are used to redirect the water. In the Mto wa Mbu area an irrigation 7-day rotation scheme is used to equally divide all the water along the farmers (Igbadun and Salim, 2014).

The aim of this study was to determine the main factors that influence the area of Lake Manyara. The specific objectives were:

1. Determine the main climatological changes of the past 40 years in the Lake Manyara region.
2. Identify the water extractions for irrigation or other purposes.
3. Use the data to assess the impacts of the main driving factors on the extent of Lake Manyara.

Study area

The study location, Lake Manyara catchment, is located in northern Tanzania (figure 1). Lake Manyara National Park, includes the lake and its immediate surroundings. The lake covers an average area of 550km^2 and the catchment covers an area of about 11.000km^2 (Bachofe, 2014). The catchment is in its turn part of the East African Rift System (EARS) and can be found in the eastern branch. It is situated in the most southern basin of this eastern branch of the EARS (Casanova and Hillaire-Marcel, 1992). The EARS is a narrow zone where a divergent plate boundary is developed, which started 22-25 million years ago (Maslin et al., 2014). The African plate is splitting into two tectonic plates (Ebinger et al., 1997). This process led to the occurrence of volcanic complexes. An example of such a complex is the Ngorongoro volcanic complex, this is also the northern boundary of the Manyara catchment. In the south it is limited by the Loya Mountains (Bachofe et al., 2014, Casanova and Hillaire-Marcel, 1992). Lake Manyara is situated in an asymmetrically shaped half graben, with a plateau of 200-600m high in the west and a west dipping monocline in the east (Bachofe et al., 2014). Its asymmetry controls the sedimentation pattern. Along the western shore thick fluvial deposits or delta formations are observed, while on the eastern shore organic muds and evaporate crusts are observed. The northern and southern shore mainly consist of swamps (Casanova and Hillare-Marcel, 1992). According to Ring et al. (2005) however, the sediments and the lake are not disturbed by faulting.

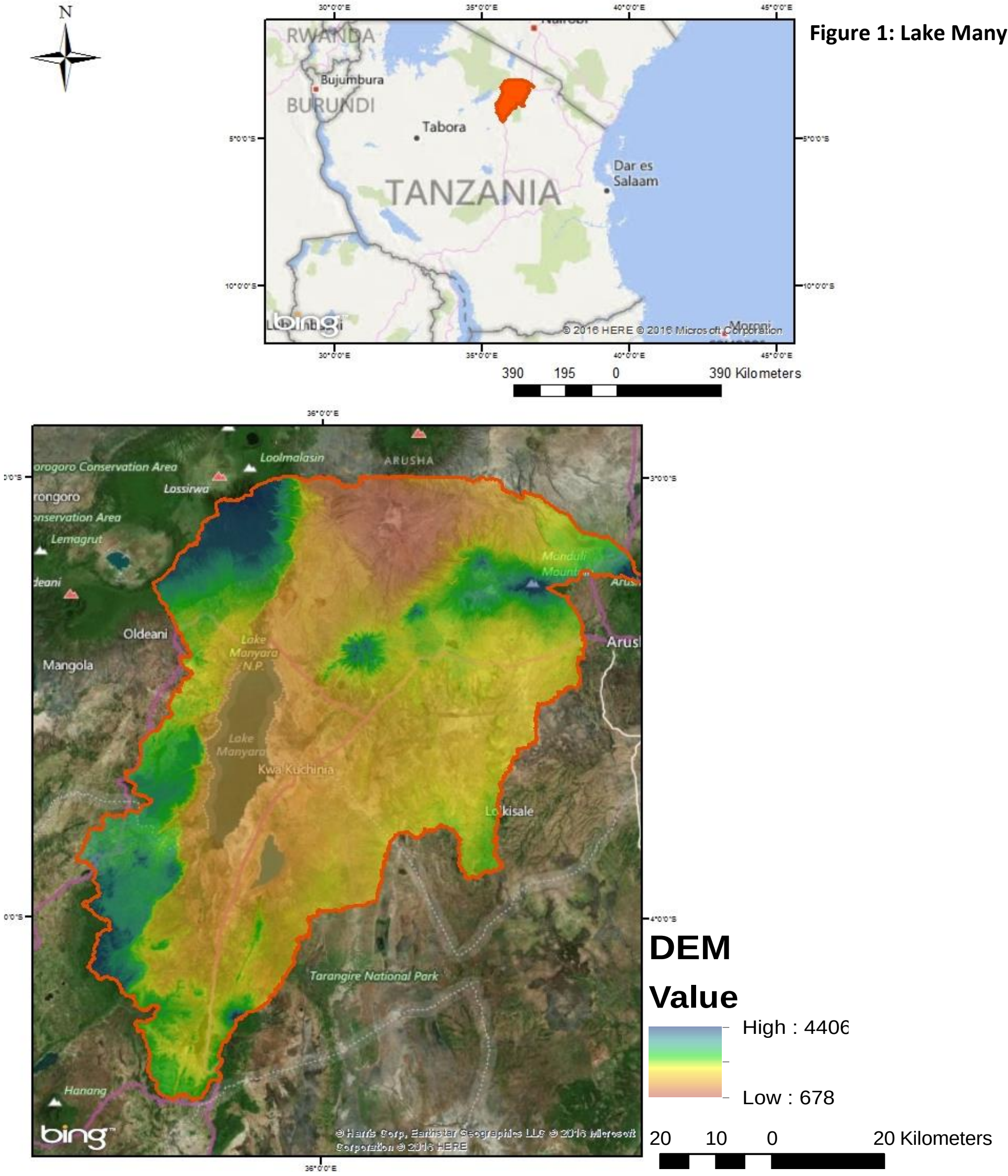

Figure 1: Lake Manyara catchment.

Lake Manyara receives its water from various perpetual and seasonal sources. There is a seasonal river input by the Makuyuni river from the east and a perpetual input by the Simba river from the north, originating from the highlands to the northwest of the basin. (Yanda and Madulu, 2005). Other water sources are the underground springs which are replenished by crater highlands above the Manyara basin (Schwartz et al., 2012). According to the Agricultural office of Mto wa Mbu (2016) the main tributaries to Lake Manyara are: the Kirurumu river, the Mto wa Simba and the Mto wa Mbu. Lake Manyara is an alkaline-saline lake with a maximum depth of 1.18m. Its pH varies between 9.05-10.25 and its salinity varies from 4%-34% (Bachofe et al., 2014, Yanda and Madulu, 2005).

The average amount of precipitation in the catchment is approximately 600 mm per year (figure 2) (Deus et al., 2011) and ranges between 1200 mm at the top of the plateau to 700 mm at the eastern part of the plain (Bachofe et al., 2014). It varies per year whether the largest amount of precipitation falls during the short or the long rains. The short rains occur in November-December and the long rains occur in March-May (Getnet et al., 2014).The potential evapotranspiration is estimated at 1200mm per year by Ngana et al. (2004), due to the high amount of evapotranspiration and low precipitation the climate in the lake Manyara catchment can be considered as semi-arid, with an average temperature ranging between 16°C - 23°C (figure 2). The highlands are covered with forest while the eastern part of the catchment is sparsely covered with vegetation, with a few exceptions of savanna type bushes and shrubs (Yanda and Mudulu, 2005).

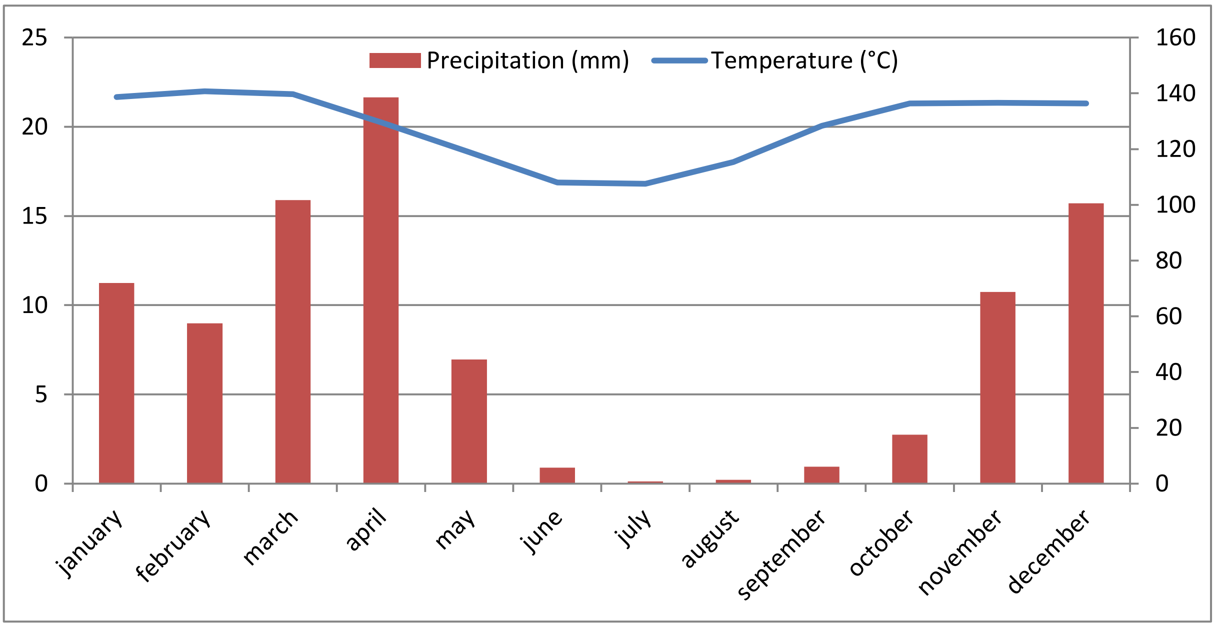

Figure 2: Average temperature and precipitation in the Lake Manyara catchment, source: TANAPA (2016) & CFSR (2010).

The lake Manyara catchment is partly located in the Babati- and the Mondulli district (Ministry of agriculture, food security and cooperatives, 2006). The catchment houses approximately 560.000 people who are members of about 50 different tribes (Agricultural office Mto wa Mbu, 2016). In Tanzania 80% of the population depends on agriculture for its livelihood (Nonga et al., 2011), in the Manyara catchment this is even 90% (Deus et al., 2011). The most dominant types of land use in the Manyara catchment are pastures, rain-fed agriculture and savanna (Maerker et al., 2015). The most frequently cultivated crop types are bananas, rice and vegetables (Agricultural office Mto wa Mbu, 2016). Ngana et al. (2003) state that during the dry season herds of livestock migrate to the Lake Manyara catchment, increasing the pressure on the pastures. The traditional land use by the Masai is the most suitable and ecological stable land use since it is adapted to the environment. However, this is not the most efficient way to use the land due to a low level of technology involved (Geerling and Breman, 1986). The modernization of agriculture and the shift from pastoral to agro-pastoral societies have again increased the pressure on the availability of irrigation water.

The catchment of lake Manyara was part of the joint flood control and irrigation programme. This programme made several measures possible. For example, the installation of two flood control drains, a main irrigation channel to irrigate the eastern part of Mto wa Mbu, the diversion of the Mto wa Mbu which now flows into Mto wa Simba and the restoration of the Kirurumo network. Not all the works could be finished due to a lack of financial resources (Paudyal, 1990; Burton, 1990). According to the agricultural office in Mto wa Mbu (2016) an area of 1100 ha was irrigated in the 1980s. Currently an area of 3600 ha is irrigated, including 1200 ha of traditional irrigation, of the potential 15000 ha irrigational area. The most cultivated crops are bananas, maize and rice (Ministry of Agriculture, 2006). The current status of the irrigation system in Mto wa Mbu area is still traditional and uncontrolled (Agricultural office Mto wa Mbu, 2016). The irrigation system is divided in eleven sub-systems (see figure 2). A few sub-systems (1, 2 and 3) abstract irrigation water using permanent intake structures, a remnant of the joint flood control and irrigation programme, in combination with non-permanent structures. The other subsystems use non-permanent structures the gravity to abstract irrigation water (Agricultural office Mto wa Mbu, 2016).

