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Analysis of the potential overflow of Lake Bogoria towards Lake Baringo, Kenya

submitted by

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Affidavit

I hereby declare that I have authored this master thesis independently, and that I have not used any assistance other than that which is permitted. The work contained herein is my own except where explicitly stated otherwise. All ideas taken in wording or in basic content from unpublished sources or from published literature are duly identified and cited, and the precise references included.

I further declare that this master thesis has not been submitted, in whole or in part, in the same or a similar form, to any other educational institution as part of the requirements for an academic degree.

I hereby confirm that I am familiar with the standards of Scientific Integrity and with the guidelines of Good Scientific Practice, and that this work fully complies with these standards and guidelines.

Vienna, 11.05.2023 Pierre KRAY *(manu propria)*

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Table of Abbreviations

AET .... Actual evapotranspiration

BoBa .... Bogoria-Baringo

CHIRPS .... Climate Hazard group Infrared Precipitation with Station

DAHITI .... Database of Hydrological Time Series of Inland Waters

DEM .... *Digital Elevation Model*

DGFI-TUM .... Deutsches Geodätisches Forschungsinstitut at the Technische Universität München

ENSO .... Pacific El Niño-Southern-Oscillation

ERA5L ERA5-Land

GAC .... German Aerospace Center

GIS .... Geographical Information System

GOK .... Government of Kenya

ICR .... Integrated Catchment Response

IOD .... Indian Ocean Dipole

ITCZ .... Inter-Tropical Convergence Zone

LULCC .... Land use and land cover changes

Q_{gw} .... Underground flow from watersheds or groundwater

Q_{out} .... Runoff from lake or outflow through seepage fluxes

R.. .... Catchment rainfall

S... .... Storage of the lake

SRTM .... Shuttle Radar Topography Mission

SST .... Sea Surface Temperature

TanDEM-X .... TerraSAR-X add-on for Digital Elevation Measurements

UNDP .... United Nation Development Programme

WGS84 .... World Geodetic System 1984

Abstract

The Great Rift Valley Lakes in Kenya have experienced significant water level increases in the past decade, with major social and ecological implications. There is a concern that a potential cross-contamination between the alkaline Lake Bogoria and freshwater Lake Baringo, could worsen these problems. Experts have debated on the potential causes of the rising water levels, pointing out geologic, hydro-climatic and anthropogenic influences.

This study aims to investigate the influence of increased rainfall in the study area on lake levels and the potential cross-contamination between the lakes. Satellite-based elevation, rainfall and lake surface data, as well as long-term hydrometeorological analysis, are used as data basis. This allows to asses needed rainfall changes to achieve an overflow of Lake Bogoria, which is an important threshold for the eventual merge of the study lakes.

According to the results, a 7% increase in rainfall over a ten-year period, compared to the reference data from 2010-2020, is sufficient for Lake Bogoria to overflow. During the time period 1984-2020, the rainfall trend caused several hydrological years to accumulate enough rainfall to create a sustained flow between Lake Bogoria and Lake Baringo. These findings demonstrate how hydrological changes are sufficient to explain the water level rises and how even small rainfall deviations in the lake catchment can have big impacts on the ecosystem.

While underground permeability changes and land use and land cover changes (LULCC) may also contribute to the overall phenomena, the results suggest that they are not the primary drivers of the lake level rises. This study highlights the influences of the hydro-climatic changes on an endorheic water body, while also underlining the necessity of developing mitigation strategies to minimize potential upcoming damages.

Kurzfassung

Im letzten Jahrzehnt ist der Wasserspiegel der Afrikanischen Grabenbuch-Seen in Kenia signifikant angestiegen. Dies hat soziale und ökologische Probleme verursacht. Experten haben sich mit der Thematik befasst und geologische, hydroklimatische und anthropogene Einflüsse als potenzielle Ursachen identifiziert. Es besteht die Sorge, dass eine mögliche Kreuzkontamination zwischen dem alkalischen See Bogoria und dem Süßwassersee Baringo die Situation verschlimmern könnte.

Das Ziel dieser Masterarbeit ist es, den Einfluss erhöhter Niederschläge im Untersuchungsgebiet auf den Wasserstand der Seen und die mögliche Kreuzkontamination zwischen ihnen zu untersuchen. Als Datengrundlagen dienen satellitengestützte Höhen-, Niederschlags und Seenoberflächendaten sowie hydrometeorologische Langzeitanalysen. Dies ermöglicht es die notwendigen Niederschlagsänderungen zu ermitteln, um den Bogoria-See zum Überlaufen zu bringen, welches eine bedeutende Schwelle für das mögliche Vermischen des Bogoria- und Baringo-Sees darstellen würde.

Die Ergebnisse zeigen, dass ein Anstieg der Niederschläge um 7% über einen Zeitraum von zehn Jahren gegenüber den Referenzdaten von 2010-2020 ausreicht, um den Überlauf des Bogoria-Sees zu erreichen. Während dem Zeitraum 1984-2020 hat der Niederschlagstrend dazu geführt, dass viele hydrologische Jahre ausreichend Niederschlag akkumuliert haben, um einen fortwährenden Wasserlauf zwischen dem Bogoria-See und Baringo-See zu schaffen. Dies demonstriert, dass hydroklimatische Einflüsse ausreichend sind um die Wasseranstiege zu erklären und wie kleine hydrologische Veränderung im Einzugsgebiet große Auswirkungen auf das Ökosystem haben können.

Obwohl Veränderungen in der unterirdischen Permeabilität und der Landnutzung auch eine Rolle spielen können, deuten die Ergebnisse darauf hin, dass sie nicht die Hauptursachen für den Anstieg der Seespiegel sind. Die Studie beleuchtet die Einflüsse der hydro-klimatischen Veränderungen auf einen endorheischen Wasserkörper und betont die Notwendigkeit, Minderungsstrategien zu entwickeln, um mögliche zukünftige Schäden zu minimieren.

1 Introduction

Lakes are fundamental ecosystems that provide important services and goods, supporting the livelihood of millions of people (Omweno et al. 2021). Yet water resource systems across the whole globe are affected by natural and anthropogenic influences (Herrnegger et al. 2021). In Eastern Africa global warming causes climate disasters, where prolonged droughts and floods are intensified by more frequent weather extremes (Pereira, 2017). In semi-arid areas water scarcity is a critical issue and many communities depend on rain-fed systems, such as the Rift Valley lakes in the sub-Saharan regions (Muita et al. 2021). These lakes support the local economy by providing water for domestic use, livestock, agriculture, sustaining fisheries and by promoting tourism through occurring geothermal fields and rich biodiversity (Nicholson 2022, Herrnegger et al. 2021). However, during the last decade the Rift Valley has witnessed upsurges of its lakes water levels (GOK & UNDP 2021). This is problematic for different reasons, since the enhanced lake area and volume affect the ecosystems and the settlements that evolved around the Rift Valley lakes (Muia et al. 2021, Herrnegger et al. 2021). The rising water levels of the Rift Valley is one of the recent climate extremes in Eastern Africa, it has destructive effects on nature, human life and livelihood of the local populations in proximity of the riparian areas (Muita et al. 2021).

The phenomena of the uplifting Rift Valley lakes in Kenya was first described in the early 2010s by Onywere et al. (2013), while it has been found that higher rainfall periods in the Kenyan Highlands are correlated with the water level increases in the lakes (Herrnegger et al. 2021). The variability of the Eastern African climate and it's distinct wet and dry periods have been documented in the past (Herrnegger et al. 2021), and it is suggested that bigger flood events are returning based on a 50-year cycle (Muita et al. 2021). Nevertheless, the situation of the rising water levels has become more aggravated with the latest enhanced rainfall seasons of the Rift Valley during 2018-2020, which led to drastic changes in lake levels (Muita et al. 2021, Herrnegger et al. 2021). For instance, the latest developments raised the concern about the potential merging of alkaline Lake Bogoria with freshwater Lake Baringo, which could lead to significant ecological impact through cross-contamination (Chepkoech, 2020). With Lake Bogoria situated at a higher elevation than Lake Baringo, further water level upsurges could cause the former to overflow, representing an important threshold for the potential merging of the two lakes. This could result in an ecological disaster as both lakes and their surrounding wetlands are internationally recognized as eco-regions of great biodiversity. They were designated as Wetlands of International Importance during the Convention on Wetlands during the 10th January 2002 (Ramsar 2002).

Lake Baringo is Kenya's third largest freshwater lake after Naivasha, surrounded by riparian vegetation and provides habitat for great species abundance (Onywere et al. 2013). Lake Bogoria is famous for its geological history, since it has significant physiographic and geothermal features, such as more than 200 hydrothermal springs, most of which had been submerged (Mugo 2007, McCall 2010, GOK & UNDP 2021). Furthermore, both lakes are Important Bird Areas (IBA), with nearly 500 bird species reported to inhabit Baringo and millions of flamingos known to feed on algae in Bogoria (Ramsar 2002, GOK & UNDP, 2021). The Loboi Plain lies in between the two lakes and is a semi-arid region that is fed by ephemeral and perennial streams, as also by different spring systems (Owen et al. 2004). Numerous extensive wetland systems have developed, such as the Loboi Swamp, that is 3 km long and 0.3-0.5 km wide (Ashley et al. 2004). The wetlands encounter different habitats, such as hot spring marshes, floodplain marshes, hypersaline littoral wetlands, and freshwater littoral wetlands (Owen et al. 2004). Lake Bogoria and Lake Baringo are highly valuable due to their significantly abundant biodiversity and habitat variety, which makes their ecosystems very fragile and unique.

Lakes Baringo and Bogoria are crucial to sustain the livelihood of the communities living around them (Muia et al. 2021). Fisheries, for example, are an important source of income and food for local people, and yields have increased in correlation with higher water levels (Walumona et al. 2022). However, the benefits of ecosystem services that occurred to the local populations are limited due to the flooding. Water level fluctuations affect the ecosystem functions of a lake, which in turn limits the ecosystem services of aquatic systems (Walumona et al. 2022). This is also confirmed by Nyakeya et al. (2022), who stress that environmental disturbances are causing a decline in water quality, which poses a threat to the stability of biotic integrity. This, in turn, is hindering the ability of these ecosystems to perform vital functions and provide essential services (Nyakeya et al. 2022). For instance, Lake Baringo serves as a source of drinking water for local communities, while cross-contamination between Lake Bogoria and Lake Baringo would amplify the current humanitarian challenges, regardless of the ecological consequences. The flooding has a far-reaching impact according to Muita et al. (2021) and Muia et al. (2021), as it is not only affecting critical infrastructure, including schools, hospitals, agricultural land, grazing land and residential areas but also cultural ecosystem services. The touristic attractions from the study lakes, which are highly valued for their recreational significance (Muia et al. 2021), are mostly submerged due to the flooding.

The increased rising water levels of the Great Rift Valley received country-wide media attention. However, public debates and expert opinions by scientists have argued about the potential causes for the uplifting lake levels (Herrnegger et al. 2021). A report published by the Government of Kenya and the United Nation Development Programme states that the enhanced lake levels were caused by a combination of hydrological, meteorological, land use changes and geological factors (GOK & UNDP, 2021). A study by the Kenya Water Towers Agency concluded that the upsurging lakes are caused by enhanced rainfall activity in combination with seismic activity, since the Rift Valley is a tectonic highly active zone (Muita et al. 2021).

Nevertheless, without data support it is unclear how tectonic activity contributes to the phenomena (Muita et al. 2021). Most studies focusing on the matter rely on rainfall data, which is quantifiable but also uncomplete due to data quality issues (Herrnegger et al. 2021). Thus, rainfall data estimation by remotely sensed satellite information is used in addition to local measurements, to compensate the limited rainfall observation on the ground and to correct deficits related to uncertainties (Herrnegger et al. 2021). Putting the rainfall data into relation with the uplifting Rift Valley Lakes is very relevant to the challenges that the region is facing in the present, as it helps understanding the underlying mechanisms of the phenomena. Moreover, the probability assessment of the potential of a cross-contamination between Lake Bogoria and Lake Baringo reveals important information regarding future challenges that the region can face.

1.1 Objectives and research questions

The objective of this work is to assess the potential cross-contamination between the study lakes, by identifying the needed changes in the water balance. Since the raising water level have implications on a social and ecological scale, it is crucial to gain more information on the matter. The findings of this work contributes to the knowledge of the recent flooding of the area, allowing the optimization of management plans and decision-making processes that affect the hydrology of Lake Bogoria and Lake Baringo and preserve the valuable ecosystems that are found in the study area.

This work focuses on the hydrological changes of Lake Bogoria and its catchment area, while the assessment is generally divided in four parts. As Lake Bogoria is situated on a higher elevation than Lake Baringo, the needed water level upsurges for an overflow towards lake Baringo is firstly assessed. Secondly, it is crucial to understand the necessary volume changes of Lake Bogoria for the overflow to occur, which is then, third, followed by the analysis of the needed hydrological changes in the catchment area that allow the accumulation of the volume changes. The last part of the analysis consists of the probability assessment of the cross-contamination. The procedure for the latter includes the generation of a hypothetical stream between the two study lakes and again the calculation of needed hydrological changes in the catchment to allow a sustained flow of the stream between Bogoria and Baringo. The comparison of the needed hydrological situation with the present situation allows to make statements about the probability of a continued flow between Lake Bogoria and Lake Baringo.

To answer the described aspects of hydrological assessment, following research questions are assessed throughout this paper:

(i) What further lake level rises are necessary until Lake Bogoria overflows?
(ii) What further lake volume changes are necessary until this tipping point occurs?
(iii) Can these necessary lake volume changes be related to rainfall and evapotranspiration conditions?
(iv) Is it reasonable to assume that a continued flow can be expected towards Lake Baringo in case of an overflow?