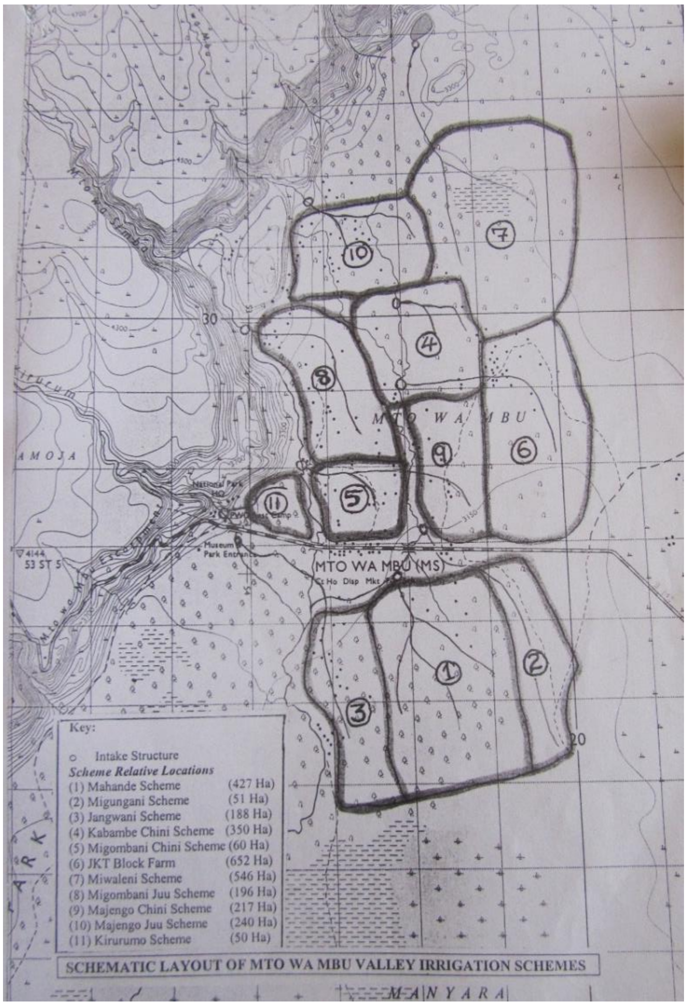

Figure 3: sub irrigation systems Mto wa Mbu, source: local agricultural office (2016).

Methodology

In this study, the method developed by Getnet et al. (2014) was used as a guideline to disentangle the impacts of land use change, climate change and irrigation in the Lake Manyara catchment. In the following section the methods used to assess these impacts will be explained.

Land cover change

A possible cause of the shrinkage of lake Manyara is the land cover change in the Manyara catchment over the past 40 years. In order to evaluate land cover changes Landsat satellite images were used to create land cover maps. The used images were obtained via the United States Geological Survey (USGS). They had a 30m resolution and were taken during 1973-2016. An unsupervised classification has been used in order to assess whether there were significant changes in land cover. For the unsupervised classification this was not the case, according to the Agricultural office of Mto wa bu (2016) most significant land cover changes took place before the focus period of this research. The classes which were used for the classification process are:

- Woodland
- Shrub land
- Grassland
- Crop land
- Bare soil
- Urban area
- Water body
- Marsh

These types of land cover have been found present in the lake Manyara catchment by other researchers (Getnet et al., 2014; Deus et al., 2011).

Besides the Landsat images also a literature study was conducted in order to assess the impact of land cover changes on the hydrology dynamics of lake Manyara. Other studies showed that those changes have a minimal impact on the surface area of a lake (Getnet et al., 2014; Günter et al., 2009; Deus et al., 2011). Because of these findings in literature and the time constraint no supervised classification was carried out. Therefore the land use changes in the Manyara catchment will be disregarded as a possible driver of changes in the surface area of lake Manyara during this research.

Climate change

Another possible cause for the shrinkage of Lake Manyara is climate change. Rainfall and temperature are considered to be the proxies to establish whether that is the case. Rainfall may affect the hydrology since it is the only water input to the system. Temperature may affect the hydrology through evapotranspiration both from the lake and from land use (Getnet et al., 2014). According to Deus et al. (2011), evapotranspiration is often the largest component of the water balance in semi-arid areas.

Monthly precipitation data was obtained for the period January 1961-March 2016 from the ecological office of the Tanzanian National Parks (TANAPA) headquarters in Mto wa Mbu. No records of temperature, wind speed or solar radiation were freely available at TANPANA or at the Tanzanian Meteorological Agency (TMA). Therefore, the dataset of the Climate Forecast System Reanalysis (CFSR) from the National Centres for Environmental Prediction (NCEP) was used. This CFSR is developed and used as a global, high resolution, coupled atmosphere-ocean-land surface sea-ice system to provide the best estimate of the state of these coupled areas during a certain period (NCEP, 2010). It has a spatial resolution of 0.5° x 0.5° (Appendix I). This dataset contains daily data of temperature, precipitation, wind, relative humidity and solar radiation during the period 1/1/1979-1/1/2010.

The obtained data were used to analyse possible trends in temperature and precipitation in order to determine whether there is climate change in the lake Manyara catchment and if the possible climate change affects the surface area of the lake.

Irrigation

The third possible cause for the water level decrease of Lake Manyara is the increase of water abstraction for irrigation or other purposes. Using irrigation for agriculture means that the farmer, on average, has two crop cycles per year, of which one falls in the rain season and the other crop cycle falls in the dry season. For the crop cycle in the rain season the irrigation is only used as an additional water source while in the dry season the crop cycle completely depends on irrigation water (Getnet et al., 2014). Fieldwork was conducted during the dry period (January-March 2016) therefore it can be assumed that the measured irrigation abstractions result in a reduced inflow into lake Manyara. During the fieldwork the flow velocity in the irrigation canals was measured in order to determine the volume of water used for irrigation. There were three sites where it was not possible to measure the discharge in the irrigation channels due to inaccessibility or multiple branching. In that case the discharge was measured before the irrigation abstraction point and after the abstraction point. The difference between those values was then used as irrigation water value.

Besides the measurements also 20 informal interviews were conducted with the local farmers in order to gain more knowledge about their irrigation water use and to fill in any possible gaps in the measured data. The questions during the interview mainly focussed on the period when water from lake Manyara is used, for how long and how often they used water from lake Manyara. The farmers were not able to help quantifying the amount of water used for irrigation since they were just using it when needed. Therefore the interviews cannot be used in any calculation.

Surface area lake Manyara

In order to assess the impact of the above listed drivers, the area of lake Manyara was calculated for the period 1973-2016. Landsat 5, 7 and 8 images were used for this purpose. They had a 30m resolution and were taken during different months. The normalized difference water index (NDWI) was used to extract the area of lake Manyara from the satellite images. Water bodies have a high reflectance in the green band and a low reflectance in the near infrared band (NIR) (Rokni et al., 2014). So the equation used to calculate the NDWI is: $\frac{Xgreen-Xnir}{Xgreen+Xnir}$ (1)
For Landsat 8 images band three (green) and five (NIR) were used and for Landsat 5 and 7 band two (green) and four (NIR) were used. The equation results in a raster with values between -1 and 1. The values closest to 1 represent water (McFeeters, 2013). A new raster was created for the values closest to 1 and converted into a vector layer in order to calculate the area of lake Manyara.

SWAT model

The SWAT model was used to calculate the water balance for the catchment of lake Manyara and to model the changes in the hydrology of the past 40 years in lake Manyara. The water balance is the change in water quantity for a specific control volume over time (Dingman, 2002). The CFSR dataset and the globcover land cover map (ESA, 2009) were input data in this model. The CFSR dataset was used to enhance the reliability of the model, the CFSR data comes in the form of atmospheric, oceanic and land surface output products and is available at a 0.5° horizontal resolution, all aivailable conventional and satellite observations were included (Worley and Johns, 2013). The data of TANAPA only uses one weather station, in Mto wa Mbu. The model showed the impact of climate change and the impact of changes in water abstraction for irrigation on the hydrology of lake Manyara.

SWAT is a physically based long-term yield model. The driving force behind all the changes in a hydrological system is the water balance. In order for the model to perform correctly, the hydrologic cycle in the water shed must be equal to the one simulated (Neitsch et al., 2011).

$$SW_t = SW_0 - \sum_{i=1}^{t} = \quad (R_{day} - Q_{surf} - E_a - \omega_{seep} - Q_{gw}) \qquad (2)$$

Where SW_t is the soil water content in mm, SW_0 is the initial soil water content on day i in mm, t is the time in days, R_{day} is the daily precipitation in mm, Q_{surf} is the amount of surface runoff in mm, E_a is the evapotranspiration in mm, ω_{seep} is the amount of water entering the unsaturated zone in mm and consists of the infiltration rate minus the capillary rise, and Q_{gw} is the amount of return flow in mm.

The model divided the water basin into several sub basins (Hydrological Response Units, HRU) in order to model the amount of evapotranspiration for the different land use types and to calculate the runoff separately. Through the division in HRU's the model is also more accurate. After the division in HRU's the model distinguished a land and a water phase. The land phase controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub basin. The water phase consists of the movement of water and sediments through the channel network of the watershed to the outlet (Neitsch et al., 2011). During this study the sediment movement and the nutrient and pesticide loadings were disregarded. Only the amount of water and its movement through the catchment were of importance.

Land phase

The land phase consisted of several inputs: (1) Climate provided the moisture and energy inputs that control the water balance and determine the relative importance of the different components of the hydrological cycle. It depends on the daily precipitation, the max. and min. air temperature, the solar radiation, the wind speed and the relative humidity. (2) Hydrology, here the runoff, infiltration, evapotranspiration and potential paths of the water were calculated. (3) Land cover, a single plant growth model was used to simulate all types of land cover. This research only used these three inputs for the land phase, however there are more inputs which could be used: (4) Erosion, the Modified Universal Soil Loss Equation (MUSLE) used the runoff to calculate erosion and sediment yield. The last two inputs of the land phase were (5) Nutrients, SWAT tracked the movement and transformation of several forms of nitrogen and phosphorus in the water shed. (6) Pesticides, pesticides may be applied to an HRU to study the movement of the chemical in the watershed. SWAT simulates pesticide movement into the stream network via surface runoff and into the soil profile and aquifer by percolation (Neitsch et al., 2011).

Water balance components

As previously mentioned it is of great importance that the water cycle is correctly represented in the model. All the components of the water cycle are part of the land phase of the SWAT model.

SW_0 (Soil water content on day i) was calculated using a separate model for the calculation of lateral subsurface flow. A kinematic storage model, developed by Sloan et al. (1983), was used to predict the lateral flow in each soil layer. The model anticipated on variation in conductivity, slope and soil water content. It calculated the water content using the hillslope, porosity and the saturated thickness.

R_{day} (daily precipitation) was read into the model from an input file of the CFSR database.

Q_{surf} (surface runoff), can be calculated in two different ways in the SWAT model. Either by using the SCS curve number method (USDA soil conservation service, 1972) or by using the Green & Ampt infiltration method (Green and Ampt, 1911). During this research the SCS curve number method was used since it is simple and efficient method to determine the runoff (Schiariti, P.P.E.,). The SCS curve number equation is:

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \tag{3}$$

Where Q_{surf} is the surface runoff in mm, R_{day}, is the daily precipitation and S is the retention parameter in mm. S varies spatially due to changes in soils, land use, management and slope (Neitsch et al., 2011). It is therefore determined by the following equation:

$$S_{max} = 25.4(\frac{1000}{CN} - 10) \tag{4}$$

Where S_{max} is the maximum value the retention parameter can achieve on any given day in mm and CN is the curve number for the day. The initial value of the retention parameter is given by the following equation:

$$S = 0.9 * S_{max} \tag{5}$$

The curve number is a function of the permeability, land use and antecedent water conditions of the soil. The SCS defines three antecedent soil moisture conditions (CN): I – dry (wilting poin), II – average moisture, and III – wet (field capacity). Typical curve numbers for moisture condition II are listed in multiple tables (e.g. Neitsch et al., 2011; Dingman, 1994). These values are appropriate for a 5% slope, in case of a different slope Neitsch et al. (2011) describes how the equation of the curve number needs to be changed.

E_a (evapotranspiration) is defined as the water lost to the atmosphere from the ground surface by evaporation and transpiration by plants (FAO). In the SWAT model the evapotranspiration was calculated using the potential evapotranspiration (PET). The model gives three possibilities to calculate the PET: the Penman-Monteith method, the Hargreaves method or the Priestly-Taylor method. The methods vary in the amount of required inputs, varying from solar radiation, air temperature, relative humidity and wind speed. During this research the Penman-Monteith method was used. The Penman Monteith equation is:

$$\lambda E = \frac{\Delta * (H_{net} - G) + \varphi_{air} * c_p * (e_z^0 - e_z)/r_a}{\Delta + \gamma * (1 + \frac{r_c}{r_a})} \tag{6}$$

Where λE is the latent heat flux density, E is the depth rate evaporation, Δ is the slope of the saturation vapour pressure temperature curve, H_{net} is the net radiation, G is the heat flux density to the ground, ρ_{air} is the air density, c_p is the specific heat at constant pressure, e^0_z is the saturation vapour pressure of air at height z, e_z is the water vapour pressure of air at height z, γ is the psychrometric constant, r_c is the plant canopy resistance and r_a is the diffusion resistance of the air layer. G is always considered to be equal to zero, since the model assumed a daily soil heat flux. The aerodynamic resistance (r_a) was calculated using the following formula:

$$r_a = \frac{ln\left[\frac{z_w - d}{z_{om}}\right] \ln\left[\frac{z_p - d}{z_{ov}}\right]}{k^2 u_z} \tag{7}$$

Where z_w is the height of the wind speed measurement, z_p is the height of the humidity and temperature measurements, d is the zero plane displacement of the wind profile, z_{om} is the roughness length for momentum transfer, z_{ov} is the roughness length for vapour transfer, k is the von Kármán constant and u_z is the wind speed at height z_w. The canopy resistance (r_c) is given by the following equation:

$$r_c = r_l/(0.5 * LAI) \tag{8}$$

Where r_l is the minimum effective stomatal resistance of a single leaf and LAI is the leaf area index of the canopy.

ω_{seep} (water entering the unsaturated zone) was calculated as part of the Q_{gw} (amount of return flow).

The SWAT model makes a distinction between shallow, unconfined aquifer which contributes return flow to streams within the watershed, and deep, confined aquifers which contributes return flow to streams outside the watershed (Arnold et al., 1993). The shallow aquifer water balance consists of recharge entering the aquifer, groundwater flow, the amount of water moving into the soil zone in response to water deficits and the amount of water removed from the aquifer by pumping. The deep water aquifer water balance consists of percolation from the shallow aquifer into the deep aquifer and the amount of water removed from the deep aquifer by pumping.

Water phase

The water phase used the previous calculations to route the water through the network. The routing is separated into two sections, the main channel routing and the routing in the reservoir. Main channel routing consists of water, sediment, nutrients and organic chemicals, and the water balance for reservoirs includes inflow, outflow, rainfall on the surface, evaporation, seepage from the reservoir bottom and diversions (Neitsch et al., 2011). A digital elevation model (DEM), derived from the same Landsat images which were used to calculate the surface area of lake Manyara, was used to route the water and sediment through the catchment.

Model application

The described model was used to relate hydrological responses of lake Manyara to the impact of climate change and water abstraction change. A digital elevation model (DEM) was used to calculate the HRU's. A threshold value for the size of the HRU's was defined during the set up process of the model. For all these unit's meteorological data such as precipitation and temperature were implemented. Only measured irrigation data of the period January-March 2016 was available, obtained during fieldwork (January-March 2016). Therefore the SWAT model estimated the irrigation volumes used in the last 40 years in the lake Manyara catchment. These results were analysed in order to assess whether a trend is present or not.

Calibration and validation

The SWAT model needs calibration in order to optimize the internal parameters and achieve the most representative hydrological model. This can be done either manually or automatically. In this study the model could not be calibrated. Due to a lack of in situ datasets calibration is not possible, since calibration is generally done by comparing simulated data to measured data.

Validation is necessary for an accurate representation of the system. Since calibration is not possible for this research, the validation is important to assess whether the outcomes of the model correspond with the measurements. In this study the validation was done by comparing the size of lake Manyara, derived from the satellite images, to the outcomes of the model regarding the inflow into lake Manyara

Results

Climatological changes

Possible climatological drivers of the fluctuations of Lake Manyara are changes in temperature and precipitation. According to UNEP (2004) the Lake Manyara catchment is very sensitive to small changes in the hydrology since it is a relatively small catchment. The effect of a change in precipitation would quickly be observable in the surface area of lake Manyara. In order to assess whether there is noticeable effect of climate change in the lake Manyara catchment, trends in precipitation and temperature were analysed. The IPCC (2014) states that there has been an increase in temperature of about 1°C in Africa over the past 50 years and an increase in precipitation of 5-10%.

The variability in data from CFSR is less than the variability in the data from TANAPA (figure 4). Sub basin 10 from the SWAT model represents the area with the inflow point into lake Manyara. This sub basin was chosen for a more reliable comparison with the TANAPA dataset, since their weather station is located near the entrance of lake Manyara National Park. When the whole CFSR dataset would be displayed in figure 5 it would give a distorted view and no good comparison could be made. The difference in variability can be due to human errors, at TANAPA the data is collected manually and the rangers are not always as consistent as could be according to the national park ecologist. On the other hand, the CFSR data is a coupled atmosphere-ocean-land surface-sea ice system providing the best possible estimations of in this case precipitation (Worley and Johns, 2013). In both figures there is not a clear trend visible of a decrease or increase in precipitation during the research period. It seems more a reoccurring cycle of dry and wet years. However, the intervals between years with a lower than usual amount of rainfall seem to be getting shorter near the end of the study period.

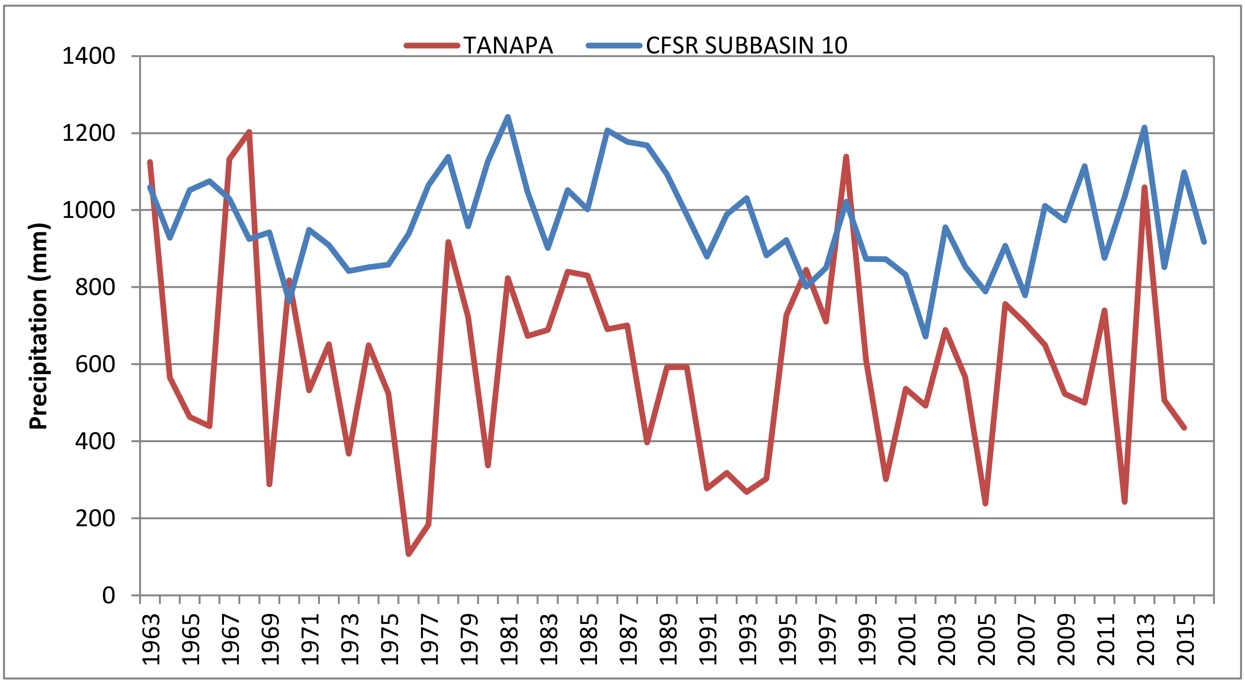

Figure 4: Precipitation dataset of TANAPA vs CFSR dataset of sub basin 10, source: TANAPA (2016) & NCEP (2010).

The long and short rains are of great importance for the agricultural sector. The shares of the short and the long rains in the total amount of precipitation have been made visible in figure 5. During the research period the CFSR dataset shows a slight increase in the share of the long rains in the total annual precipitation. Regarding the short rains a slight decrease is shown. However, there is no smooth trend line visible, it is a rather whimsical line.

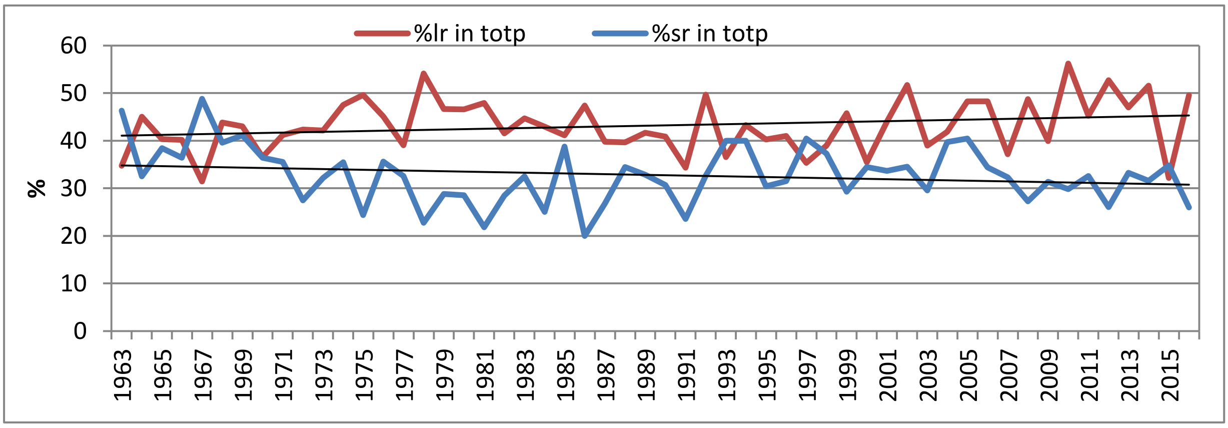

Figure 5: Shares of the long- and short rains in the total amount of precipitation. Source: NCEP (2010).

Another climatological driver can be the temperature. No temperature datasets were available at TANAPA or at the TMA, which only uses the meteo-station in Arusha, therefore the CFSR dataset is the best available option. It uses interpolation between eight different weather stations to estimate the temperature values. As can be seen in figure 6 the average minimum and maximum temperatures more or less stayed the same over a period of 53 years. The actual dataset runs only till 2010, so the last 5 years are an estimation of the model. Each year was analysed separately. There is a great variability between the years but over the entire study period the following trends are visible: during the dry season (June-October) there has been a slight increase in temperature, during the short rain season (November-December) there is a slight decrease in temperature and during the long rains (March-May) the temperature did not change (figure 7). Associated with the increase in temperature in the dry season, is the evapotranspiration which increases as well during the dry season and is affecting the total amount of inflow into lake Manyara.