2 Study Area

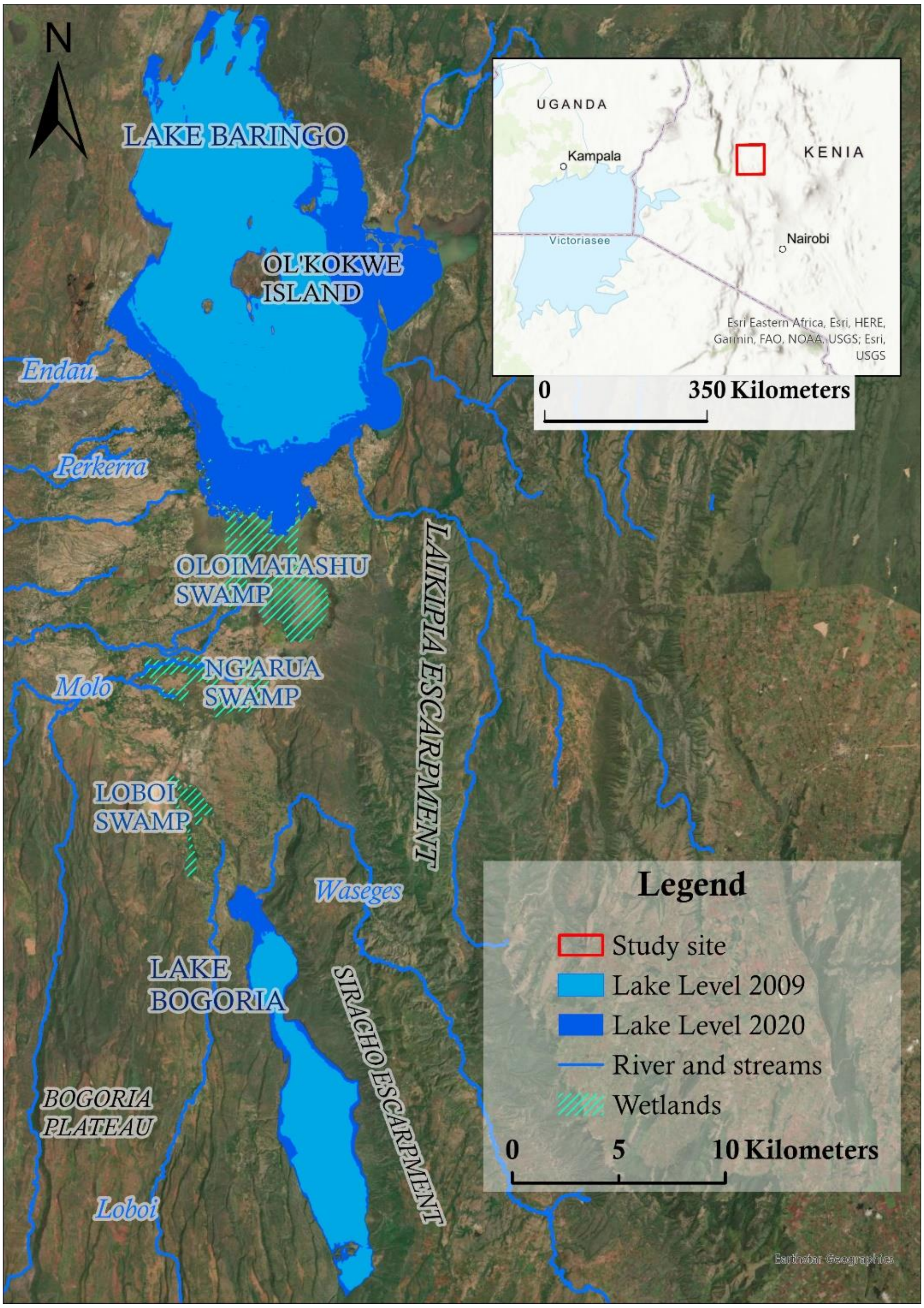

Figure 1: Locations of the study lakes within Kenya, Lake Baringo and Lake Bogoria with their surrounding river network, wetlands and their respective lake levels during the years 2009 and 2020. (DGFI-TUM, 2013, Schwatke et al. 2015, Esri, Maxar, Earthstar Geographics the GIS User Community, OpenStreetMap 2023)

Lake Bogoria lies 0°20′ N between 36°04′ E to 36°07′ E and lake Baringo 0°30′ N to 0°45′ N and 36°00′ E to 36°10′ E. The two study lakes are located in the Central Rift Valley in Kenya, namely in the Eastern arm of the Great Rift Valley (Herrnegger et al. 2021, Okech et al. 2019) just northern of the Equator. The Rift Valley System range from the Golf of Aden Middle East in the North to Mozambique in the South (Herrnegger et al. 2021), whereas the Great Rift Valley ranges from the North to the South in Kenya. The study area encompasses Lake Bogoria and Lake Baringo, their watershed areas and the region between the lakes. The study lakes are distanced about 20 km apart, separated by the Loboi Plain, which encounters the Loboi, Ng'arua and Oloimatashu swamps. The watershed area for lake Bogoria is 1060 km^2 and for lake Baringo 6600 km^2, and the mean annual rainfall for both watersheds during the period 1981-2020 is 1030 mm (Herrnegger et al. 2021). The study lakes strongly depend on inflows from rivers that originate from humid parts of their drainage basins, which are the close by Kenyan Highlands (Herrnegger et al. 2021, Muita et al. 2013). The flooding of Lake Bogoria is due to its surrounding steep topography mostly limited to the North, whereas the flat surroundings of Lake Bogoria lead to significant flooding in the east and south.

2.1 Geology of the Kenyan Rift Valley

The Rift Valley is the most geologically active site on Earth (Jirsa et al. 2013), due to its high tectonic and seismic activity, and it constitutes a significant geographic feature in Eastern Africa (Gichuki et al. 2006). In fact, the high geological activity in the African System results from continental extension and the earth's crust thinning, which is already in an advanced stage in Kenya (Ring, 2014). The Rift Valley continues to deepen with a yearly growth rate of six to seven mm, promoting the formation of various lakes (Jirsa et al. 2013). As an outcome of the region's active geology, volcanism also plays an important role in the Rift Valley, especially in influencing the morphology and hydrology of the lakes (Jirsa et al. 2013). The geological history of Lake Baringo dates to the Pleistocene, as the Ol-Kokwe island remain from the volcanic activity which occurred 1.8 million years ago at the southern end of the lake (Okech et al. 2019). According to Hackman (1988) the Korosi volcano at the north of lake Baringo was mainly involved in the formation of the islands, which fissure system is most likely reaching under Baringo until the Ol-Kokwe island. Furthermore, Ring U. (2014) stresses out that continental rift zones typically create asymmetric grabens, which is also the case for the southern part of the study Lake Bogoria, as it consists of a half-graben (McCall, 2010).

Both study lakes are geological products of past tectonic events, which are associated with the formation of the Rift Valley (GOK & UNDP, 2021). The thinning of the Earth's crust leads also to a very high hydrothermal activity within the Rift Valley, as the study area encounters many fumaroles, geysers, springs, and seepages (McCall, 2010).

The study lakes are located in the Eastern branch of the Rift Valley, also called the Gregory Rift Valley (Kiage & Liu 2009), which encounters many freshwater and hypersaline water bodies, according to their dissolved salt content (Jirsa et al. 2013. The geology of the study area consists of compositions of volcanic rocks (basalts, trachytes), gneisses, granites, and metasediments (Jarcin et al. 2013, Garcin et al. 2009). Consequently, the soils of the study lakes are characterized by fragile soils with low fertility, low nutrient content, low organic matter, resulting in low infiltration and storage capacity (Onywere et al. 2013).

2.2 Climate and precipitation

The area of the study lakes is generally semi-arid, but has also varying climatic patterns (Muita et al. 2021). The author stresses that the climate fluctuations are expressed in the observations of the monthly rainfall patterns, which are dependent of the Inter-Tropical Convergence Zone (ITCZ) (Muita et al. 2021). According to NASA (2000), the ITCZ is a region located close to the equator where trade winds from the Northern and Southern hemisphere meet, causing in combination with the intense sun and warm water that humid air becomes buoyant and rises. The seasonal migration pattern of the ITCZ's location is the main driver for rainfall patterns, resulting in dry and wet seasons of the tropic nations close to the equator (NASA 2000). Therefore, the ITCZ is the most important rainfall generating mechanism of the region (Muita et al. 2021). According to Verschuren et al. (2000), the temporal variability of rainfall patterns is influenced by the tropical monsoon circulation and its atmospheric dynamics, which governs also the migration patterns of the ITCZ. Thus, El Niño and La Niña events influence the study lakes as well, as they have also an impact on the ITCZ and contribute to rainfall anomalies and lake water changes (Nicholson and Yin 2001, Muita et al. 2021). The water level increases of the study lakes are highly correlated with the rainfall records from the Kenyan Highlands that surround the Eastern African Rift Valley Lakes (Muita et al. 2021). The main rain seasons occur from March to May and short rain seasons occur in June-August and October-December (Herrnegger et al. 2021). In those periods monsoonal winds from the Indian Ocean contribute to the moisture and the rainfall of the area (Bessems et al. 2008). The rainfall of the study lakes is erratic and characterized by short-lasting and unpredictable precipitation patterns (Onywere et al. 2013, Bessems et al. 2008). This is also confirmed by Dunkley et al. (1993), who describes the rainfall pattern of the region as concentrated in short periods of intense precipitation.

As the endorheic lakes Bogoria and Baringo are missing a surface outlet, they are highly sensitive to effects of climatic changes (Jirsa et al. 2013, Omweno et al. 2021). Their water budget is defined by direct precipitation, evaporation, inflows and by anthropogenic diversion (Jirsa et al. 2013). Nowadays, lake Baringo's catchment experiences daytime temperatures from 16.7 °C during the cold months of June and July to 33.8 °C during the warmer months of January to March and September-October (Muita et al. 2021). Although the recurrent climate and the rising precipitation in the last decade led to the rising of the study lakes water levels, it is proved that the climate of East Africa can be highly variable (Okech et al. 2019). Previous studies have shown that the climate has alternating dry and wet periods, which led to the drying out of Lake Baringo 200 years ago or to the eventual connection of lake Bogoria and Baringo at ca. 16.3- 13.8 ka BP (Garcin et al. 2009, Okech et al. 2019).

2.3 Biodiversity

As the study lakes are designated Ramsar and IBA sites (Ramsar 2002, GOK & UNDP, 2021), it is apparent that the natural value of the area is significant. Lake Baringo is home to an endemic fish species (*Tilapia Oreochromis niloticus baringoensis*) and inhabits also a high population of other aquatic animals, such as hippopotamus, crocodiles, while also mammals, reptiles and amphibians settle at Lake Bogoria (Ramsar 2002). Lake Bogoria has a high biodiversity value for over 300 waterbird species and provides important refugee for the lesser flamingo (*Phoenicopterus minor*), which was reported to have a population of one to one and a half million (Ramsar 2002). Lake Bogoria supports the dense blooms of cyanobacteria Sprulina platensis, which is a food resource for the lesser famingo (Hickley et al. 2003).

However, the lakes ecosystems and watershed areas are being pressured by deforestation, water diversion for irrigation, water pollution and overall watershed degradation (Ramsar 2002, Onywere et al. 2013). Intensive agriculture has been introduced to the Loboi Plains about 70 years ago, which strongly affected the mosaic of the landscape, rendering it more homogeneous due to cultivations (Ashley et al. 2004). Nearly 20 years ago, Ashley et al. (2004) underlined the environmental stress of the Loboi swamp due to water diversion for irrigation, which led between 1969 and 2004 to a reduction of the swamps area of about 60%. Furthermore, the study lakes are impacted by local and internationals tourists, as the landscapes are known for its unique biodiversity and scenery (Omondi et al. 2016). The consequences of the impacts can be seen within the occurring species of the ecosystems. The endemic *O.n. Baringoensis* of lake Baringo is dominated by *P. Aethiopicus*, which was introduced in 1975 (Omondi et al. 2016), while the lesser flamingo population of lake Bogoria is experiencing a higher mortality rate, eventually due to the degradation of the water quality through algal toxins or heavy metal concentrations (Ramsar 2002). Moreover, the soils of the catchment are more exposed due to cultivations and deforestations, leading to high soil erosion and sedimentation in the lakes (Kenya Water Towers Agency 2015). Odada et al. (2006) stress that the semi-arid region of the study lakes is a fragile environment, which rich aquatic and terrestrial life resides in intact habitats and require urgent conservation attention.

2.4 Study Lakes

Table 1: Lake characteristics (Herrnegger et al. 2021)

Lake characteristics	**Bogoria**	**Baringo**
Mean Lake level [m]	994.4	973.8
Range lake level 1984-2020 [m]	993.1 - 998.1	971.4 - 979.6
Mean annual catchment rainfall 1984 – 2020 [mm]	1036.1	1023.7
Orographic catchment area [km^2]	1060.0	6608.7
Mean annual lake area 1984-2020 [km^2]	34.9	146.3
Range in annual lake area 1984-2020 [km^2]	31.4 – 41.2	118.3 – 197
Conductivity [µS/cm] (Obando et al., 2016, Omondi et al. 2014))	31046	577

2.4.1 Lake Bogoria

Lake Bogoria, formerly known as Lake Hannington, lies at an elevation of ca. 994 m.a.s.l. with a surface area of approx. 35 km^2 and a catchment area of 1060 km^2 (Herrnegger et al. 2021). The lake is 17 km long, approximately 3.5 km wide and has a maximum depth of ca. 10-12m (McCall 2010, Herrnegger et al. 2021). The meromictic lake is known for its abundant hydrothermal springs and geysers, which partly feed the lake and are mainly found at its shoreline and in the surrounding area (McCall 2010). The springs temperature ranges from 34-98.5 C° and have according to McCall (2010) deep groundwater sources and a high sodium carbonate content. The latter contributes to the high salinity of the water body, which is > 40%, while the lake has also a pH of >10.3 (Jirsa et al. 2013) and a high alkalinity with a conductivity of 31046 µS/cm (Obando et al., 2016). Due to the recent water levels rises and the floodings that the lakes of the Eastern African Rift Valley experienced, many of the hot springs and geysers of Lake Bogoria are not possible to access anymore as they have been submerged (Muita et al. 2021). The high salinity of Bogoria contributes also to its chemical stratification, the upper surface waters are less saline than the denser and more saline bottom layer, which result in a permanent anoxic monimolimnion (De Cort et al. 2018).