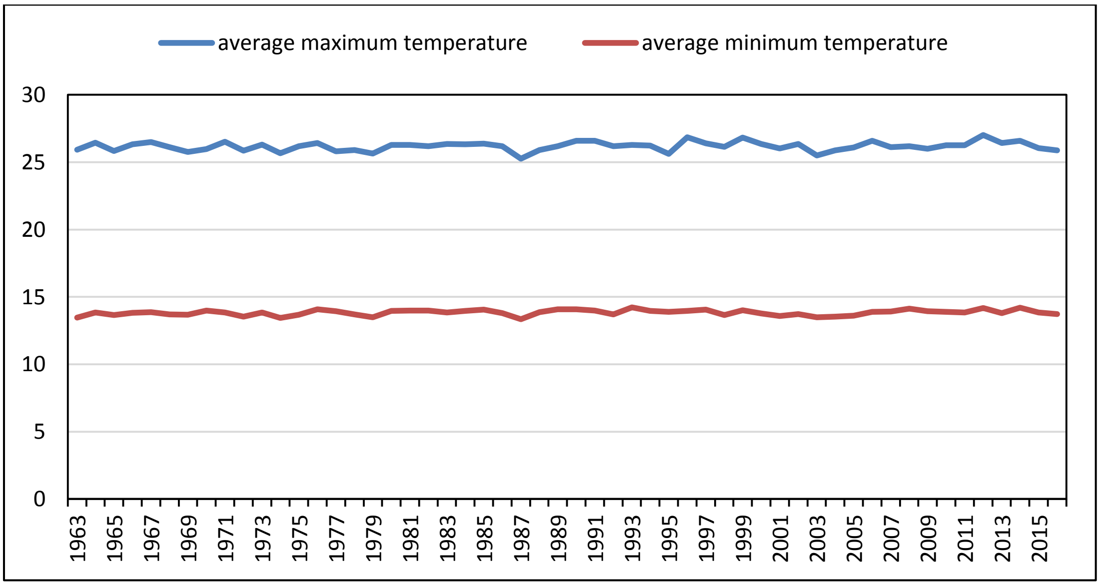

Figure 6: Average minimum and maximum temperature in lake Manyara catchment. Source: NCEP (2010).

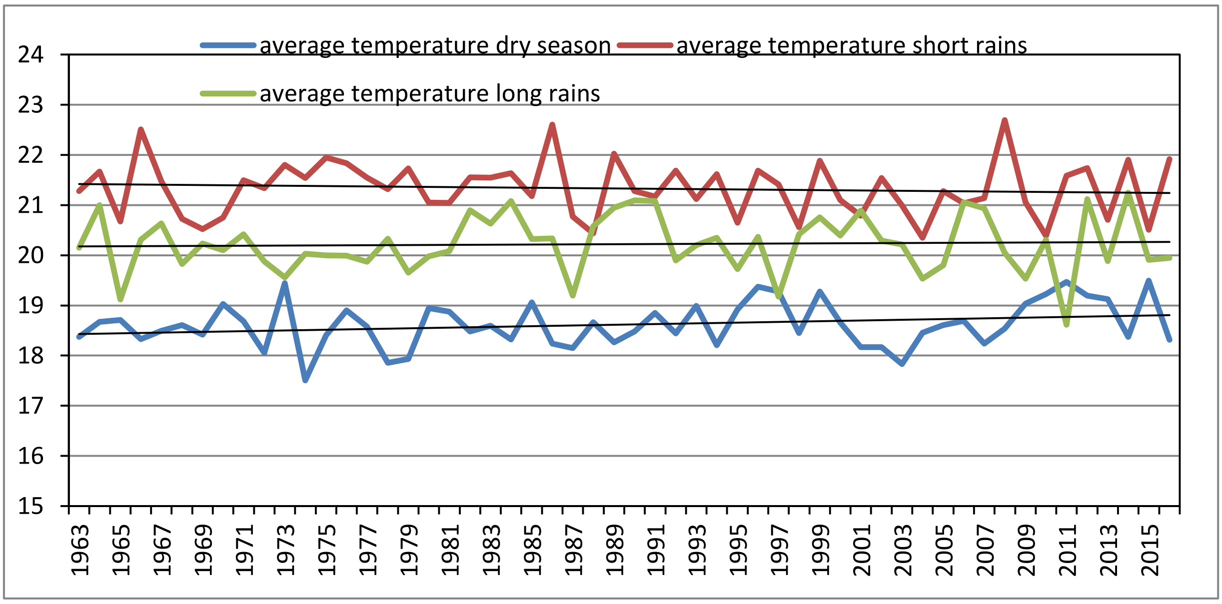

Figure 7: Average temperatures during dry season, short rains and long rains. Source: NCEP (2010).

Irrigation

Each year the population of Tanzania increases with about 2% (Peters, 2014) combined with the seasonal migration due to droughts, this increases the pressure on existing water resources. During the fieldwork in the research area the discharge of three of the main tributaries of Lake Manyara was measured. Both before and after the withdrawal of irrigation water (see appendix II for a map with the measuring points). This was done in order to make an estimation of the share of irrigation water in the total inflow in the lake. It was not possible to determine how much water is used for drinking and washing since there are houses almost along the streams and its branches, resulting in too many measuring points. Figure 8 shows the amount of water used for irrigation over a period of three months. There are no daily datasets of precipitation available, however from field notes it is recorded that the amount of water used for irrigation decreases in case of heavy rainfall, since it is not necessary anymore. This is clearly visible at data point 2/2/2016, the inflow into the lake is higher than the discharge before the irrigation abstraction points. This seems impossible however there is a reasonable explanation for it: due to high surface runoff and the fact that irrigation water was no longer needed since the rain provided enough water for the crops. The result is a higher inflow in the lake than was expected from the measured discharge before irrigation abstraction.

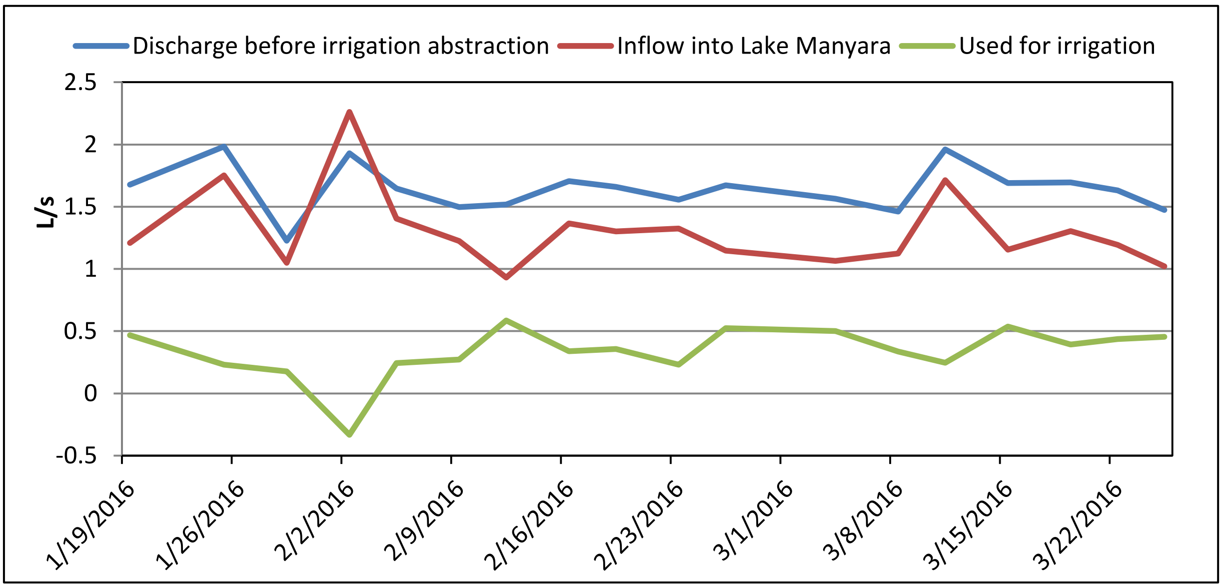

Figure 8: Volumes irrigation water abstraction (l/s). Source: fieldwork (2016).

SWAT modelling

The SWAT model has been developed and has been used to determine whether the short- or long rains, the evapotranspiration, the precipitation or the discharge is a driver of the fluctuations of the surface of Lake Manyara. Input maps for the model were: a digital elevation map, a land cover map, a soil map and a slope map. Figure 9 shows these input maps. The DEM clearly shows the escarpment on the west side of Lake Manyara with one of the highest points around the Ngorongoro crater. The land cover map shows that besides agriculture the main land covers are forest and range, range are semi open fields with shrubs and bushes. The soil map reveals that the dominant soil types are the luviosol (23%) and the andosol (16%). Lastly the slope map shows that Lake Manyara functions as a drain of the entire catchment. The slopes on the east and the west side of the lake are reasonably higher than the slopes surrounding the lake.

In order to analyse the changes in the lake Manyara catchment the SWAT model has been used to calculate the water balance in the catchment. Thornthwaite (1948) and Willmott et al. (1985) expressed the water balance for a catchment as:

$$\frac{dS}{dt} = P - ET - Q \tag{9}$$

Where dS/dt is the change in storage over time, P is the precipitation (mm), ET is the evapotranspiration (mm) and Q is the discharge (l/s). According to Deus et al. (2011) the water balance can be simplified for the lake Manyara catchment, since the changes in storage are neglectable over longer periods. Then the equation is as follows:

$$Q \cong P - ET \tag{10}$$

Using the outputs of the SWAT model in a neutral state, so without any changes in the parameters results in the following water balance for lake Manyara is obtained:

Table 1: Water balance lake Manyara.

	Inflow	Outflow
P (mm)	830.80	
ET (mm)		916.64
Inflow (cms) (Q)	169.41	
Water balance	**83.57**	

The water balance for lake Manyara shows that there is more evapotranspiration than precipitation. Part of the inflow is also evaporating, so only a small part eventually flows into lake Manyara. About 8% of the total inflow ultimately reaches the lake.

The SWAT model was run with and without irrigation water abstractions (figure 10). The results show that the discharge does not change much. Only in dry years the differences between the discharges seem to be getting larger, the farmers then need more irrigation water since there is not enough precipitation to successfully cultivate their crops.