As mentioned before, lake Bogoria's lies in an asymmetric north-south trending half-graben. The lake lies in a deep depression with steep slopes, which walls rise to 700 m above the water surface (Renaut et al. 2017). Based upon the topography and the high salinity, Renaut et al. (2017) suggest that the lake might be hydrologically closed, due to the saline hot-spring inflow and the strong regional occurring evapotranspiration.

McCall (2010) suggest as well that there is no hydrological continuity in the southern part of Bogoria, but for its northern part he argues that there is underground water connection towards lake Baringo. He supports this statement with the example of the Loboi hot spring in the northern part of Lake Bogoria, which resurfaces slightly saline groundwater mixed with natural gas that is probably originating from the lake. According to Hackman (1988), Lake Bogoria is indirectly recharged through the seasonal Waseges river at the northern end, which would also explain the increasing salinity degree of Lake Bogoria towards the south.

2.4.2 Lake Baringo

Lake Baringo's name originates from the local word "Mparingo", which means lake (Odada et al. 2006). The lake lies at an altitude of 974 m.a.s.l., has a surface area of approximately 146 km^2 and a catchment area of ca. 6600 km^2 (Hackman 1988, Herrnegger et al. 2021). The holomictic freshwater body is one of seven inland lakes in the Rift Valley drainage basin, and several seasonal rivers flow into Baringo, such as Endau and Ol Arable (Hackman 1988, Odada et al. 2006). Furthermore, lake Baringo is also fed by the permanent rivers Molo and Perkerra, which enter the lake from the south after crossing the Loboi Plains (Bessems et al. 2008). The northern part of Lake Baringo is characterized by the volcano Korosi, which formed an island with a diameter of 15 km on the lake (Hackman 1988). The fissure system from the volcanic activity is influencing the hydrology and underground pathways of the lake, as hydrogeological evidence confirms the fractured floor of the lakes allows outflow of lake water by underground seepage towards the north (Omondi et al. 2016).

The lake has a mean depth of 5.9 m at high water levels and experiences relatively high evaporation rates of 1650-2300 mm (Herrnegger et al. 2021, Omondi et al. 2016). The history of water quality measurements has also revealed that the geochemistry of the lake is strongly influenced by the occuring evaporation rate and by the rainfall patterns, while the water transparency can be reduced through suspended solids brought from the catchment by wind action (Omondi et al. 2016). To remain a freshwater body, Lake Baringo is dependent on a substantial inflow from several seasonal rivers of its wetter catchment area and from underground seepage, which enable flushing and hinder the accumulation of minerals (Herrnegger et al. 2021).

3 Literature review

3.1 Rising water levels

The lakes from the Eastern Rift Valley have previously been studied, in order to investigate the causes of the upsurging water levels (Herrnegger et al. 2021). The lakes were reaching very high water levels and the flooding claimed broad land areas, causing major damage to property and negatively affecting the livelihood of local communities, thus becoming a matter of public concern in the recent past (GOK & UNDP 2021). As the floodings of the region strongly affect the local communities, this topic has been strongly covered by national medias and the scientific community. Furthermore, it is reported that Lake Bogoria and Baringo are expected to merge if the rising trend continues (Muita et al. 2021). However, the sources of the rising water levels have been debated and three main factors can be pointed out in the scientific reviews, that contribute to the phenomena.

First, as already mentioned before the study area finds itself in a highly active zone of the earth's crust (Gregory, 1896; Smith, 1989). Consequently, recent movement of tectonic plates in the region could have caused decreases in underground permeability, thereby decreasing sub-terranean outflow or seepage. This process could be described as hasty hydrogeological instationarity (Herrnegger et al. 2021). The author further note that Lake Baringo is a freshwater lake, despite the fact that the lake has a low water depth and a high evapotranspiration is occurring, which indicates that water storage changes through groundwater or seepage flow are present by substantial freshwater mass flows. Furthermore, a study from the Kenya Water Towers Agency (2015) suggests that seismic activities could have created new fractures, which may have contributed to additional flow of water into the lakes from surrounding aquifer systems. However, it remains unclear how those new fractures may only have influenced the water levels of the lakes and no aquatic systems such as dams and rivers (Muita et al. 2021).

Secondly the land use and land cover change (LULCC) have been assessed by Kiage and Douglas (2020) for Lake Bogoria, Baringo, Nakuru and Elementaita as potential driver for the increasing lake water levels. As the lakes watersheds have been strongly altered through anthropological activity, higher amounts of sealed surfaces from the settlements and the surrounding agricultural activity may have let to the clogging of the underground water pathways, due to the degraded catchment area and resulting higher sediment input (Herrnegger et al. 2021). This could not only reduce the permeability of the underground pathways, but also higher siltation rates could impact lake volumes as it could influence on a long-term the water level (Herrnegger et al. 2021).

LULCC often lead to higher surface runoff and less infiltration processes, thereby accelerating surface runoff and peak discharges on shorter time scales (Guzha et al., 2018). This in turn affects the overall water balance on a longer time scale through decreased actual evapotranspiration (Andréassian, 2004).

The third perspective is from a hydrological point of view, as the yearly rainfall data shows a significant increase, especially in the last decade. According to Herrnegger et al. (2021), the comparison of the available data ranging from 1981-2020 shows that until 2009 the rainfall was around the long term mean of the examined period. They stress that after 2010, stronger positive rainfall deviations are occurring, as the last decade has shown a strong rainfall increase compared to long term mean of the region (Herrnegger et al. 2021). This is also well represented in the graph used in their work (Figure 2), that relates the increasing rainfall to the lake area changes for Lake Baringo (Herrnegger et al. 2021).

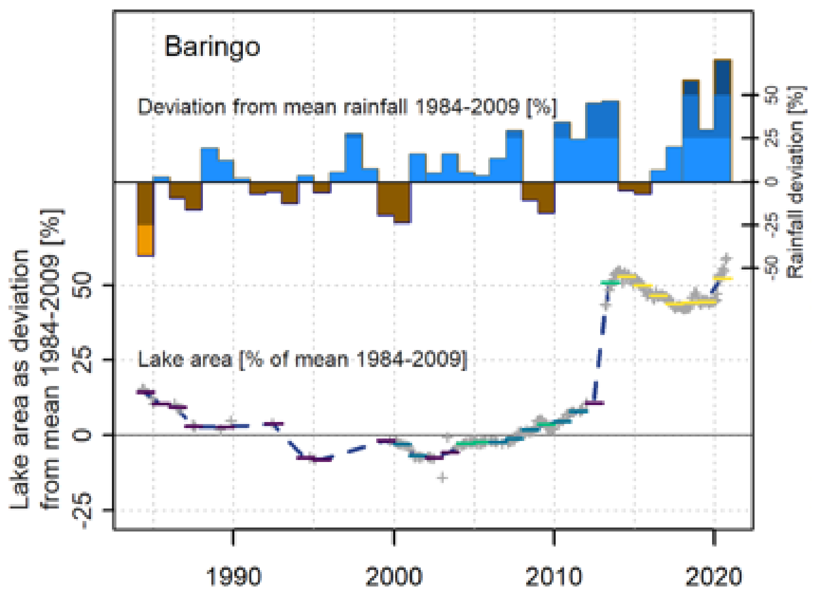

Figure 2: Lake Baringo area changes and rainfall deviation from 1984- 2020 (Herrnegger et al. 2021)

Figure 2 clearly shows that the increases in precipitation go in hand with the expansion in water area for lake Baringo. Renaut and Tiercelin (1993) stated that especially hydrological closed basins and changes in their water level are sensible after periods of exceptionally high rainfall or reduced evapotranspiration. Nevertheless, the Gregory Rift and its tectonic activity are very likely to make paths for underground water exchange, as mentioned before.

Although the influence of the tectonic activity and the LULCC cannot be ruled out, Muita et al. (2021) states that the water levels of most lakes are dependent of hydrological and meteorological factors like discharge and precipitation. They further stress that the historical water levels for the Lakes are connected to period of high rainfalls, showing the key function of precipitation for the ground and surface water. According to Herrnegger et al. (2021), the connection between the effective rainfall and the water level changes can be further explained with the integrated catchment response (ICR). The ICR is used to relate lake volume variations to annual changes in the water balance components. Based on his calculations, Herrnegger et al. (2021) demonstrate that only small deviations in the balance components are necessary to have a big effect on the water accumulation in the lake and thus also on the occurring lake levels. For instance, during the period 2010-2020 a positive ICR of 16.9 mm/a is already sufficient to explain Lake Baringo's lake level rises (Herrnegger et al. 2021). Furthermore, the authors underline that the ICR can be used to evaluate the changes of mean inflows if the lake is in equilibrium. Lake Baringo's mean inflow must have increased around 3.5 m^3/s during the period 2010-2020, in order to explain the observed increases in lake volume during that time (Herrnegger et al. 2021).

3.2 Flooding extent

The rainfall and lake water level changes become also apparent in the area that the study lakes occupy. Recent studies reveal that strong water fluctuations occur in the area. For instance, Walumona et al. (2022) stresses that Lake Baringo had its lowest recorded water level in 1956 with a minimum of 1.47 m, whereas its recorded peak level was 13.95 m in 2017. Herrnegger et al. (2021) demonstrates in Figure 3 the spatial changes that the study lakes underwent in the time period 1984-2020. The flooded lake areas are visualised by colours, while the colours are classified based upon the spatial occurrence of the floodings, compared to the areas which were very frequently under water in dark blue. Onywere et al. (2013) stress that Baringo is affected most strongly by the floodings due to its flat geomorphic structure. The riparian area where the local population is settled is flooded and this includes also the loss of agricultural, pastureland and further crucial social infrastructure. Lake Baringo extends also wider towards the East and the South, including a bigger spatial area, while Lake Bogoria is only extended towards the North, due to its steeper slopes.

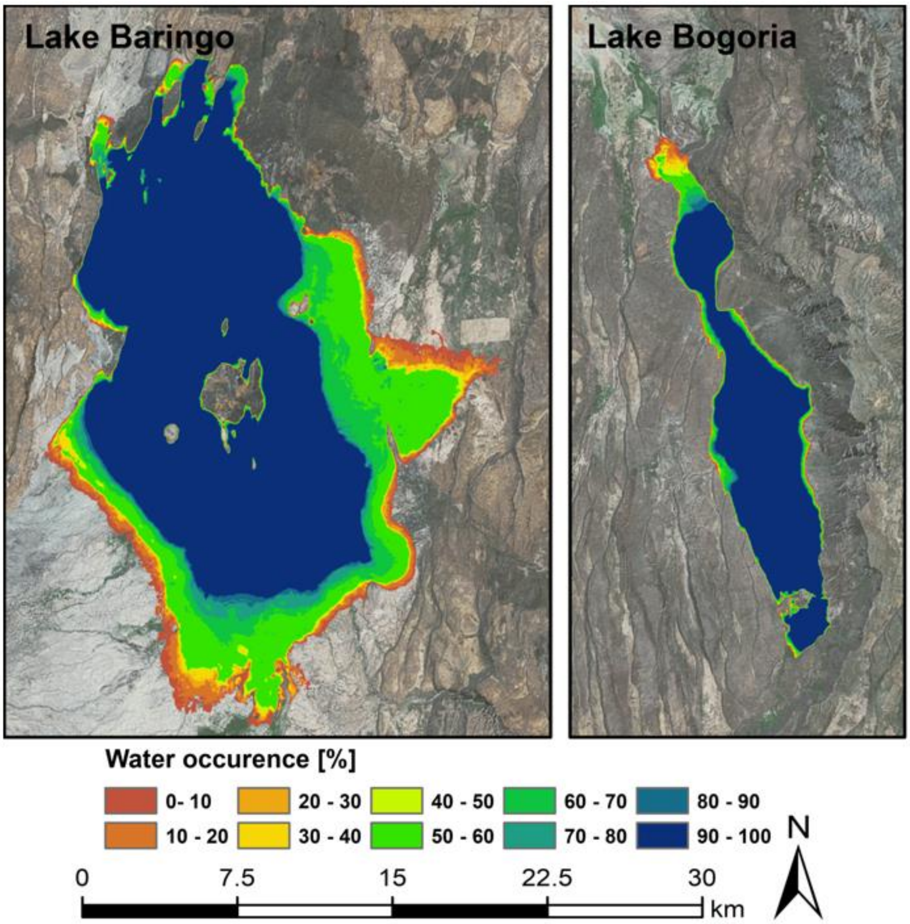

Figure 3: Changes of spatial extend (1984-2020) of the study lakes (Herrnegger et al. 2021). *The dark red water occurrence (0-10%) means that during 1984-2020, 0-10% of the time the floodings occurred in that area*

3.3 Social Implications

According to Odada et al. (2006), three indigenous communities live in the proximity of Lake Baringo, namely the Ilchamus, Pokots and Tugens, which have pastoralist and agriculturalist lifestyles and strongly depend on Lake Baringo. The freshwater lake contributes to the local's domestic needs through fisheries and water for drinking water, agricultural irrigation or water the livestock (Omondi et al. 2016, Walumona et al. 2022). Lake Baringo is also a natural resource, as vegetation products (*Ashynomena elephroxylon*) are used for boat construction and local bread (ugali) is based on water lily (Odada et al. 2006). Furthermore, the saltwater lake Bogoria is also an important source of income, as its numerous springs and geysers attracts yearly national and international tourists, making tourism an important economical asset for the region (Omondi et al. 2016). The Loboi Plain is also included as touristic destination, since the abundant wetland systems that developed here host many different habitats and species (Omondi et al. 2016).

The rising of the Great Rift Valley Lakes highlights the importance to address the damage potential that can occur through the floods (Herrnegger et al. 2021), as most settlements are found in close proximity to the lakes (GOK & UNDP 2021). For instance, the flooding damages for the settlement at Lake Baringo is worse due to the bigger spatial extent of the floodings and its higher population density (Herrnegger et al. 2021). Nevertheless the populations around both study lakes suffers from the loss of crucial infrastructure. The flood also claimed for lake Bogoria several water points, which are now at risk to be contaminated and to cause water-borne diseases outbreak (GOK & UNDP, 2021). Indigenous pastoralist communities, which lived beforehand in poverty with limited access to tap water, health and social services, are also fatally affected by the upsurging water levels (Odada et al. 2006). According to the GOK and UNDP (2021) report, approximately 3000 household communities live at the shore of lake Baringo, although many have been relocated to higher elevations and as the lake rise every few months, some had to rebuilt their homes up to five times. Due to the loss of land and relocations, many locals compete for pastoral lands as issues of legal ownership, management and land delineation (GOK & UNDP 2021).

The catchment area has been continuously degraded by anthropological activities, mainly through land use and land cover changes (Kiage and Douglas, 2020). Previously forested lands were transformed to agricultural plots, and the water from the wetlands was intercepted for irrigation through water diversion, leading to a substantial loss of natural land (Owen et al. 2004, Ashley et al. 2004). The loss of forest area and wetland has also implication for the local communities. According to Guzha et al. (2018) the sediment regime is altered, as exposed agricultural lands lead to a higher surface runoff, resulting in increased erosion, sedimentation and pollution loads in the lakes. This is an important aspect for the health of affected communities, since Lake Baringo is used as clean water access in area (Muia et al. 2021) and higher erosion reduces the water quality of the study lakes. Moreover, the sedimentation loop is enforced by the local precipitation regime, which is characterized by short intense rainfall events that lead to higher erosion on exposed soils (Onywere et al. 2013). The degradation of the prevailing ecosystems therefore affects also directly human health and livelihood (Omondi et al. 2016).

3.4 Study lakes flooding history

The rising water levels of the Kenyan Rift Valley is nothing new. According to Muita et al. (2021) observation of increased lake levels has been made during the 1730s, as it has also been done for two different periods in 1700-1900 and 1900-2020. It has been shown through previous studies that the Rift Valley Lakes have undergone many changes through water level fluctuations, which also affect the water quality and were caused by varying climatic conditions as main driver (Walumona et al. 2022). According to Renaut and Tercelin (1993), Lake Bogoria has had during the last 30000 years' periods with fresher or more saline water composition. Hackman (1988) stresses that previous works have evidence suggesting that the two lakes were combined during the late Pleistocene, which was named Loboi Lake. Gichuki et al. (2006) also stress that it is believed that the Eastern Rift Valley lakes are remnants of larger water bodies, which once occupied the valley floor during the last pluvial period. According to Renaut et al. (2017), Lake Bogoria almost reached approximately 1900 a water level that allowed the merging of Lake Bogoria and Lake Baringo, whereas it also achieved a similar level during 2013-2016.

Furthermore, Muita et al. (2021) suggests that increasing rainfall in the Kenyan Highlands is correlated to the rising lake levels of the Eastern African Rift valley and that there may be a pattern that can be retrieved based on historical data. Derived from the floodings incidences of 1901 and 1963, it seems that a 50-year cycle is recurring in the region (Muita et al. 2021). Herrnegger et al. (2021) raise a critical point while stressing that although the current lake level fluctuations occurred before, the negative effects on the local communities are not comparable. Nowadays, the population density is higher, especially when considering that most people were located around the riparian area, which became crucial for their livelihood and represents at the same time a higher damage potential (Herrnegger et al. 2021).

4 Methodology

4.1 Data basis

Table 2: Overview of used products, their information and references

Product name	Information	Reference
DAHITI	Lake water level (m)	Schwatke et al. (2015)
CHIRPS	Study area rainfall (mm)	Funk et al. 2015
TanDEM – X	Surface elevation (m)	GAC (n.d.)

The investigation of the potential overflow between Lake Bogoria and Lake Baringo is based on a ArcGIS Pro (ESRI 2022) analysis and precipitation data assessments. The quantification of potential fluxes between the study lakes or volume changes of lake Bogoria relies on the analysis of water balance components by the ICR. As the assessment of Herrnegger's et al. (2021) is based on the same region as the study lakes, the precipitation, evapotranspiration and topographic data from their work is used. The assessment of the research questions is mainly carried out through the combination of water balance calculations and geographic information handled in the software ArcGIS Pro. In this study, hydrological and topographical tools are applied on the available map products in ArcGIS Pro, to quantify and visualise the required surplus water accumulation in order to calculate and relate the needed water balance changes of the study area. Onywere et al. (2013) also used a Geographic Information System (GIS) to assess the floodings of the Rift Valley Lakes, which enabled the mapping and interpretation of flooding patterns. Schwatke et al. (2019) highlighted the importance of remote sensing as well, as it allows the monitoring of flooded regions, wetlands and also the quantities of lake and reservoir water storages. Furthermore, the observation of the water cycle changes contributes significantly to the development of hydrological models and the monitoring of the water cycle, especially in the context of climate change (Schwatke et al. 2019).

According to Herrnegger et al. (2021) it is needed to analyse the changes in the water balance and inflows, in order to understand lake level changes. The authors bring the storage term to the left, in order to define the long-term water balance equation for a lake watershed. The equation refers to the storage of the lake (*S*) as annual lake volume variations, which are the product of the catchment rainfall (*R*), actual evapotranspiration (*AET*), storage changes through additional potential underground flow from neighbouring watersheds or groundwater (Q_{gw}) and runoff from the lake or outflow through seepage fluxes (Q_{out}). However, the water balance is simplified due to data unavailability for the storage changes and feasibility of this assessment.

$$S = R - AET + \cancel{Q_{gw}} - \cancel{Q_{out}} \quad (1)$$

By neglecting the storage changes through potential underground flow (Q_{gw}) and runoff or outflow through seepage (Q_{out}), it is assumed that these water balance components are stable and in equilibrium, meaning that there are no storage changes happening from one year to the next (Herrnegger et al. 2021). They also state that this assumption implies a stationarity of the boundary conditions, as any decrease or increase in lake level is related to variations in rainfall or evapotranspiration.

The lake surface area is derived from optical image analyses of Sentinel-2 and Landsat satellite data, while the water level series are provided by the “Database of Hydrological Time Series of Inland Waters” (DAHITI) (Herrnegger et al. 2021). DAHITI contains the data of Lake Baringo and Lake Bogoria and is a continuous dataset from 1984 to the present, free of charge, developed and maintained by the “Deutsches Geodätisches Forschungsinstitut at the Technische Universität München” in 2013, also referred to as DGFI-TUM (Herrnegger et al. 2021). The DAHITI dataset is a product of multiple satellite altimeter system, in order to allow an increased temporal and spatial resolution (Schwatke et al. 2015, Herrnegger et al. 2021). DAHITI processes its images based on a combination of the extended outlier detection and a Kalman filtering approach (Schwatke et al. 2019). According to Herrnegger et al. 2021, DAHITI recorded the lakes of the East African Rift Valley, on the 24th October 2020, providing optical images that are also used in this overflow potential analysis. Furthermore, DAHITI delivers also time series on lake volume variations (Schwatke et al. 2020), which allow to assess yearly volume and inflow changes (Herrnegger et al. 2021).

However, satellite altimetry has certain limitations, such as the need for the satellite to cross the respective inland water body in question, as satellites follow specific orbits during their altimeter missions (Herrnegger et al. 2021). The authors also note that temporal resolution is limited to the to the particular orbit configuration of the satellite mission, which ranges from 10 to 35 days. Nevertheless, satellite altimetry allows for fairly accurate estimation of hydrological lake water levels without local infrastructure (Herrnegger et al. 2021), which is useful as an alternative data source in areas without gauging stations, as it has proven its ability to monitor changing inland water levels (Schwatke et al. 2019).

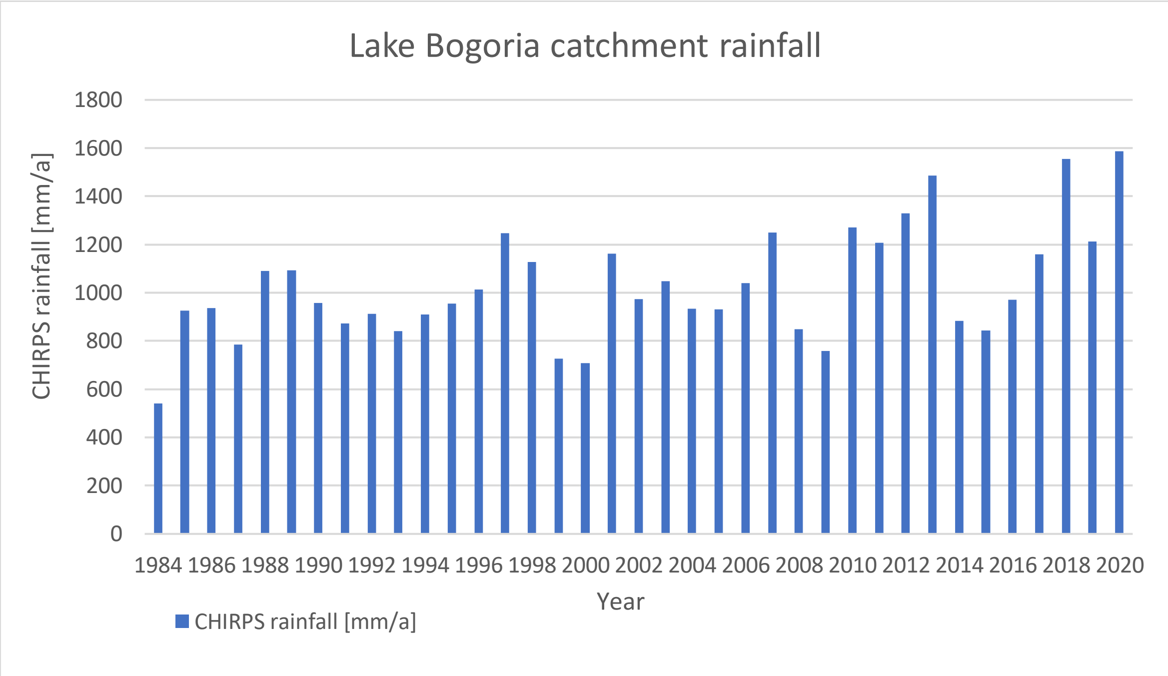

Figure 4: CHIRPS rainfall dataset from 1984-2020 for Lake Bogoria's catchment

The rainfall data stems from the Climate Hazard group Infrared Precipitation with Station (CHIRPS) environmental record, which is a satellite-based algorithmic product that provides precipitation datasets (Herrnegger et al. 2021). According to the authors, CHIRPS has a quasi-global (50°S-50°N) high resolution (0.05°) with daily, pentadal and monthly records based on interpolation techniques, which are developed on infrared Cold Cloud Duration (CCD) observations. The CHIRPS rainfall dataset for Lake Bogoria is shown in Figure 4. Although the time period ranges from 1984-2020, some calculations in this work use the mean rainfall from 2010-2020 as reference. Due to the recent trend of rising water levels and higher precipitation rates, the last decade is found to be more representative of the study area than the 1984-2010 dataset. The ERA5-Land (ERA5L) is also compared with CHIRPS to evaluate the dataset. Herrnegger et al. (2021) note that ERA5L has global coverage and gap-free time series for 15 meteorological variables for the period 1981 to the present). The authors further state that ERA5L derives from the ERA5 climate reanalysis, which covers only terrestrial variables with enhanced spatial resolution. According to Nicholson et al. (2019), CHIRPS is limited by its reliance on geothermal satellite observation, which were unable to detect sub-daily rainfall changes before 2001. Nevertheless, Herrnegger et al. (2021) claim that the differences between the measurements from the limited gauging stations are greater with ERA5L than with CHIRPS.

Nicholson (2022) stresses that assessing the water balances for East African lakes is complex, due to the difficulty of obtaining meteorological and hydrological data. As precipitation measurements in the study area are limited due to its remoteness, rainfall data is mostly retrieved from remote sensing data and, where possible, corrected by observations from local gauging stations (Herrnegger et al. 2021). The authors emphasized that while ground observations are important, they are subject to deficits due to uncertainties in systematic and random errors from in-situ measurements, while they are also unable to capture the spatio-temporal variability of rainfall in lake catchments. However, they also stress that local gauging stations can be used to correct rainfall data estimations derived from remote sensing satellites. In this paper, precipitation and evapotranspiration data are based on rainfall time series collected from 1984-2020.

In addition, a digital elevation model (DEM), provided by the German Aerospace Centre (GAC) was used, namely the TerraSAR-X add-on for Digital Elevation Measurements (TanDEM-X). The TanDEM-X satellite works on the basis of a synthetic-aperture radar that can operate independently of weather conditions (GAC n.d.). The TanDEM-X raster data set has a grid size of 12 x 12 m per cell with a high vertical accuracy of at least 2 m (GAC n.d.). The use of digital elevation models makes it possible to reproduce the topographical situation of the study area (GAC n.d.), which can be used to retrieve hydrological information. According to Nobre et al. (2011), elevation is a primary landscape parameter that defines soil-water dynamics. They further emphasise that topography imposes a strong control on soil moisture, water fluxes and drainage dynamics (Nobre et al. 2011). The elevation data provided by the TanDEM X elevation model is the mean elevation of the area for each cell. The TanDEM X model has implausible elevation values for some cells due to the reflection from the water surface or other bright surfaces. Reconstructing the data gaps is therefore also an important step in creating the data base, so that the analysis can be performed with a consistent and complete elevation model. The interpolation of elevation values is achieved by using a GIS tool that obtains missing elevation values from the neighbouring cells, thus performing a spatial interpolation.