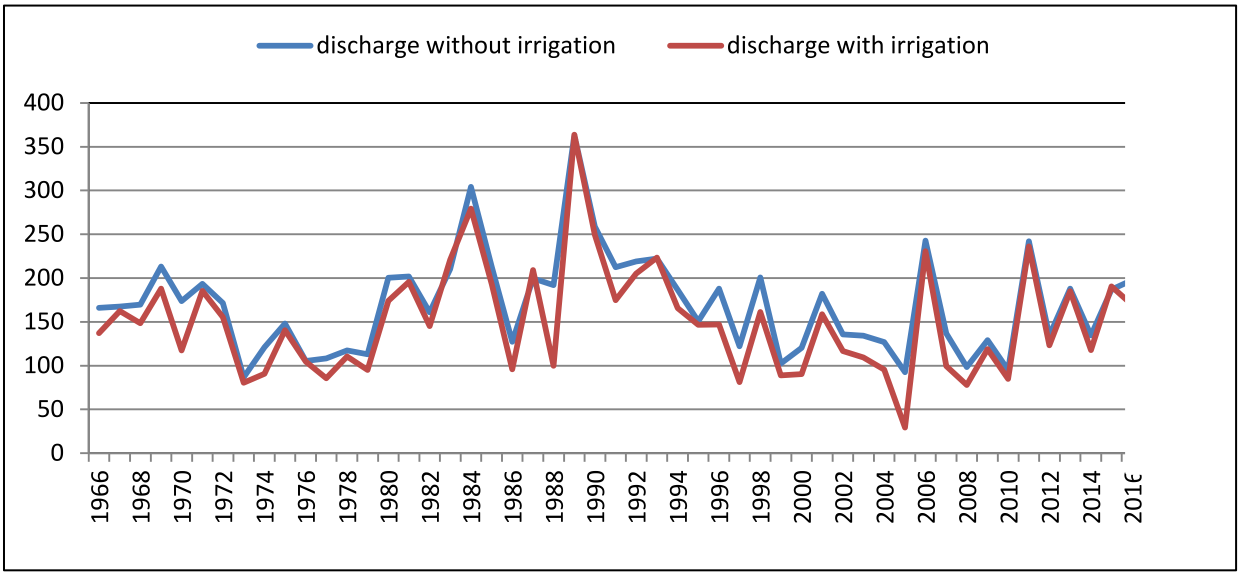

Figure 10: SWAT model outcomes with and without irrigation water abstractions

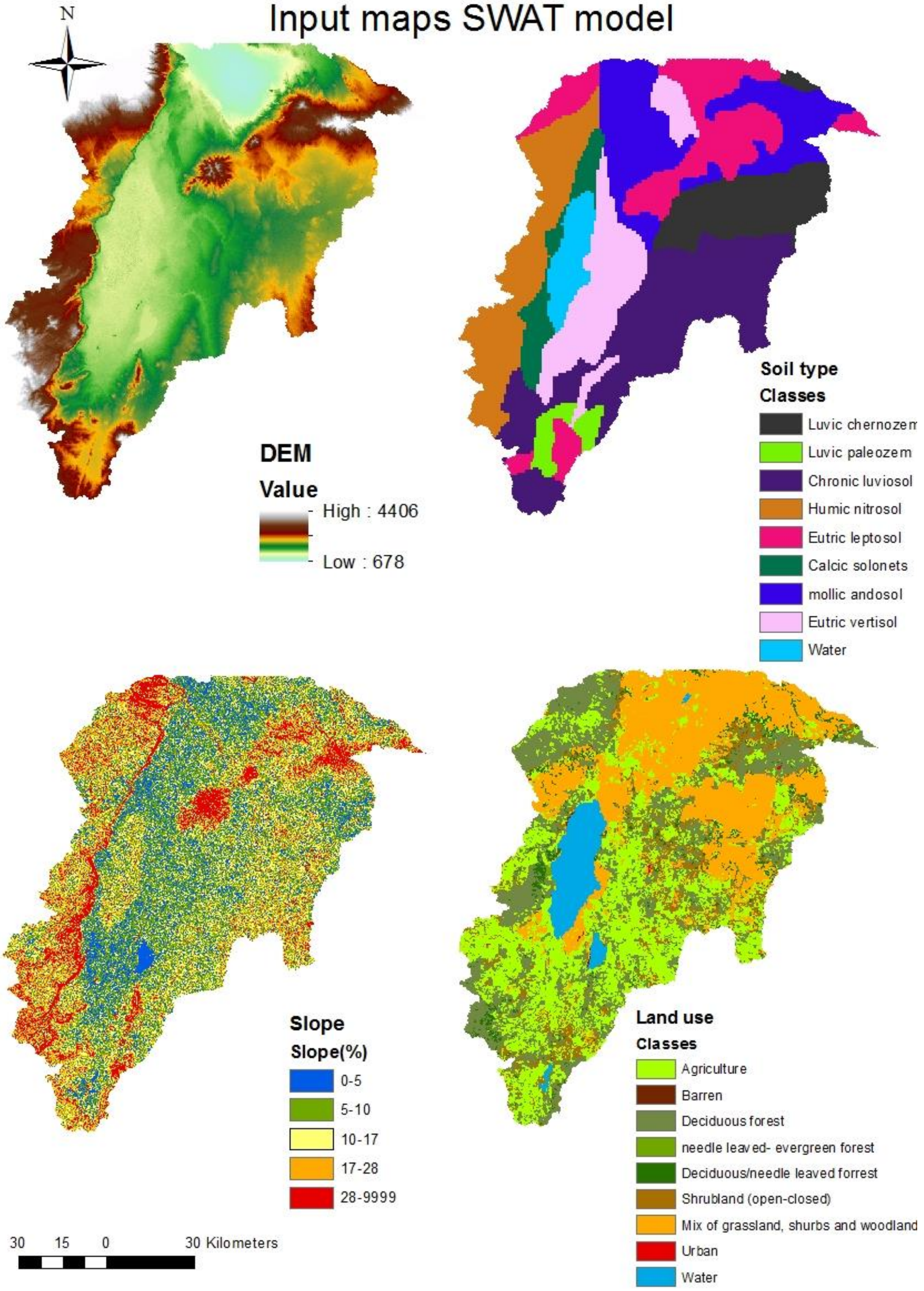

Figure 9: Input maps SWAT-model

The output tables of the model have been compared to the area of the lake for a period of 40 years. In order to assess which driver influences the surface area of lake Manyara the most a multiple regression analysis has been carried out. Possible drivers that were taken into account were: discharge four months prior to the satellite image, long rains, short rains, evapotranspiration, precipitation four months prior to the satellite image, precipitation/yr and discharge/yr. No conclusive answer came from this analysis (see appendix III-V). This can be linked to the sensitivity of the lake to the hydrology. Moreover 25 satellite images have been used for the analysis. These images have been taken during 1973-2015 in different months which probably caused some bias in the data. 50% of the images is from January or February and the other half of the images is from the period June – November. When all the data is taken into the analyses, the short rains, the evapotranspiration and the discharge four months prior to the satellite image are the most important drivers. When the group is split into an A group, containing the data from January/February, and a B group, containing the data of the remaining months, the results are quite different. For the A group all drivers lie pretty close to each other (see appendix V), but the precipitation 4 months prior to the satellite image is the most important one. The long rains are the least important driver for this group. Regarding the B group, the drivers with the most influence on the lake area are: precipitation/yr, the long rains and the precipitation 4 months prior to the satellite image.

Table 2: Important drivers in the fluctuations of the area of Lake Manyara

All		**A**		**B**	
Driver	***P***	***Driver***	***P***	***Driver***	***P***
Short rains	0.09407	Precipitation 4 months prior to satellite image	0.19547	Precipitation/yr	0.14597
Discharge 4 months prior satellite image	0.13975			Precipitation 4 months prior to satellite image	0.17264
Evapotranspiration	0.14918			Long rains	0.18784

Figure 11 shows the correlation between the surface area of Lake Manyara and the short rains. The short rains cannot explain the entire curve for the lake Manyara surface area. For example, in 2001 the lake seems to grow while the short rains decrease. Another example can be seen in 2003 where the lake is shrinking but not with the intensity of the decrease in the short rains. Sometimes the short rains show a more drastic decrease than the surface area of lake Manyara, or the other way around. Data points 1994 and 1995 show a decrease in precipitation of 114 mm to 15 mm (decrease with a factor 7.6), while the surface area of lake Manyara decreases from 345 km^2 to 20 km^2 (decrease with a factor 17.2). The relationship between the short rains and the surface area of Lake Manyara is visualised in figure 12. It shows that the short rains influence the area of Lake Manyara however, it is not always the deciding factor.

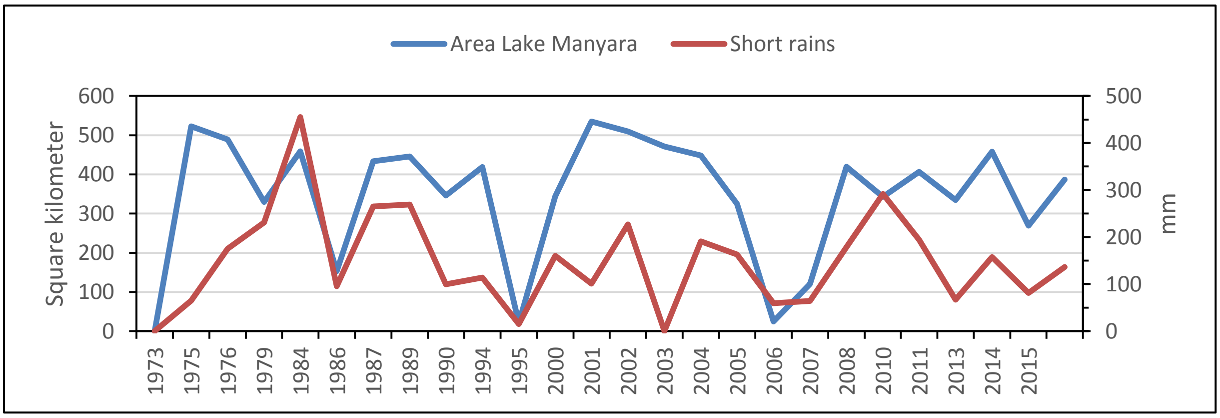

Figure 11: All data points, surface area explained by the short rains rainfall amount.

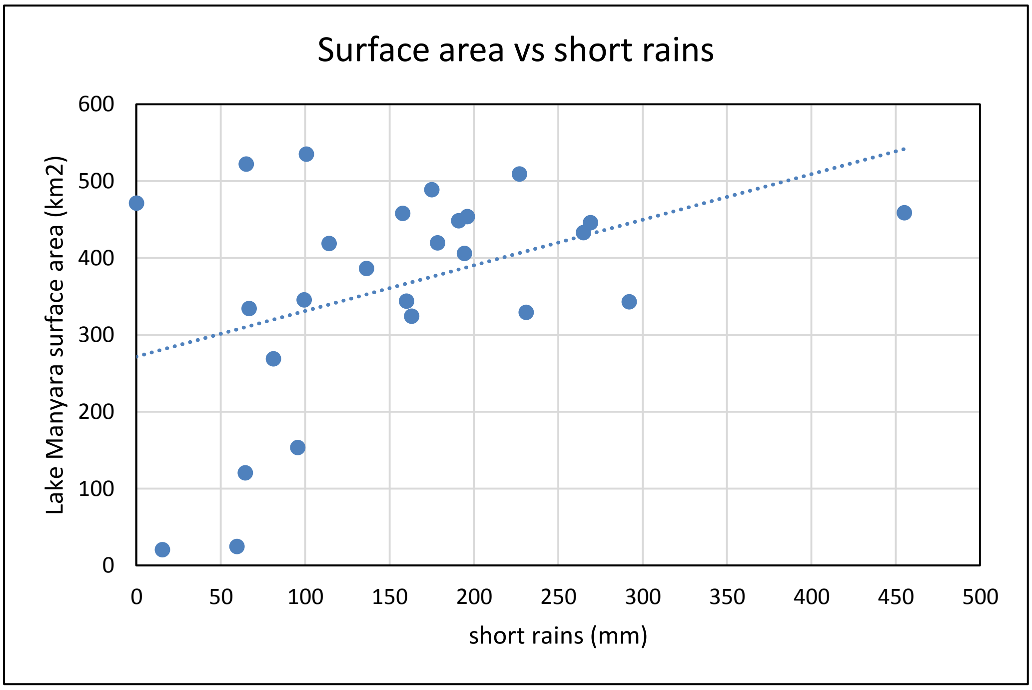

Figure 12: Relationship between Lake Manyara surface area and the short rains rainfall amount.

Regarding the B group, the relationship between the main drivers and the lake Manyara area have been visualized in figure 13. There is quite some dispersion in the data and not one of the drivers determines the lake area indisputable. This, again, supports the assertion of UNEP (2004) regarding the sensitivity of the catchment to different drivers. A possible source of this dispersion are the dates of the satellite images. A part of the images have been taken in the dry period and the other part has been taken during the transition period to the short rain season. The different drivers can also affect each other and can, while not being the determined driver alone, together affect the area of lake Manyara.