4.2 Methods

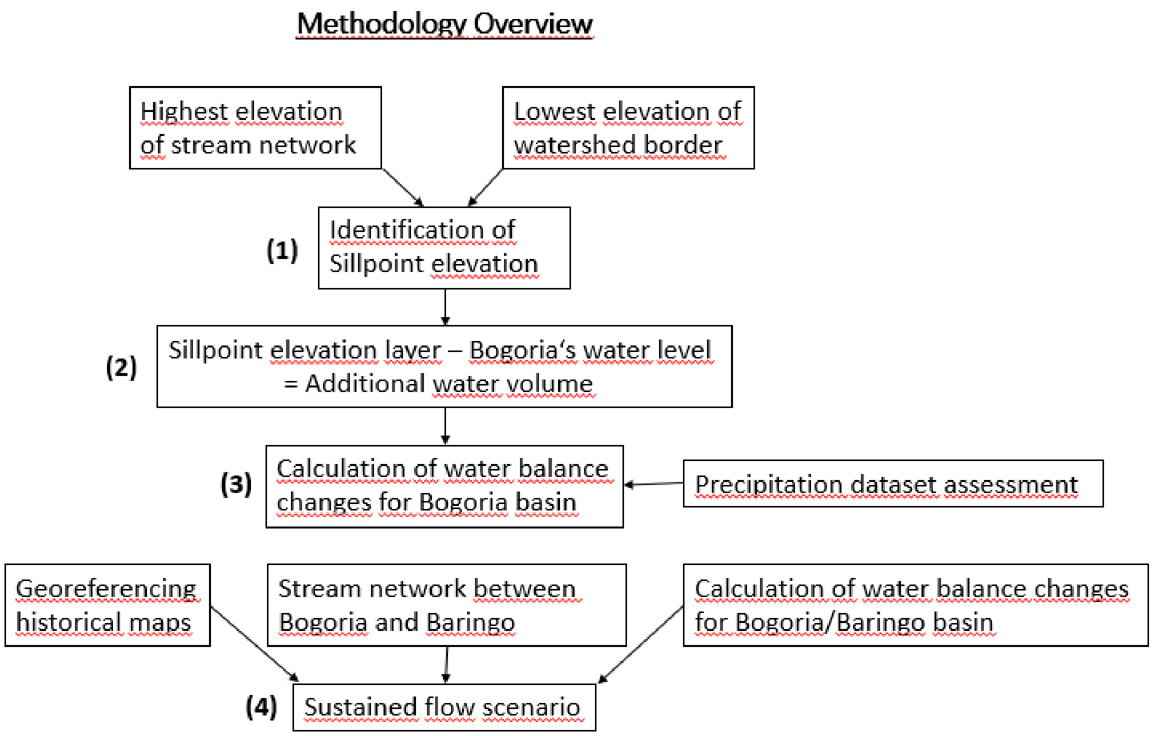

Figure 5: Methodology overview of the working steps and numeration with relating research questions

4.2.1 Identification of Sill point

The assessment of Lake Bogoria's overflow towards Lake Baringo is based on the local topography. As mentioned previously, Lake Bogoria lies in a deep depression surrounded by steep slopes and is according to Herrnegger et al. (2021) located at a higher altitude (994 m) than Lake Baringo (974 m). It is necessary for the incidence of a cross-contamination that Lake Bogoria rises to a certain water level, which allows its water to overcome the surrounding steep slopes and flow towards Lake Baringo. The depression of Lake Bogoria is the only topographical barrier that hinders a flow between the study lakes. Through the visualisation of the flooding extent in Figure 3, it becomes apparent that the northern part of Lake Bogoria has a topography with a gentler slope and lower elevation. Thus, the investigation of Lake Bogoria's northern area is important for a potential overflow towards Lake Baringo, putting this area at the focus of the first research question. This work calls the water level of Lake Bogoria that allows an overflow towards Lake Baringo the sill point, which is indicated in Figure 6 with a red dotted circle.

Built on the elevation data of Bogoria's northern DEM and GIS analysis, the identification of the sill point was performed in two different ways. As the assessment of the potential overflow between the study lakes are based on the elevation value of the sill point, the two different approaches and the comparison of their results contribute to the overall quality of this work.

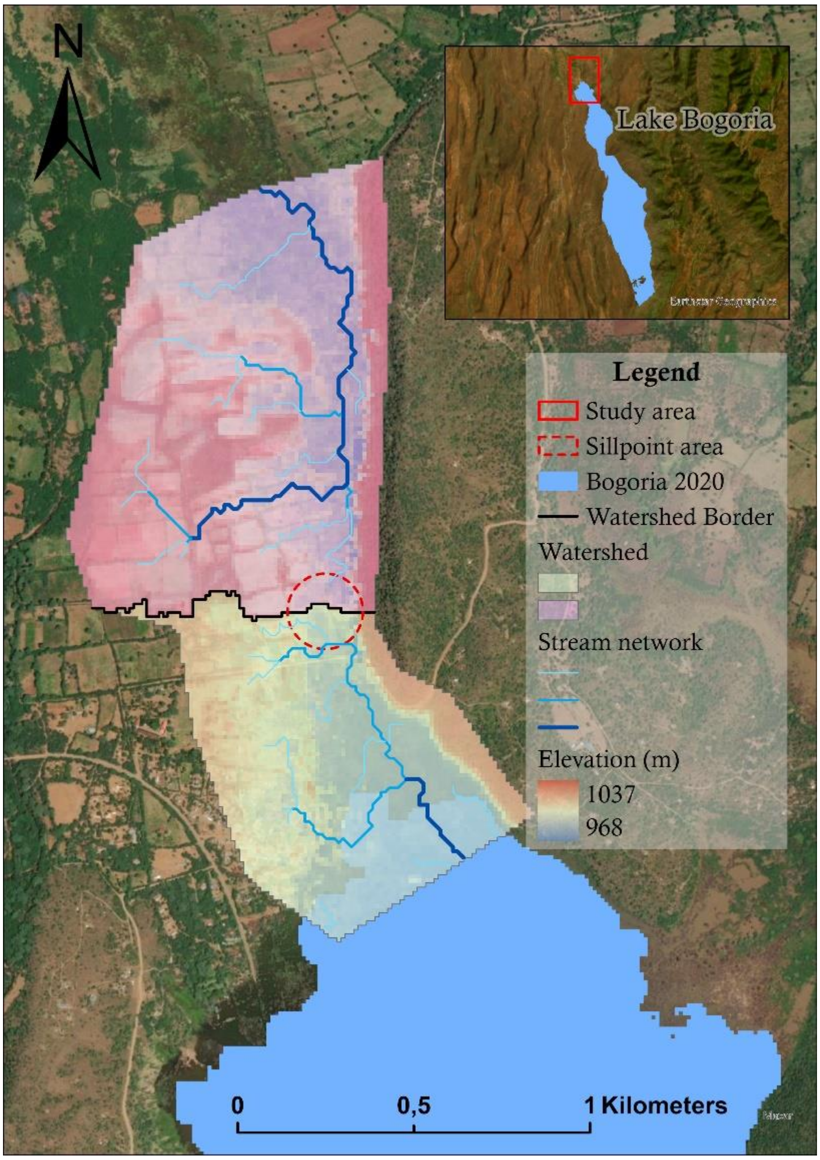

Figure 6: Visualisation of northern part of Lake Bogoria, including the sill point area in the red dotted circle, the watersheds and their border and the stream network. (DGFI-TUM, 2013, Schwatke et al. 2015, Sources: Esri, Maxar, Earthstar Geographics the GIS User Community)

The first approach identifies the sill point by finding the highest elevation along Lake Bogoria's northern stream network. The stream network of the study area (see Figure 6) is based on the DEM from the northern part of Baringo and represents the cells that have the highest flow accumulation from their neighbouring cells. It includes two different watersheds, which both have their own stream networks. In order to reach a potential overflow towards Lake Baringo, both stream networks need to be connected. Thus, the sill point has an elevation that merges the two networks and is located between their watersheds. The stream network link is created by tracing the cells with the lowest elevation values that could accumulate a flow. By combining both stream networks, elevation information and the link between the two watersheds, the cell with the highest elevation can be identified. The second approach is based on the border between the two watersheds of the northern Bogoria area. This approach is also built on the fact that the sill point is located between the two watersheds of Bogoria's northern DEM. The elevation information of the watershed border is retrieved from the DEM tracing the course of the watershed border. This approach differs to the first one by aiming at the lowest elevation, since this cell represents the area where flow between two watersheds could occur.

4.2.2 Additional water volume

The volume change assessment was performed through GIS analysis and calculations. The assessment is based on the sill point elevation, as the second research question investigates the needed additional water volume that is necessary for Lake Bogoria to reach the water level of the sill point. The difference between the sill point height and the water level of 982.8 m of Lake Bogoria is equal to the additional volume. The first step involves the creation of an elevation layer, which has the height of the sill point and includes the whole area around Lake Bogoria. The "sill point elevation layer" includes every raster cell that is below the height of the tipping point and represents Lake Bogoria with a water level of the sill point elevation. This elevation layer will be referred to as Layer A. As a result, the spatial extend of Lake Bogoria is increasing in Layer A, while it is also necessary to delete some cells. This applies for the cells that have a lower elevation than the sill point, but are falsely included in the DEM since are not connected to other cells that contribute to Lake Bogoria.

Afterwards, another layer was created with the height of Lake Bogoria's water level from DAHITI's record of the 24th October 2020, which is referred to as Layer B. In order to identify the water level of this day, the satellite data from DAHITI was combined with the TanDEM-X. This occurred by assigning Layer B the elevation value of Lake Bogoria's shore cell at its intersection with the stream network (see Figure 6). Layer B represents the actual height of Lake Bogoria, which can also be perceived as the reference for Bogoria's present water level. However, Layer A has due to its higher elevation or water level a bigger spatial extend than Layer B. Therefore, Layer B surrounding topography is extended to the same spatial extent as Layer A with Lake Bogoria water level. It is also important to mention that Layer A and B are not exceeding the sill point, since further flooded areas are beyond the scope of the second research question.

After obtaining Layer A based on the sill point and Layer B based on DAHITI's satellite data of Lake Bogoria and the surrounding topography, the volume was calculated by subtracting Layer B from Layer A.

This allowed to calculate the additional water volume, as the result from the subtraction is the height difference for each cell between Lake Bogoria's water level or its close by topography and the elevation height of the sill point. Each cell in the TanDEM-X has a spatial resolution of 12 x 12 m. Thus, the total additional needed volume was summarized as the height difference for each cell, multiplied by the spatial resolution of the DEM.

4.2.3 Water balance changes

After identifying the needed volume changes, an assessment was made of the changes in the water balance that enable the accumulation of the additional volume. This was performed by calculating the integrated catchment response (ICR). As mentioned before, the ICR is used to analyse annual water balance changes. However, as the additional total volume is known, the calculation of the ICR for lake Bogoria ICR_B was made by dividing its additional volume V_{AB} by its catchment area C_B.

$$ICR_B = \frac{V_{AB}}{C_B} \tag{2}$$

The ICR of Lake Bogoria's catchment reveals the hydrological alterations in each m^2 of the watershed that would be necessary, based on the simplified water balance, to accumulate enough water volume to reach the sill point. The assessment of the ICR analyses the annual changes in the components of the water balance. The water balance for a water body includes precipitation, actual evaporation and storage changes.

Instead of the formula above, following formula can also be used for the calculation of the ICR's components (Herrnegger et al. 2021):

$$ICR_{calc} = R - AET + Q_{gw} - Q_{out} = R - AET = R - \frac{AET}{R} * R = R * (1 - \frac{AET}{R}) \text{ (mm/a)} \tag{3}$$

where, ICR_{calc} is the integrated catchment response, leading to annual changes in lake water volume, R is the rainfall in Lake Bogoria's catchment in mm/a, AET is the actual evapotranspiration in mm/a, Q_{gw} is the potential underground flow, such as through groundwater and Q_{out} is the runoff from Lake Bogoria, e.g. by underground seepage. As mentioned before, the storage changes of the study area are unknown, it is assumed that Q_{gw} and Q_{out} are in equilibrium and cancel each other out, as it is done in the paper of Herrnegger et al. (2021).

Furthermore, *AET/R* is a ratio that describes the relationship between the actual evapotranspiration and the rainfall of the region, i.e. how much water from the rainfall is evaporated in Lake Bogoria's watershed compared to actual evapotranspiration. The AET/R ratio is based on the combination of CHIRPS and DAHITI dataset as in the work of Herrnegger et al. (2021) paper, which was derived from the period 2010-2020 for Lake Bogoria. The following formula was used in combination with equation (3), allowing to calculate the annual rainfall changes that lead to the ICR.

$$R = \frac{ICR_{calc}}{(1-\frac{AET}{R})} \text{ (mm/a)} \tag{4}$$

As a result, the rainfall R represents the precipitation that is occurring per m^2 in the catchment of Lake Bogoria, that leads to the annual change of the ICR. Due to the high dependency of the ICR towards changes in precipitation and actual evapotranspiration, the reliability of Herrnegger et al. 2021) data basis was investigated.

4.2.4 Sustained Flow

The fourth research question investigates the probability of a flow between the two study lakes. Therefore, a scenario was created, which assumed a hypothetical sustained flow between lake Bogoria and Baringo after Lake Bogoria's water level reaches the sill point. Based on the sustained flow scenario, the needed rainfall and water balance changes through the ICR were calculated to attain a theoretical flow of for example 10 L/s. As the water balance remains simplified, infiltration and altering evapotranspiration rates were denied. Stationarity is assumed. The first task for creating a sustained flow scenario consists in identifying the flow path of the stream between the study lakes. The combination of the GIS-generated stream network between the study lakes, historical maps from the 1970s (Figure 7) and local observations allowed the generation of a flow path. The historical maps were georeferenced through GIS and served as a valuable information source as they contain information about the past stream network. By combining the stream network generated by the DEM and the historical river information, a stream through the Loboi Plain was created. The local observations were based on field trips in the study area, which confirmed the presence of a flow channel between the study lakes.

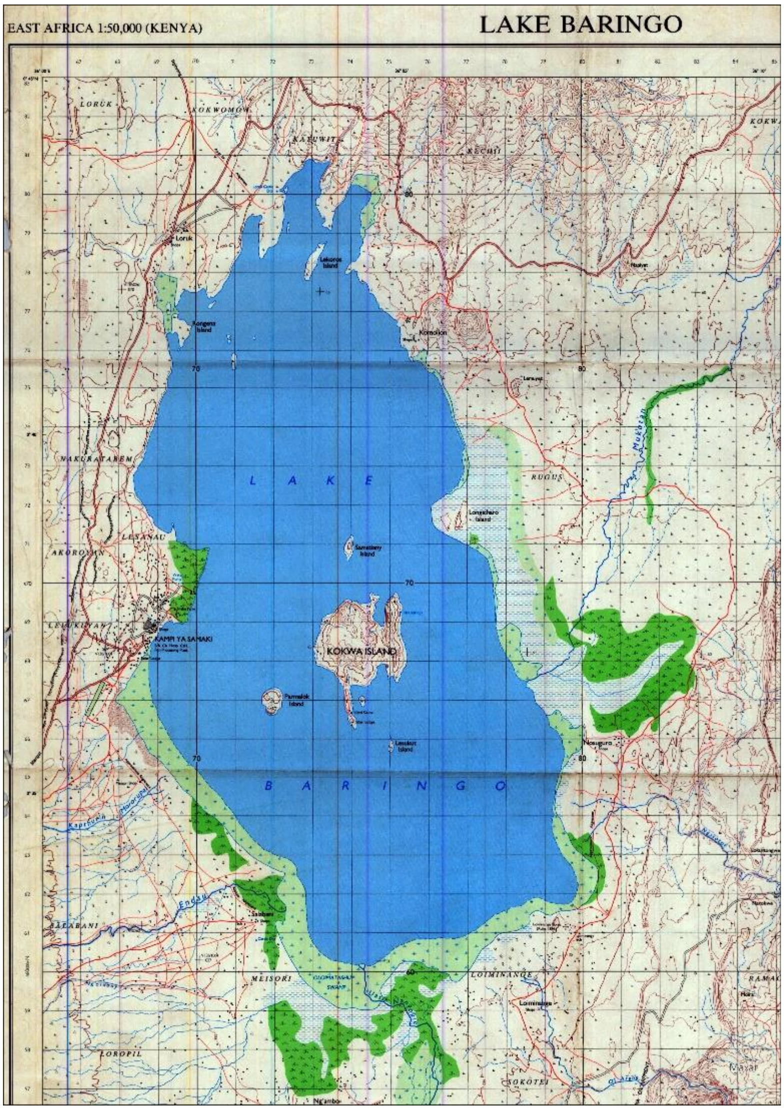

Figure 7: Visualisation of Lake Baringo's historical map contained various information, such as river network or lake extent. Grid: UTM Zone 37. Published by the Kenyan Government (1982)

The fourth research question assumes that Lake Bogoria has reached the water level of the sill point. The necessary changes for a sustained flow were determined based on the ICR and rainfall trend calculations in the precipitation data from 1984 to 2020. The necessary volume to reach a hypothetical flow of e.g. 10 L/s and the correspondent rainfall in the catchment are unknown. Therefore, a regression equation that relates the CHIRPS rainfall and the ICR during the 1984-2020 period is used to interpolate the rainfall. As the ICR relates annual water balance changes, the hypothetical flow scenarios and their respective volume accumulations are adapted to a yearly time scale. Furthermore, the calculation of the runoff depth (mm) occurs, by dividing the yearly volume accumulation through the catchment size. Based on the different volumes and runoff depths, threshold rainfall values for different flow scenarios are established, in order to assess the extent of ICR changes that are realistic and make a cross-contamination possible.

5 Results

5.1 Sill point height

The sill point height was consistent through the approach with the highest elevation point in the stream network and the lowest elevation in the watershed border. The same raster cell from the DEM has been identified as the sill point with an elevation value of 986.74 m. This elevation (and all elevations in this work) are based on the TanDEM-x DEM and may differ from other elevation data, e.g. from the Shuttle Radar Topography Mission (SRTM). The reason is that the vertical datums of the data sets may differ, while a vertical datum is a reference surface used as a zero elevation point (National Geodetic Survey, 2018). The horizontal and vertical datum of TanDEM-X DEMs is the World Geodetic System 1984 (WGS84) in G1150 realization (ellipsoid) (Rexer and Hirt, 2016; Wessel et al., 2013). In contrast, SRTM uses the World Geodetic System 1984 (WGS84) as horizontal datum and Earth Gravitational Model (EGM96) geoid as vertical datum. The elevation difference between TandDEM-x and SRTM in the north of Bogoria lies around 14.8-15 m (UNAVCO, 2021).

As mentioned in the methods, the first approach aimed at identifying the sill point through the highest elevation value in the stream network, whereas the second approach identified the sill point through the lowest elevation in the watershed border of Bogoria's northern DEM. On Figure 8, the intersection between the stream network and the watershed border occurs at the location of the sill point. As the different methods identified the same sill point, the highest point of the stream network represents at the same time the lowest elevation at the watershed border. For an overflow towards Lake Baringo, Lake Bogoria needs to rise to 986.74 m, which is approximately 3.85 m higher than the reference height used from the DAHITI records, i.e. the water level of October 2020. The water level of Lake Bogoria in October 2020 was – based on the WGS84 (G1150) ellipsoid of TanDEM-x and on the northern shoreline elevation of Lake Bogoria – 982,8 m.

When using the DAHITI product to retrieve water level data for Lake Bogoria, it is important to note that the accuracy of this data is not absolute in the present. The current water level of Lake Bogoria, as displayed in Figure 9, is based on satellite observations from 2023. The positioning of a nearby street can serve as a useful reference point for orientation. By comparing Figure 8 and Figure 9, it is evident that the street is now closer to the lake, indicating that the actual lake level is higher than the reference point used in this assessment. Consequently, Lake Bogoria may be closer to the sill point than initially assumed. Despite of the fact that the DAHITI product suggested a lower water level for Lake Bogoria, the approximate location of the sill point is not affected by its accuracy, as the threshold sill point elevation is a physical feature of the lake and its outflow.

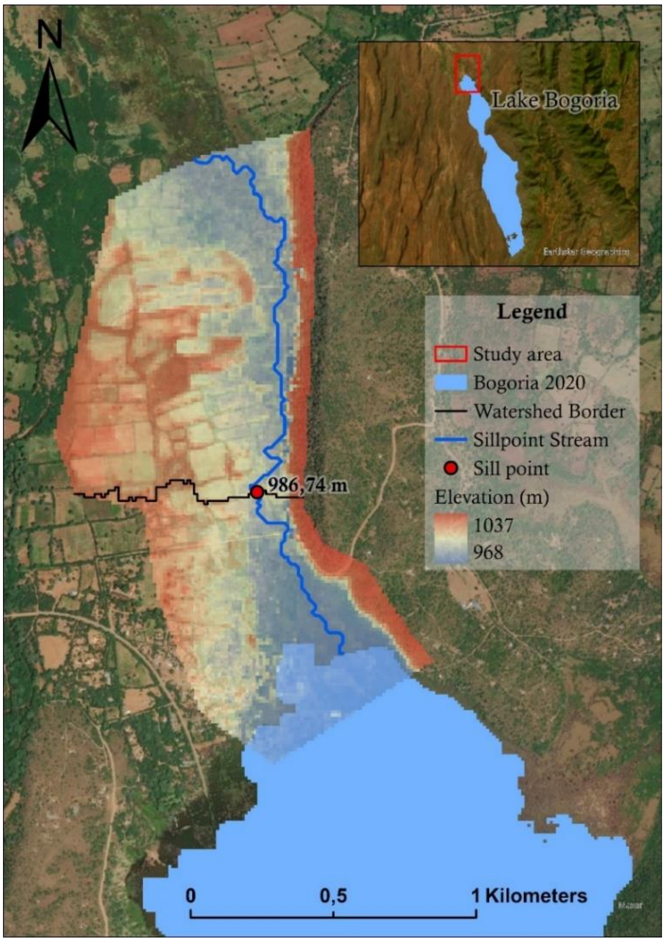

Figure 8: Location of the sill point at the intersection of sill point stream and watershed border. (DGFI-TUM, 2013, Schwatke et al. 2015, Sources: Esri, Maxar, Earthstar Geographics the GIS User Community)

Figure 9: Recent satellite water level observation of Lake Bogoria with increased accuracy (Google Earth, 2023)

5.2 Lake Bogoria volume changes

The spatial extent of Lake Bogoria is directly affected by its volume changes. As the lake's volume increases, its surface area expands, as seen in Figure 10. The latter compares the lake's extent in October 2020 to its level when the sill point elevation is reached. The increase in volume causes flooding in the northern part of the lake towards the Loboi Plain and submergence of the Kisibor Swamp in the North-East.

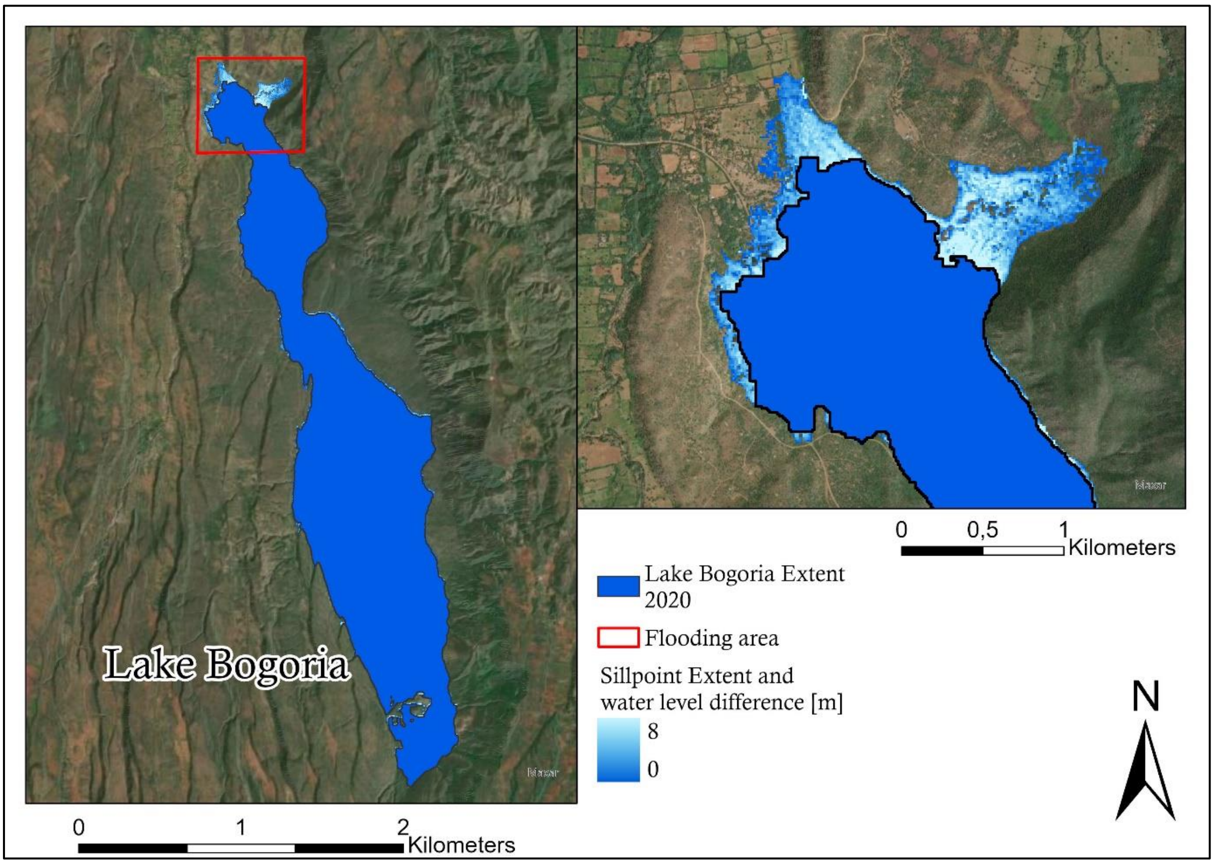

Figure 10: Lake Bogoria volume and extent changes with reference water level from 2020. (DGFI-TUM, 2013, Schwatke et al. 2015, Sources: Esri, Maxar, Earthstar Geographics the GIS User Community)

The calculation of Lake Bogoria's required volume changes included land area that is submerged for sill point Layer A, but not for the reference Layer B, due to their differences in spatial extents. The height differences of both layers at the water surface were 3.85 m, while the land areas surrounding Bogoria had elevation differences of up to 8 m, which were more pronounced at the northern part of Lake Bogoria or the Kisibor swamp. As a result, Lake Bogoria needed to accumulate an additional water volume of 166 440 480 m^3 or approximately 0.17 km^3 to reach the sill point, which expanded the lake's surface area from 42.1 km^2 to 44.1 km^2.

As mentioned before, it should be considered as shown in Figure 9 that Lake Bogoria is already closer to the spatial extension that equals the sill point, resulting in a overestimation of the needed volume changes and the calculations that are based on it.

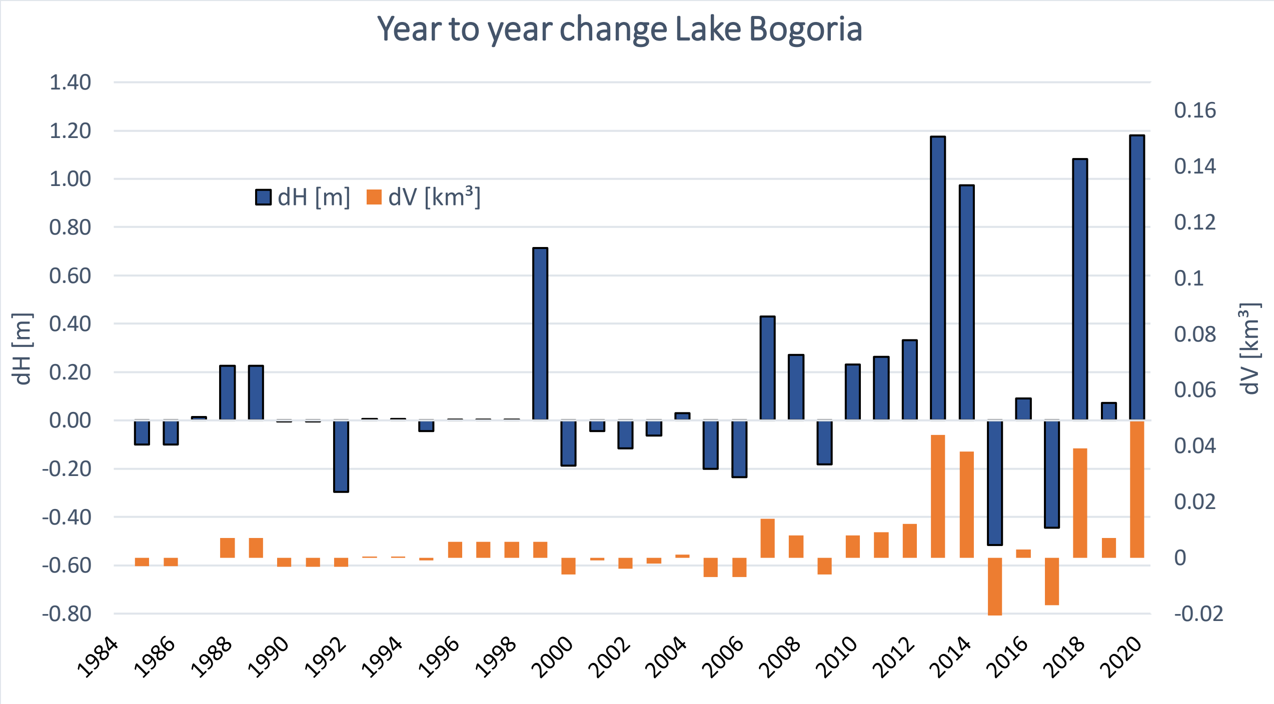

Figure 11: Yearly changes in Lake Bogoria 1984-2020 regarding (1) the differences in water level height – dH [m] and (2) the differences in lake volumes – dV [km3]

The yearly height and volumes changes during the measurement period 1984-2020 are displayed in Figure 11. The information from the plot shows a high variability in the lake water level and volume gains and losses, but it becomes apparent that especially during the reference period 2010-2020, bigger water surpluses have occurred. For instance, in 2020 Lake Bogoria received nearly additionally 0.5 km^3 water volume, whereas during the same period its water level increased almost 1.2 m. While putting those in relation with e.g. the needed surplus volume of 0.17 km^3, it shows what significant contribution 2020 has made to Lake Bogoria's potential overflow. Between 2010-2020 the mean yearly water level rate has a surplus of 0.4 m, while the mean volume increased 0.2 km^3. In the last decade, a few hydrological years managed to accumulate those substantial water amount and if this trend continues, it is foreseeable that Lake Bogoria will accumulate the needed additional volume and reach the sill point .