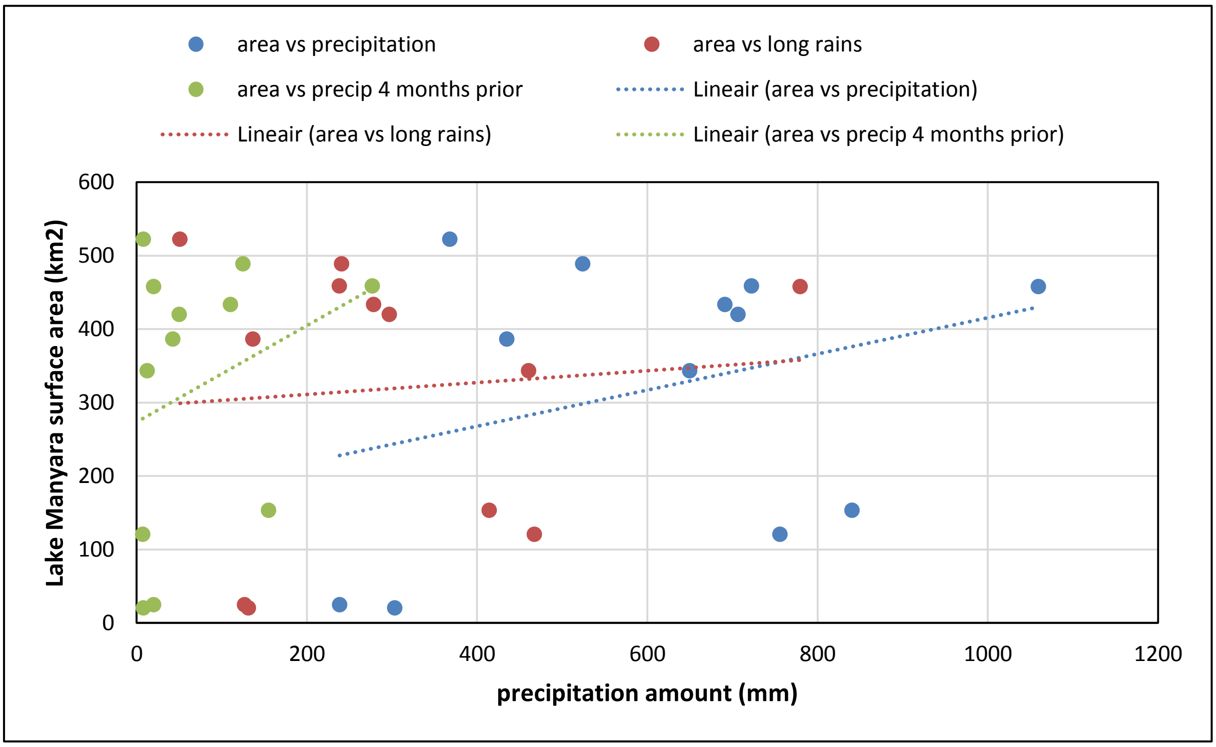

Figure 13: Relationships between the main drivers of group B and the surface area of Lake Manyara.

The relationship between the most important driver of the A group, precipitation four months prior to the satellite image and the area of Lake Manyara has been visualized in figure 14. It shows that in most cases the cummulative precipitation four months in advance determines the size of Lake Manyara. This relationship is also affected by the date at which the satelite images are taken. All images in this group have been taken shortly after the short rain season, which is consequently the most influencial source for changes in area of lake Manyara. The precipitation/yr, discharge/yr and the short rains are together the second most important drivers (Appendix IV).

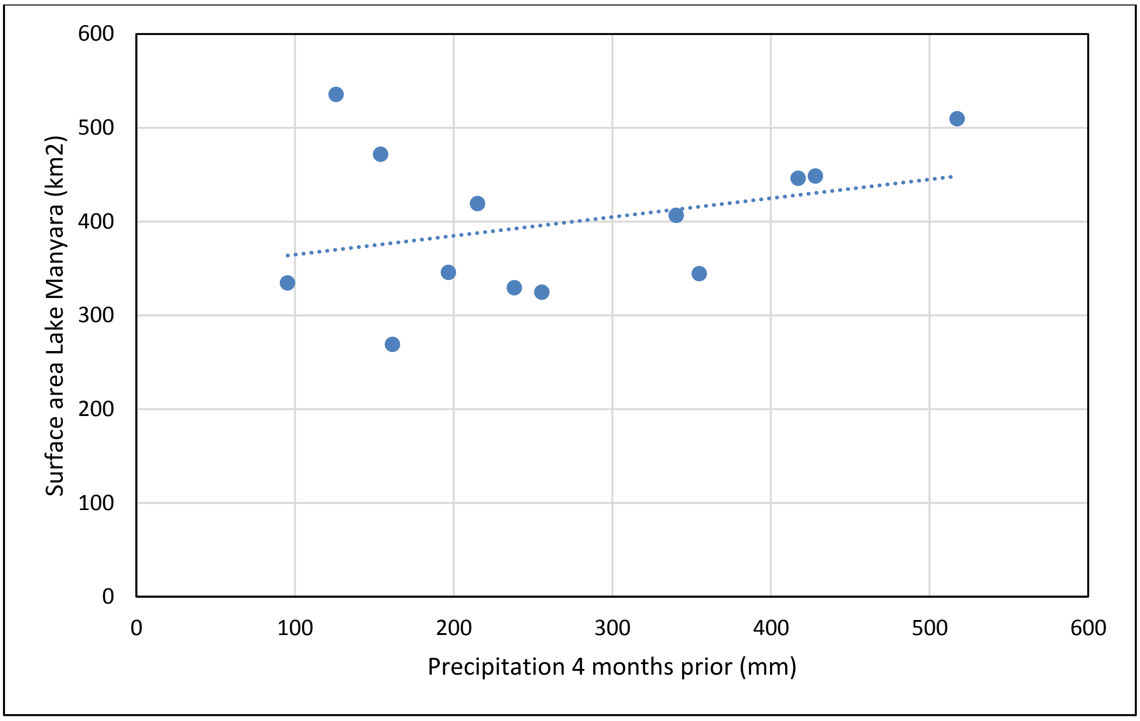

Figure 14: Relationship between the main driver of group A and area of Lake Manyara

As the multi regression analysis above shows, the amounts of irrigation water abstraction do not significantly affect the surface area of lake Manyara. The measured amount of irrigation water which is abstracted is contradictive to the amounts of irrigation water which are abstracted in the model (figure 15). This discrepancy is clearly visible in the period between February and March. The model shows a decrease of irrigation water while the measurements show an increase. From field notes it was observed that on average the month March was relatively dry. The dataset in the model used an average of 101 mm precipitation in March, while the actual precipitation in March 2016 was 48mm at the TANAPA Lake Manyara headquarters (TANAPA, 2016).

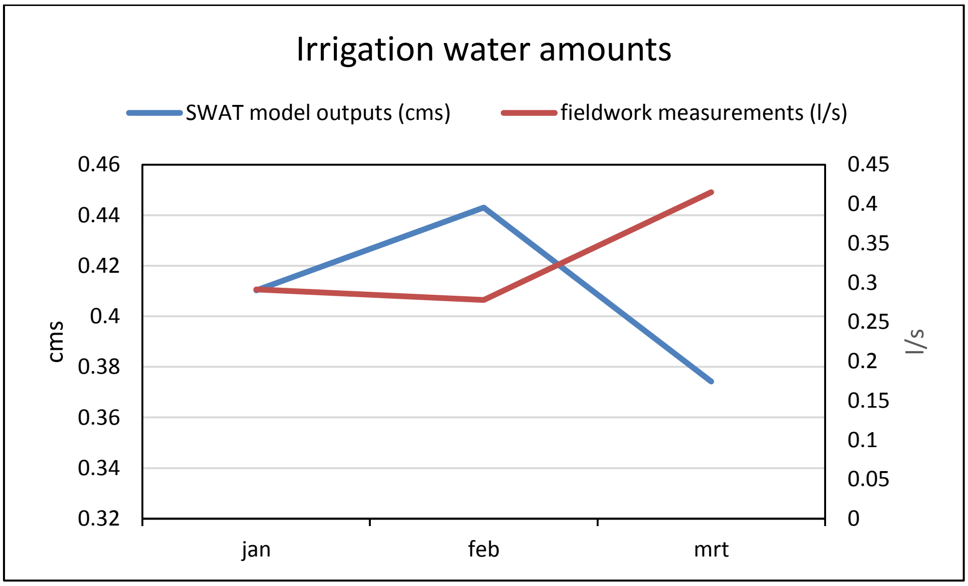

Figure 15: Irrigation water amounts, SWAT model cubic meter per second (CMS) compared to fieldwork measurements (l/s).

El Niño/La Niña

During the research the idea rose that it could also be possible that el Niño/la Nina influences the surface area of Lake Manyara. El Niño and la Niña are opposite phases of the El Niño-Southern Oscillation (ENSO) cycle. This ENSO cycle globally affects weather and climate conditions (NOAA, 2016). El Nino is commonly known as the warm phase. The winds across the tropical pacific are weaker than usual and the oceans temperature is warmer, resulting in more rainfall in the eastern Pacific (NOAA, 2016). For the lake Manyara catchments this usually results in more rainfall during the short rains. La Niña is commonly known as the cold phase. During this phase the winds across the tropical pacific are stronger than usual and the oceans temperature is cooler, resulting in a decrease of rainfall in the eastern Pacific (NOAA, 2016). For the lake Manyara catchment this usually results in less rainfall during the short rains. On average El Niño and La Niña phases last between nine and twelve months. Their occurrence is irregular however, in general they occur every two to seven years.

Figure 16 shows a time series of the changes in the surface area of Lake Manyara. There is no subsequent dataset of the surface area available. Therefore, satellite images have been used to analyse the surface area of Lake Manyara. There are no images available for every year, thereby there sometimes is a gap of several years between the data points. Figure 17 shows in which year an el Niño or la Niña event took place. The el Niño and la Niña effects are not always applicable or visible on the area of Lake Manyara but in some cases it enhances the effects of the other possible drivers. For example, between data points 1994-1995. The surface area of Lake Manyara rapidly increases and as figure 17 shows there is an el Niño phase. An example of la Niña is given by the data points 2010-2011, a decrease of surface area is visible while there is a la Niña event.

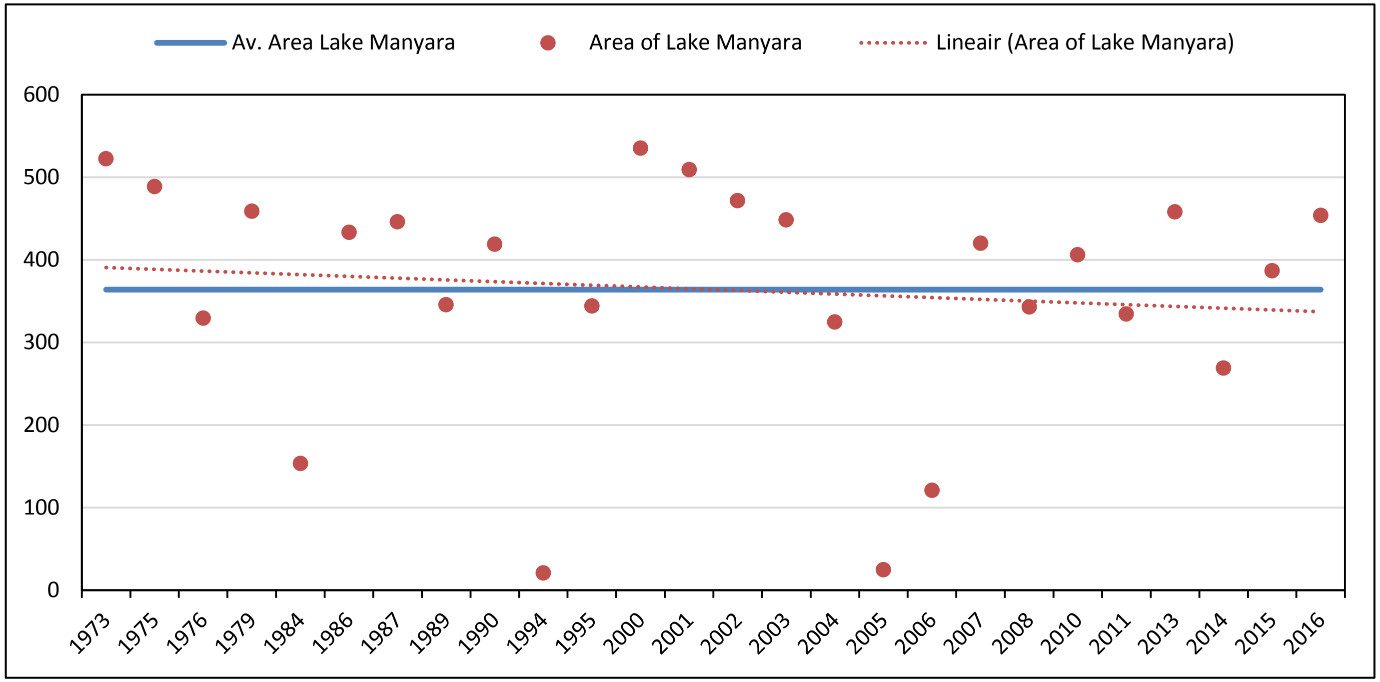

Figure 16: Time series of the surface area of lake Manyara.

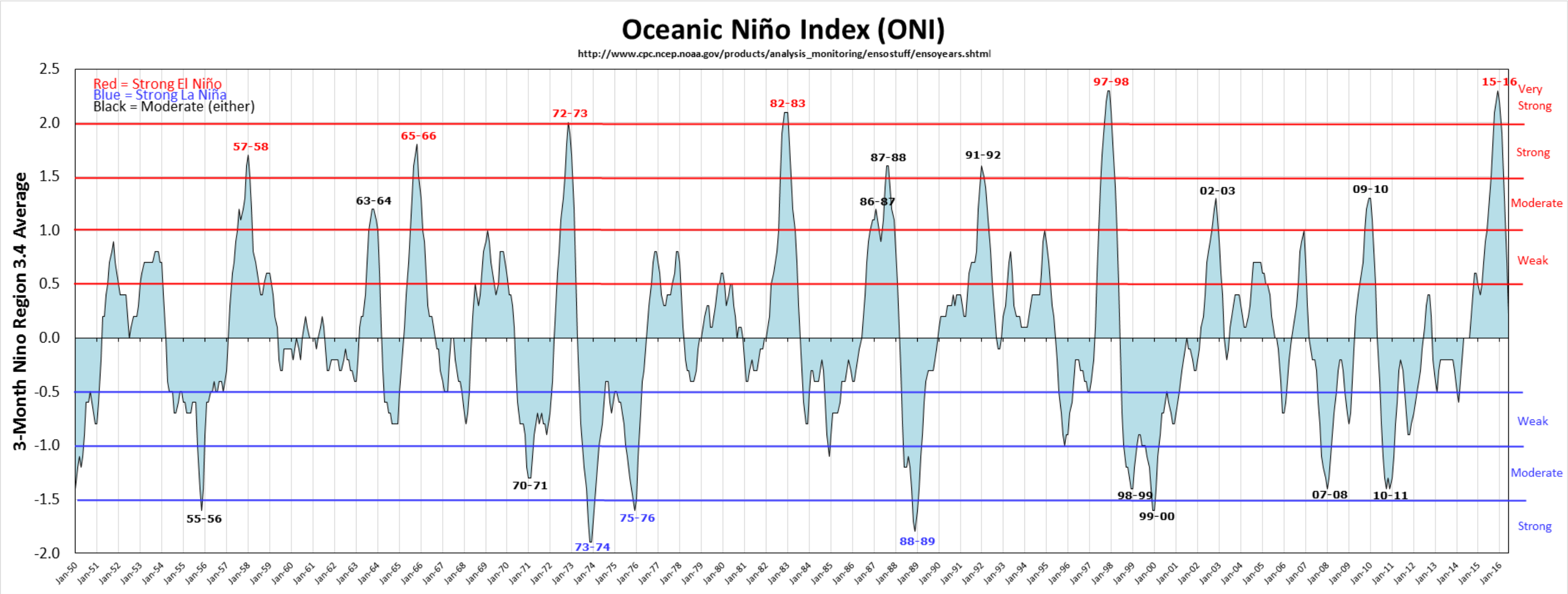

Figure 17: Time series of el Niño and la Niña events, source: Jan Null, CCM (2016).

Discussion & conclusion

Limitation of data and methods

The limitations in the data and the methods used in this research might affect the results. A difficulty concerning the analysis of the surface area of lake Manyara was the lack of a successive time series of Landsat satellite imaginary. This also affected the relationship between possible drivers of surface area changes and the calculated surface area, which was strongly influenced by the moment at which the satellite image was taken. Furthermore there were no datasets available of temperature, evapotranspiration, precipitation or irrigation water abstraction for the entire catchment, thereby several assumptions had to made in order to create a functioning model. Regarding the precipitation TANAPA had a dataset from one location, however to make the SWAT model more reliable the CFSR dataset was used, assuming that its variability and area coverage would improve the modeling results. The difficulty regarding the irrigation water abstraction was the lack of reference material. The measurements during fieldwork could not be compared to an existing dataset.

Effects of climate change, land use and irrigation

The analysis carried during this research provides insight in the changes in the lake Manyara catchment over the past 40 years with expected drivers to be: climate change, land use change and irrigation water abstraction. Climate change has not affected the surface area of lake Manyara significantly. The results showed no clear visible trend, either a decrease or an increase, in precipitation (figure 4). The only thing that stood out are the intervals between years with a lower than average amount of precipitation, they seem to be getting shorter. Regarding the temperature, small changes in trends could only be found when the seasons were analysed separately. The dry season (June-October) showed a slight increase in temperature while the short rain season (November-December) showed a small decrease in temperature and no change could be detected during the long rains season (March –May). These findings did not match with the prior expectations nor literature. According to the IPCC (2014) global warming would increase the temperature and amount of precipitation. Girons (2011) also modelled the impacts of climate change on a lake in the CRV where the predicted increase of precipitation by the IPCC would result in an increase of surface area of lake Manyara. The deviation from the IPCC predictions may be caused by the fact that it was not a prediction only for Tanzania but for eastern Africa, so local variabilities were not taken into account. A critical note regarding the CFSR database has to be made, it was not possible to assess the precipitation variability between the different meteostations due to a the ambiguous listing of the precipitation values.

The initial analysis of Landsat imaginary of the area did not show significant changes in land use changes, supported by literature (Getnet et al., 2014; Günter et al., 2009; Deus et al., 2011) the land use changes were disregarded as a possible driver of changes in surface area of lake Manyara. However, the results of fieldwork partner van den Bergh did show significant changes in land use. This was probably due to the fact he took the entire Monduli district into account in contrast to the relatively small catchment area of lake Manyara. Unfortunately there is no Landsat satellite imaginary available before 1970 and according to the local agricultural office (2016) the main changes in land use and population increase took previously place. Therefore it cannot be determined to which extend land use changes can affect the surface area of lake Manyara.

Before the fieldwork was conducted it was thought that the amounts of irrigation water which were abstracted would play a large role in the changes of surface area of lake Manyara. It was thought that the abstracted amounts would be getting larger over time, resulting in an eventually disappearance of lake Manyara. The results do show a small decrease in average surface area of about 40 km^2 during the research period (figure 16). However this is strongly related to the moment at which the satellite image, which has been used for the surface area analysis, was taken. An image taken during the dry season would give a completely different result than an image taken after a rain season. The amounts of irrigation water measured during fieldwork and calculated by the SWAT model are so little that it does not affect the surface area of lake Manyara significantly. The model was run with and without irrigation water abstractions and the differences were negligible (figure 10). The results show a strong relation between the precipitation and the amount of irrigation water used. In case of heavy rainfall, the irrigation water amount drops. It is then considered as an additional water source. According to Machibya (2003), the efficiency drops when water is abundant, this is supported by observations during the fieldwork. In case of heavy rainfall events the farmers allow their fields to get flooded and try to divert as much water as possible into larger streams. There is no storage capacity. The results from the SWAT model however, do not show such quick adaptations. The amount of water used for irrigation in the model is very small compared to the measurements. This discrepancy is probably due to the fact that there are a lot of uncertainties in the model, especially concerning the precipitation where it does not work with real-time data. Plus, a lot of assumptions have been made in order to get the model working. On the other hand, the difference between the model outcomes and the measurements can also be explained by the fact that it was not possible to measure the discharge in all the tributaries of lake Manyara.

The results of the multiple regression model showed that there were other possible drivers which could affect the surface area of lake Manyara. The importance of these drivers was assessed using the outcomes of the SWAT-model. The results of this analysis are not conclusive. It strongly depends on how the data is organised whether the short rains, the long rains, the discharge or the evapotranspiration is the main driver behind the area changes of lake Manyara. The fact that there is not a single significant driver supports the claim of UNEP (2004) that the catchment is very sensitive to local changes in hydrology. The results of this analysis would have been better when the model was calibrated. Due to a lack of in situ datasets this was not possible.

Conclusion

In order to answer the question what the main driver is behind the changes in surface area of lake Manyara the results of this research has been studied. The following can be concluded:

- Over the past 40 years there have been no significant climatological or land use changes. Therefore, it is assumed that the changes in surface area of Lake Manyara are sensitive to local hydrological changes.
- There are several main drivers that influence the surface area of Lake Manyara. The long rains, short rains, precipitation four months prior the satellite image and the yearly precipitation are all important. The level of importance strongly depends on the date of the satellite image what is used for the analysis. The event prior to the date of the satellite image is of greatest importance.
- There is no reason to believe that Lake Manyara is disappearing. The shrinkage and expanding of the lake has a more cyclic nature. They do not occur on a regular base and the intervals between a small and a large lake appear to be getting longer (figure 13).

Recommendations

The results may not always have been as conclusive as was hoped for, however they give a good impression of the main drivers behind the changes in surface area of Lake Manyara. It is recommended to assess the influence of sediment on the local hydrology and the surface area of lake Manyara. With focus on the aspects how it moves through the catchment and if all the sediment reaches the lake. Moreover a more thorough study regarding the effect el Niño/la Niña have on the changes of the surface area of lake Manyara should be conducted, since this could lead to more understanding of the local hydrology and the potential impact they have regarding the food security.

Literature

Articles

Adams, W.M., Potkanski, T. and Sutton, J.E.G. (1994) *Indigenous farmer-managed irrigation in Sonjo, Tanzania*. The geographical journal 160, 17-32.

Andermann, C., Bonnet, S. and Gloaguen, R. (2011) *Evaluation of precipitation data sets along the Himalayan front.* Geochemistry Geophysics Geosystems 12, nr 7.

Agricultural office Mto wa Mbu (2016). *Several documents concerning irrigation in the Mto wa Mbu area.*

Arnold, J.G., Allen, P.M. and Bernhardt, G. (1993) *A comprehensive surface groundwater flow model.* Journal of Hydrology 142, 47-69.

Ayenew, T. (2003) *Evapotranspiration estimation using thematic mapper spectral satellite data in the Ethiopian rift and adjacent highlands.* Journal of hydrology 279, 83-93.

Bachofe, F., Quénéhervé and Märker, M. (2014) *The delineation of Paleo-shorelines in the lake Manyara basin using TerraSAR-X data.* Remote sensing 6, 2195-2212.

Burton, M.A., (1990) *Technical cooperation programme: institutional support for irrigation development in Tanzania.* A report prepared for the government of Tanzania and the food and agriculture organisation of the UN.