5.3 Water balance changes

As the water balance analysis for lake Bogoria's volume changes was dependent on the ratio between the AET/R and the work generally relied on few parameters, the results were very sensitive towards changes in evapotranspiration and especially precipitation. In order to investigate the reliability of the input data, the CHIRPS dataset and the ERA5-Land (ERA5L) dataset were assessed.

Herrnegger et al. (2021) also compared the CHIRPS and ERA5L datasets, as their analysis heavily relies on remotely sensed data as well. The assessment revealed that ERA5L provided substantially higher and unrealistic AET and rainfall values, while CHIRPS has been found to provide reliable precipitation data, which was confirmed by several studies in East Africa that show improved agreements with CHIRPS and gauging observations (Herrnegger et al. 2021). Furthermore, Nicholson et al. (2022) compared six products in the Lake Victoria region and stated that the CHIRPS satellite product showed in many studies excellence performance, especially for over-lake rainfall. Table 2 visualises the values from the ERA5L and CHIRPS products and strong deviations occur regarding Lake Bogoria's rainfall values for ERA5L (2118.1 mm) and CHIRPS (1227.5 mm). Due to the strong overestimation of ERA5L, the rainfall assessments in this work relied only on the CHIRPS product. Herrnegger et al. (2021) emphasizes the significance of benchmarking rainfall products derived from remote sensing or numerical modelling, such as CHIRPS or meteorological parameters obtained from ERA5L.

Table 2: Mean catchment water balance and Integrated Catchment Response (ICR) for Lake Baringo and Lake Bogoria during time periods 1984-2020, 1984-2009 and 2010-2020. Adapted from Herrnegger et al. 2021.

Water balance components and Integrated Catchment Response (ICR)

Lake	Period	ERA5L rainfall [mm/a]	ERA5L AET [mm/a]	ERA5L AET to rainfall [-]	CHIRPS rainfall [mm/a]	Adj. AET [mm/a]	Deviation of Adj. AET from 1984-2009 [mm/a]	Deviation CHIRPS rainfall from 1984-2009 [mm/a]	Dev. effective CHIRPS rainfall from 1984-2009 [mm/a]	Integrated Catchment Response [mm/a]
Baringo	1984-2020	1239.6	994.4	0.80	1020.7	816.6	28.4	82.4	54.0	6.9
Baringo	1984-2009	1158.7	969.5	0.84	938.3	788.2	0.0	0.0	0.0	-1.0
Baringo	2010-2020	1430.8	1053.0	0.74	1215.5	899.5	111.3	277.2	165.9	16.9
Bogoria	1984-2020	1840.1	1194.2	0.65	1029.5	669.2	16.6	83.7	67.1	6.6
Bogoria	1984-2009	1722.5	1187.6	0.69	945.8	652.6	0.0	0.0	0.0	-0.8
Bogoria	2010-2020	2118.1	1210.0	0.57	1227.5	699.7	47.1	281.7	234.6	14.6

Based on the equations in the methods, the ICR was first calculated by dividing the additional volume V_{AB} (166 440 480 m³) by the catchment area of Bogoria C_B (1 060 000 000 m²), resulting in the ICR (mm) that was necessary to accumulate the additional water volume. It was found through formular (1) that the ICR has a value of 0.157 m or 157 mm. Thus, the ICR result indicated that the water balance of Lake Bogoria's watershed needed a surplus of in total approximately 157 mm, to let the water level of Bogoria rise to the sill point.

In order to relate this ICR to its respective rainfall, the ratio between the actual evapotranspiration and precipitation *AET/R* was used, which had a mean value for the period 2010-2020 of 0.988. This value was based from Herrnegger et al. (2021) work, while the DAHITI volume variation time series and the CHIRPS rainfall were used to derive the *AET/R* ratio. Consequently, the rain is mostly evaporating in the catchment area and 1.2 % from the total rainfall contributes to the lake water. Based on this AET/R ratio, the necessary rainfall to achieve an ICR of 157 mm was calculated by formular (4) in the methods. In order to reach this ICR and sill point in one year, a rainfall of 13085 mm would be needed. This is very unrealistic, since the value is over 10 times higher than the average reference value of 1228 mm. Figure 12 visualizes the relationship between the percentual mean change in rainfall and the respective number of years that allows the study lakes to merge. The reference rainfall data included the period 2010-2020 and had a mean value of 1227,5 mm. Furthermore, Table (3) displays also the numeric values for different ICR scenarios. In case the sill point would be reached in one year, a rainfall surplus of 966 % would be needed, whereas the same surplus could be accumulated in 10 years with a yearly rainfall surplus of 7%.

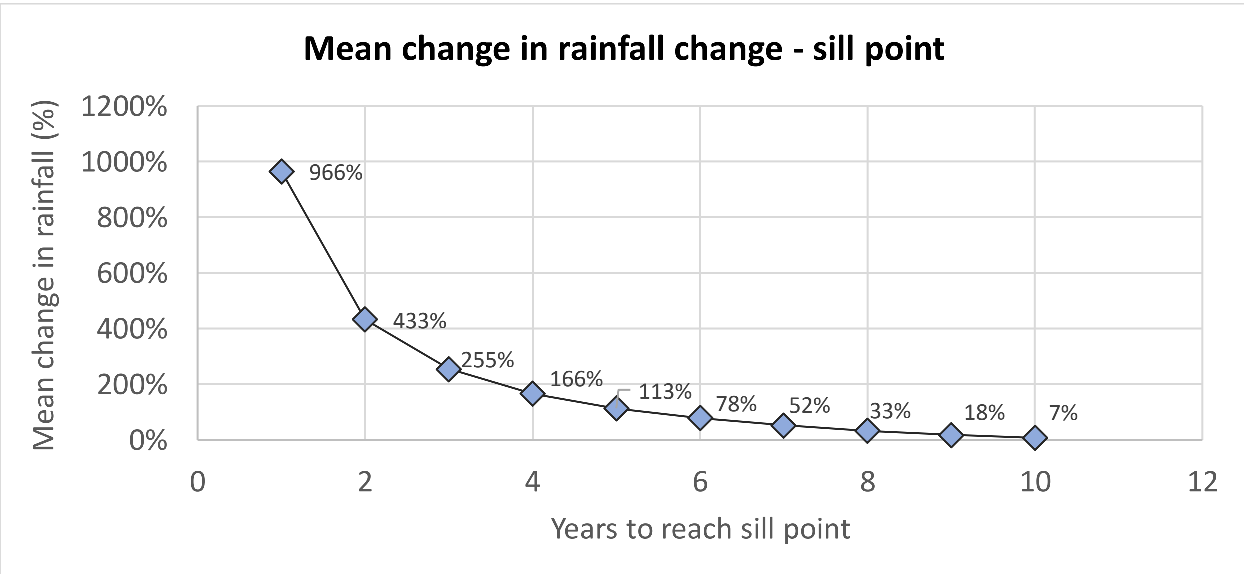

Figure 12: Relationship between percentage rainfall changes and number of years that lead to ICR - sill point

Table 3 : Calculations of percentage rainfall changes and ICR changes to reach the sill point

Years until water level reaches sill point	Necessary ICR (mm/a)	Rainfall (mm/a)	Reference rainfall (mm/a)	Mean change in rainfall (mm/a)	Mean change in rainfall (%)
1	157	13085	1227,5	11857	966
2	79	6542	1227,5	5315	433
3	52	4362	1227,5	3134	255
4	39	3271	1227,5	2044	166
5	31	2617	1227,5	1390	113
6	26	2181	1227,5	953	78
7	22	1869	1227,5	642	52
8	20	1636	1227,5	408	33
9	17	1454	1227,5	226	18
10	16	1308	1227,5	81	7

When comparing the ICR values required to reach the sill point and the actual ICR values for the period 1985-2020 (Figure 13), it became apparent that only few hydrological years exceeded the needed ICR values that would allow the ICR to be reached in 5 years. The highest ICR occurred with 46 mm in 2020, but nonetheless it was observed that an ICR of 157 mm in one year was unprecedented and was highly unlikely to occur. However, all hydrological years with a higher excess water balance for the lakes occurred in the period 2010-2020, confirming that the precipitation trend has been increased during this period, although the driest years also took place during this time period. The mean ICR value for the period 2010-2020 is 14.6 mm and the needed ICR value to reach the sill point in 10 years amounts up to 16 mm. For a potential cross-contamination between the study lakes it is crucial that the trend of excessive precipitation continues over the next few years, so that the sill point can be reached within approximately one decade.

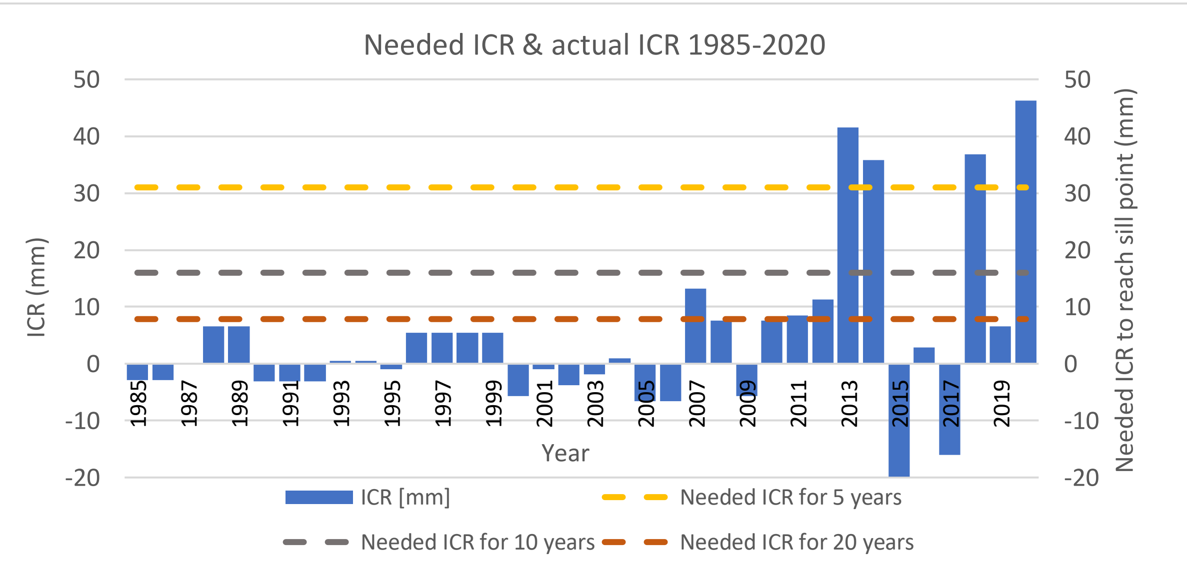

Figure 13: ICR of the period 1985-2020 and the needed ICR for 5,10 or 20 years to reach the sill point

5.4 Sustained Flow

The results of the sustained flow indicate the probable stream position between the study lakes. The sustained flow represents the scenario of a continuous flow between the study lakes, as its flow path overlaps well with the rivers and streams of the historical maps of Lake Baringo and Lake Bogoria. The hypothetical flow between the study lakes could contribute to the cross-contamination of the lakes, as salt water from Bogoria is flowing into the freshwater system Baringo. This stream will be referred to as Bogoria-Baringo (BoBa) stream. The BoBa stream drains northwards of Lake Bogoria through the swamps of the Loboi Plains and finally flows into Lake Baringo. It joins the Loboi river according to the historical maps from the 1970s, while it connects the Ng'uara swamp also with the Molo river (Figure 14).