Casanova, J. and Hillaire-Marcel, C. (1992) *Chronology and Paleo-hydrology of late Quaternary High Lake levels in the Manyara basin (Tanzania) from isotopic data on fossil stromatolites.* Quaternary research 38, 205-226.

Deus, D. and Gloaige, R. (2013) *Remote Sensing analysis of lake dynamics in semi-arid regions: implication for water resource management. Lake Manyara, East African Rift, Northern Tanzania.* Water 5(2), 698-727.

Deus, D.; Gloaguen, R.; Krause, P. (2013) *Water balance modelling in a semi-arid environment with limited in situ data using remote sensing in Lake Manyara, East African Rift, Tanzania*. Remote Sensing 5, 1651–1680.

Dingman, S.L. (1994) *Physical hydrology.* Prentice-Hall inc., Englewood Cliffs, NJ

Dixit, P.C. Pleistocene lacustrine ridged oncolites from the Lake Manyara area, Tanzania, East Africa. Sediment. Geol. 1984, 39, 53–62.

Ebinger CJ, Poudjom Y, Mbede E, Foster F, Dawson JB (1997*) Rifting Archean lithosphere: The Eyasi Manyara Natron rifts, East Africa.* Geol Soc London Special Publications 154, pp 947–960.

European Space Agency (ESA) (2009) *Globcover-land cover maps.*

Food and agriculture organisation of the united nations (FAO). *Guidelines for computing crop water requirements.* Ch 1.

Ficklin, D.L., Luo, Y., Luedelin, E. and Zhang, M (2009) *Climate change sensitivity assessment of a highly agricultural watershed using SWAT.* Journal of hydrology 374, 16-29

Fitzpatrick, M., Butler, S., Ham, A. and Hardy, P. (2015) *Lonely planet of Tanzania*. 175-179

Getnet, M., Hengsdijk, H. and Ittersum, van M. (2014) *Disentangling the impacts of climate change, land use change and irrigation on the Central Rift Valley water system of Ethiopia.* Agricultural water management 137, 104-115.

Girons Lopez, M. *Modelling climatic and hydrological variability in Lake Babati, Northern Tanzania.* MSc thesis Physical geography and quaternary geology, 2011.

Green, W.H., Ampt, G.A.,(1911). *Studies on soil physics, 1. The flow of air and water through soils*. Journal of Agricultural Sciences, 4,. 11-24.

Herder, C. (2013) *Impacts of land use changes on the hydrology of Wondo Genet catchment in Ethiopia.* MSc thesis, Utrecht University.

Igbadun, H.E. and Salim, B.A. (2014) *Simulation study of yield and soil water balance responses of a maize crop to farmers irrigation scheduling practices in Tanzania.* Irrigation and systems engineering 3:1.

IPCC, (2014): Summary for Policymakers. In: Climate Change 2014: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Keller, C.M.; Hansen, C.; Alexander, C.S. Archaeology and paleo-environments in the Manyara and Engaruka Basins, Northern Tanzania. Geogr. Rev. 1975, 65, 364–376.

Lankford, B.A. (2004) *Resource-centred thinking in river basins: should we revoke the crop water requirement approach to irrigation planning?* Agricultural water management 68, 33-46.

Legesse, D., vallet-Coulomb, C. and Gasse, F. (2003) *Hydrological response of a catchment to A climate and land use changes in tropical Africa: case study South Central Ethiopia.* Journal of Hydrology 275, 67-85.

Machibya, M., (2003*) Challenging established concepts of irrigation efficiency in a water scarce river basin: a case study of the Usangu basin, Tanzania*. PhD Thesis. University of East Anglia, Norwich.

Maerker, M., Quénéhervé, G., Badhofer, F. and Mori, S. (2015) *A simple DEM assessment procedure for gully system analysis in the Lake Manyara area, northern Tanzania*. Natural hazards 79, 235-253.

Maslin, M.A., Brierly, C.M., Milner, A.M., Schultz, S., Trauth, M.H. and Wilson, K.E. (2014) *East African climate pulses and early human evolution.* Quaternary science reviews 101, 1-17.

McFeeters, S.K. (2013) *Using the normalized difference water index (NDWI) within a geographic information system to detect swimming pools for mosquito abatement:a practical approach.* Remote sensing 5, 3544-3561.

Ministry of agriculture, food security and cooperatives (2006). *A draft masterplan for improvement of irrigation schemes in Mto wa Mbu valley- Mondulli district, Arusha region.*

Nejadhashemi, A.P., Wardynski, J., Munoz, J.D., 2011. Evaluating the impacts of land use changes on hydrological responses in the agricultural regions of Michigan and Wisconsin. Hydrology and Earth System Sciences Discussions, 8, pp. 3421-3468.

Ngana, J.O., Mwalyosi, R.B.B., Yanda, P. and Madulu, N.F. (2004) *Strategic development plan for integrated water resources management in Lake Manyara sub-basin, North-Eastern Tanzania.* Physics and chemistry 29, 1219-1224.

Nonga, H.E., Mdegela, R.H., Lie, E., Sandvik, M. And Skaare, J.U. (2011) *Assessment of farming practices and uses of agrochemicals in lake Manyara basin, Tanzania.* African journal of agricultural research 6, 2216-2230.

Paudyal, D.N., (1990) *Socio-economic and labour supply assessment survey in Namtumbo.*

Ring, U.; Schwartz, H.L.; Bromage, T.G.; Sanaane, C. (2005) *Kinematic and sedimentological evolution of the Manyara Rift in northern Tanzania, East Africa*. Geological Magazine 142, 355–368.

Rokni, K., Ahmad, A., Selamat, A. and Hazini, S. (2014) *Water feature extraction and change detection using multitemporal landsat imagery.* Remote sensing 6, 4173-4189.

Schiarti, P.E.E. *Basic hydrology runoff curve numbers*. Mercer county soil conservation district

Schwartz, H., Renne, P.R., Morgan, L.E., Wildgoose, M.M., Lippert, P.C., Frost, S.R., Harvati, K., Schrenk, F. and Saanane, C. (2012) *Geochronology of the Manyara beds, northern Tanzania: New tephropstratigraphy, magnetostratigraphy and 40Ar/39Ar ages.* Quaternary Geochronology 7, 48-66.

Sechambo, F. (2001) *Land use by people living around protected areas: The case of Lake Manyara national park.* UTAFITI special issue 4, 105-116.

Sloan, P.G., Moore, I.D., Coltharp, G.B., Eigel, J.D., 1983. *Modelling surface and subsurface stormflow on steeply-sloping forested watershed*s. Water Resources Institutional Report, 142, University of Kentucky, Lexington.

Thornthwaite, C. (1948) *An approach toward a rational classification of climate*, Geogr. Rev., 38, 55–94..

Vogelmann, J. E., Howard, S. M., Yang, L., Larson, C. R., Wylie, B. K., & Van Driel, N. (2001). *Completion of the 1990s National Land Cover Data Set for the conterminous United States from Landsat Thematic Mapper data and ancillary data sources*. Photogrammetric Engineering and Remote Sensing, 67(6). ISO 690

Uhlig, C.; Jaeger, F. Die Ostafrikanische Bruchstufe und die angrenzenden Gebiete zwischen den Seen Magad und Lawa ja Mweri sowie dem Westfuß des Meru; Mittler: Leipzig, Germany, 1909; p. 63.

UNEP, 2004. East African Rift Valley Lakes. University of Kalmar, Kalmar, Sweden.

USDA Soil Conservation Service, (1972). *National Engineering Handbook* Section 4 Hydrology, Chapters 4-10.

Willmott, C. J., Rowe, C. M., and Mintz, Y.(1985) *Climatology of the terrestrial seasonal water cycle*, Int. J. Climatol., 5, 589–606.

Williams, J.R., (1975) *Sediment-yield prediction with universal equation using runoff energy factor. Present and prospective technology for predicting sediment yield and sources: Proceedings of the sediment yield workshop*, Oxford, Great-Britain.

Yanda, P.Z. and Madulu, N.F. (2005) *Water resource management and biodiversity conservation in the Eastern Rift Valley Lakes, Northern Tanzania.* Physics and Chemistry of the Earth 30, 717-725.

Websites

National Oceanic and Atmospheric Administration (NOAA) (18/01/2016). *El Niño and La Niña: frequently asked questions.* Accessed on 25/08/2016 <https://www.climate.gov/news-features/understanding-climate/el-ni%C3%B1o-and-la-ni%C3%B1a-frequently-asked-questions>

National Oceanic and Atmospheric Administration (NOAA) (28/06/2016). *What are el Niño and la Nina?* Accessed on 25/08/2016 <http://oceanservice.noaa.gov/facts/ninonina.html>

Null, J. (2016) *El Niño and La Niña years and intensities.* Accessed on 25/08/2016) <http://ggweather.com/enso/oni.htm>

Worley, W. and Johns, E. (2013) *NCEP Climate Forecast System Reanalysis (CFSR).* Accessed on 25/08/2016 < (http://rda.ucar.edu/pub/cfsr.html>

Appendix I: CFSR meteostations

Appendix II: Measuring points

Appendix III: Multiple regression analysis - All data points

SUMMARY OUTPUT

Regression statistics	
R	0.589966
R^2	0.34806
Adjusted R^2	0.130747
Standard error	134.2673
Observations	25

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	6	173244.8	28874.13	1.601652	0.203901
Residual	18	324498.9	18027.72		
Total	24	497743.7			

	Coefficients	*Standard error*	*T Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	1639.363	907.138	1.807182	0.087478	-266.463	3545.19
precip/yr	0.105573	0.155195	0.680257	0.504998	-0.22048	0.431626
discharge/yr	0.559141	0.849436	0.65825	0.518709	-1.22546	2.343739
precipitation 4 months prior	0.142039	0.244139	0.581795	0.567921	-0.37088	0.654955
discharge 4 months prior	1.072882	1.112604	0.964298	0.347674	-1.26461	3.410377
short rains	0.527485	0.341212	1.545917	0.139525	-0.18937	1.244344
ET	-1568.3	1016.155	-1.54336	0.140141	-3703.16	566.5658

Appendix IV: Multiple regression analysis – A group

SUMMARY OUTPUT

Regression statistics	
Multiple R	0.598095
R^2	0.357717
Adjusted R^2	-0.10106
Standard error	84.83005
observations	13

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	5	28055.07	5611.015	0.779726	0.59443
Residuals	7	50372.96	7196.137		
Total	12	78428.03			

	Coefficients	*Standard error*	*t Stat*	*P/value*	*Lower 95%*	*Upper 95%*
Intercept	485.6483	125.8556	3.858774	0.006221	188.0471	783.2494
precip/yr	-0.29426	0.222106	-1.32487	0.226824	-0.81946	0.230935
discharge/yr	0.481252	0.650394	0.739939	0.483409	-1.05669	2.01919
precip 4 months prior	0.570064	0.398312	1.431198	0.195465	-0.3718	1.511923
short rains	-0.92725	0.668603	-1.38685	0.208044	-2.50825	0.653742
long rains	-0.0844	0.162493	-0.51938	0.619509	-0.46863	0.29984

Appendix V: Mutiple regression – B group

SUMMARY OUTPUT

Regression statistics	
Multiple R	0.739279
R^2	0.546534
Adjusted R^2	0.168645
Standard error	169.4456
Observations	12

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	5	207626.8	41525.35	1.446282	0.33018
Residuals	6	172270.8	28711.8		
Total	11	379897.6			

	Coefficients	*Standard error*	*t-Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	628.593	1265.914	0.496553	0.63717	-2468.99	3726.173
precip/yr	1.191017	0.707656	1.683046	0.143355	-0.54055	2.922589
precip 4 months prior	-1.6063	1.123906	-1.42921	0.202875	-4.3564	1.143797
short rains	1.169011	0.631403	1.851452	0.113561	-0.37598	2.713998
long rains	-1.27926	0.788461	-1.62248	0.155826	-3.20856	0.65003
ET	-715.028	1336.426	-0.53503	0.611867	-3985.15	2555.089