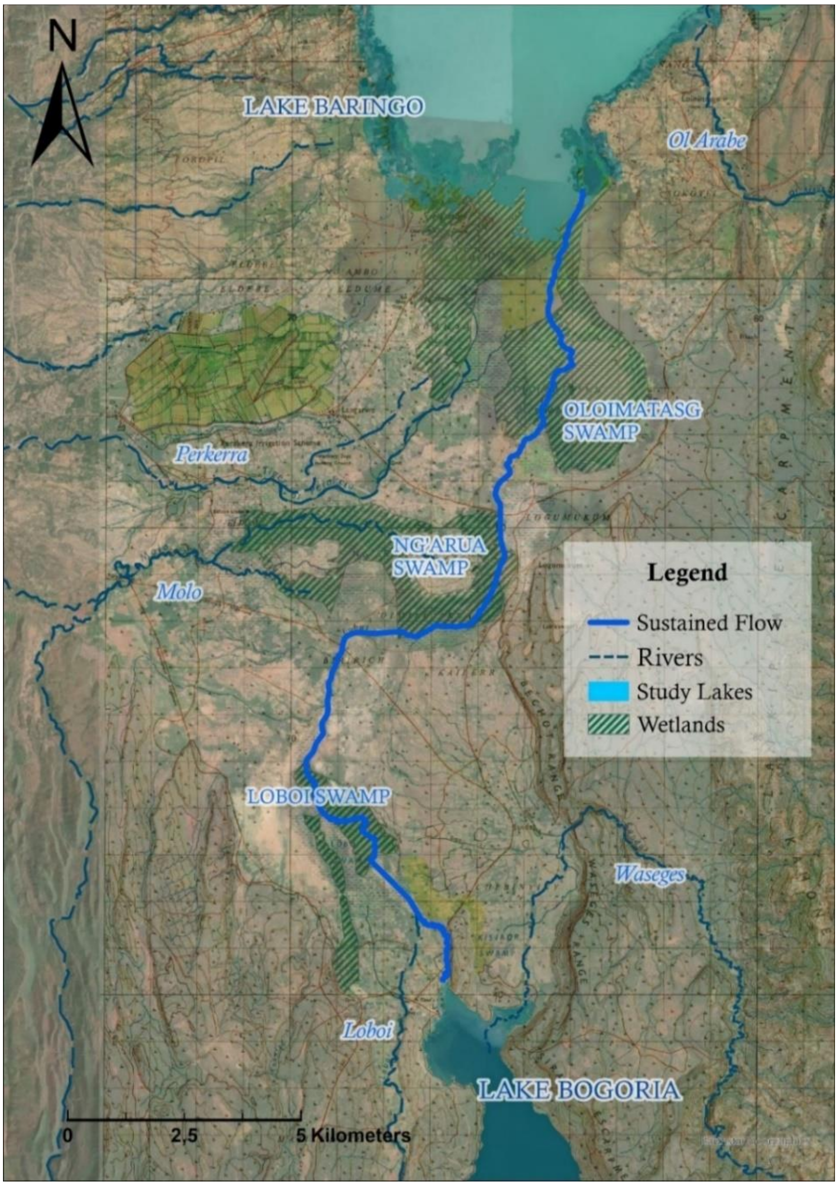

Figure 14: Visualisation of possible BoBa stream course between the study lakes (DGFI-TUM, 2013, Schwatke et al. 2015, Sources: Esri, Maxar, Earthstar Geographics the GIS User Community, OpenStreetMap 2023)

The rainfall amount for different sustained flow scenarios was derived from regression equations that related the CHIRPS rainfall and the ICR, which is represented in Figure 15. To ensure accuracy in data representation, very dry and wet years were eliminated by using two, three and five and ten yearly means of rainfall values and ICRs. The mean ICR values are higher for five-year means (M5) than for ten-year means (M10) due to the higher rainfall variability of the latter. The resulting precipitation value that is obtained from the regression equation served as the basis for creating different sustained flow scenarios, while the R^2 value represents the goodness-of-fit between CHIRPS and ICR, based on a linear model and a value of at least a value of 81 %. This represents a low variation outside of the model and a high linearity between the rainfall and the ICR. Thus, the rainfall increase corresponds also to a increase of the ICR.

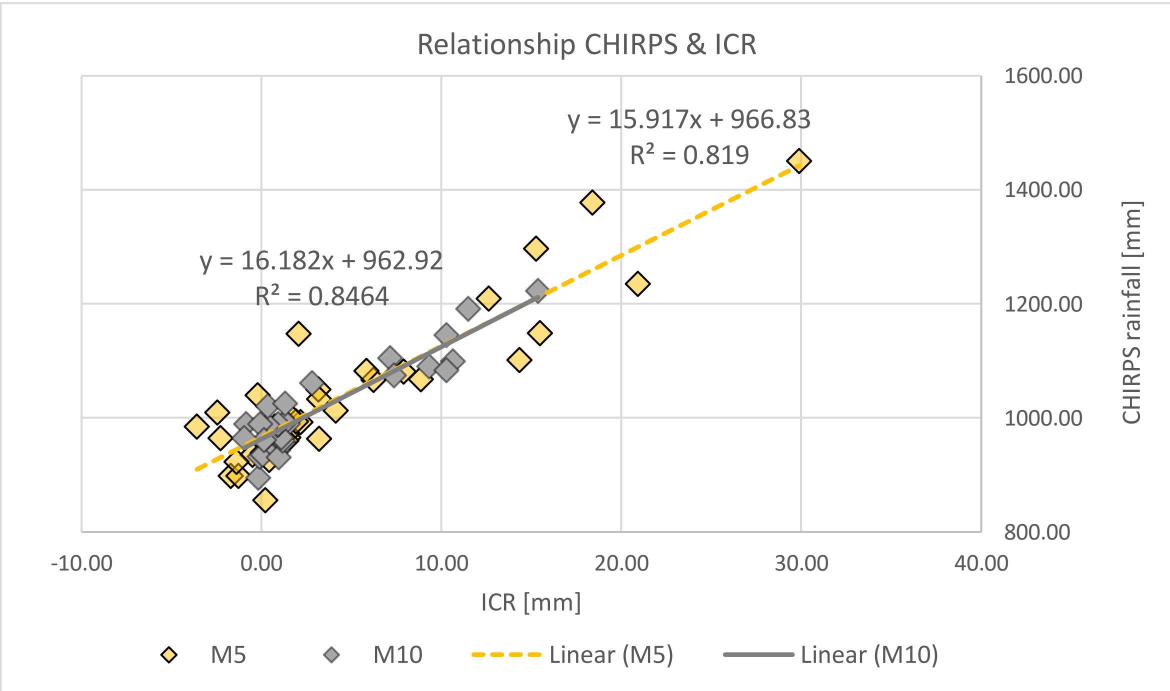

Figure 15: Relationship between AET/P and ICR based on (1) M2: two year means and (2) M5: five-years means; regression equations and correlation-indications

Based on the precipitation derived from the regression equations, the minimum and maximum rainfall was calculated to identify the precipitation range that would need to occur, in order to achieve different sustained flow scenarios for the BoBa stream of given 10 L/s, 50 L/s or 500 L/s. The minimum and maximum values were defined by the ICR's and CHIRPS moving average rainfall values of two, three, five and ten years in combination with the respective flow scenarios. Since the rainfall amount was derived from the regression equation, it is important to examine the value range of the rainfall amount. It can be retrieved from Figure 16 that the value range between the minimum and the maximum precipitation is not significant. The BoBa stream of 10 L/s can be achieved with a rainfall range between 972-988 mm, whereas the stream scenario of 1000 L/s ranges from 1349-1440 mm.

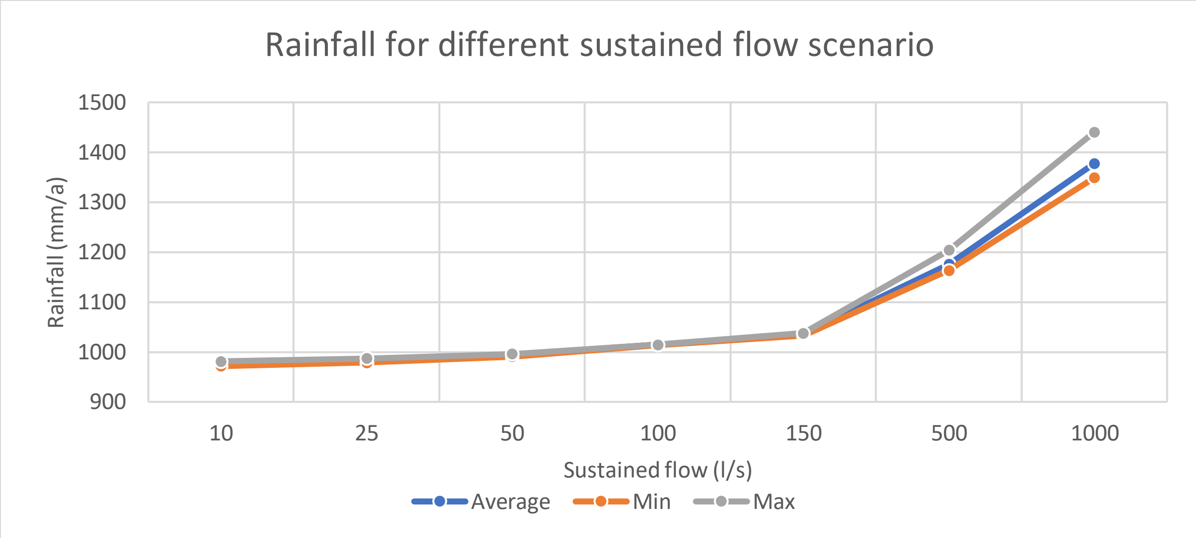

Figure 16: Relationship between different rainfall scenarios and respective occurring sustained flow towards Lake Baringo

The calculation of different rainfall threshold values for respective BoBa sustained flow scenarios revealed that small rainfall changes in the whole catchment are sufficient to reach the needed water accumulation to make a cross-contamination occur. The boundary conditions were assumed to be the same than in the past in these calculations, as the water balance has been simplified. This stationarity is especially true for the AET/P ratio, since this variable is crucial for the calculations of the precipitation values. Figure (17) summaries the calculations of this work and displays the precipitation values during the measured period (1984-2010) and threshold rainfall values that indicate whether or not it has rained enough in a specific year to fulfil a sustained flow between the study lakes. Especially in the last decade, the rainfall amount increased and was nearly every year sufficient to create a flow of 10 L/s between the study lakes, while the watershed experienced also enough rain to accumulate a sustained flow of 500 L/s. All these scenarios assume that Lake Bogoria water level has reached the sill point elevation described in the previous sections.

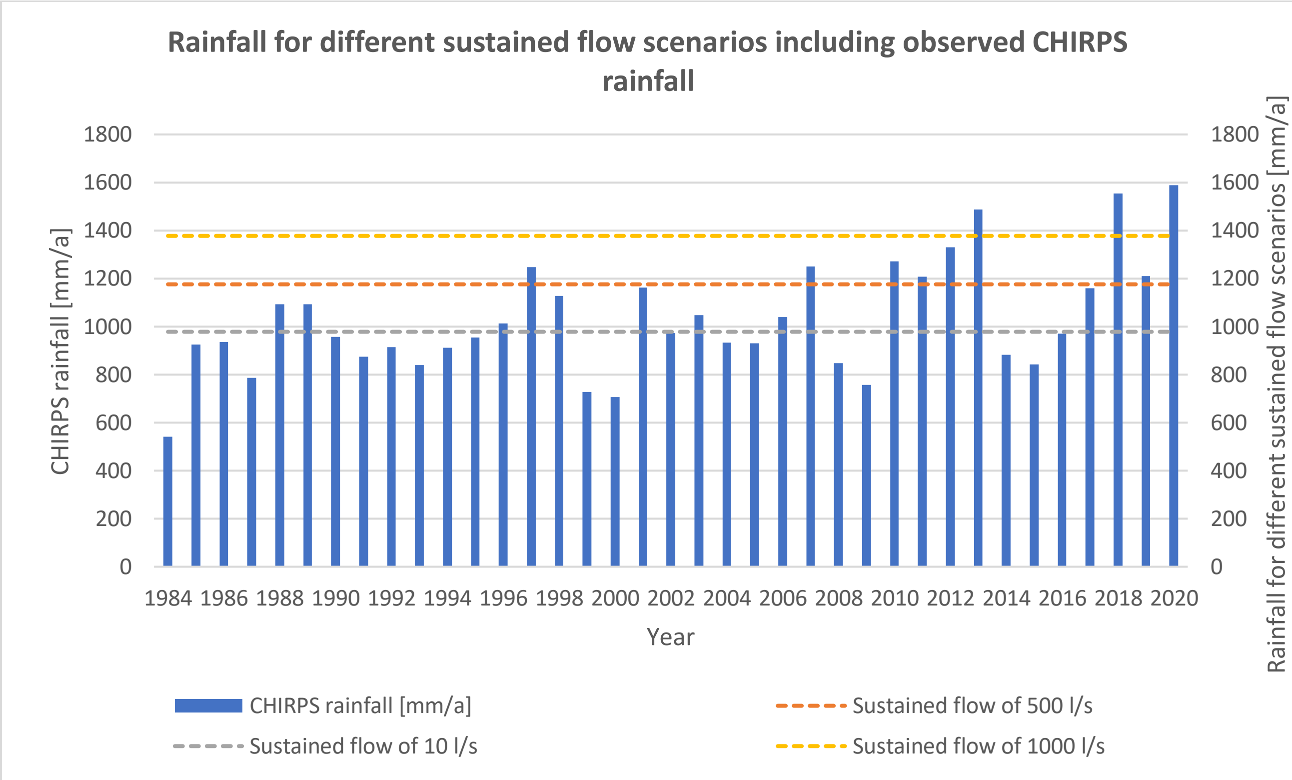

Figure 17: Relationship between the occurring rainfall from 1984-2020 and the necessary rainfall rate for different sustained flow scenarios

6 Discussion

The water balance analysis through the ICR supports the assumption that rainfall is an important component in relation to the study lakes upsurging water levels. The rainfall anomalies during 2010-2020 and the simultaneous volume increases of the Rift Valley Lakes are interconnected, which is confirmed by the calculations of this work. Although stationary boundary conditions were assumed, it could be shown that the rainfall increases alone led to substantial water volume changes. The fact that Lake Bogoria's reference rainfall of 1227.5 mm during 2010-2020 needs only to increase 7% for a duration of 10 years in order to reach a ICR surplus of approximately 16 mm showcases well how little climatic changes can have a big impact on lake water levels and ecosystems. Okech et al. (2019) supports this, by stating that East African lakes are sensitive to climate variations, while the effects on water levels are especially reflected in endorheic lakes. The calculations of this work mainly focused on the needed rainfall magnitude to make Lake Bogoria overflow and to create the BoBa stream towards Lake Baringo. While taking in consideration that a cross-contamination between the study lakes occurs stepwise over several years and that the sill point overflow and BoBa stream formation are processes, which slowly progress in a semi-arid area with high evapotranspiration, it is found that the needed rainfall changes are realistic on a long-term.

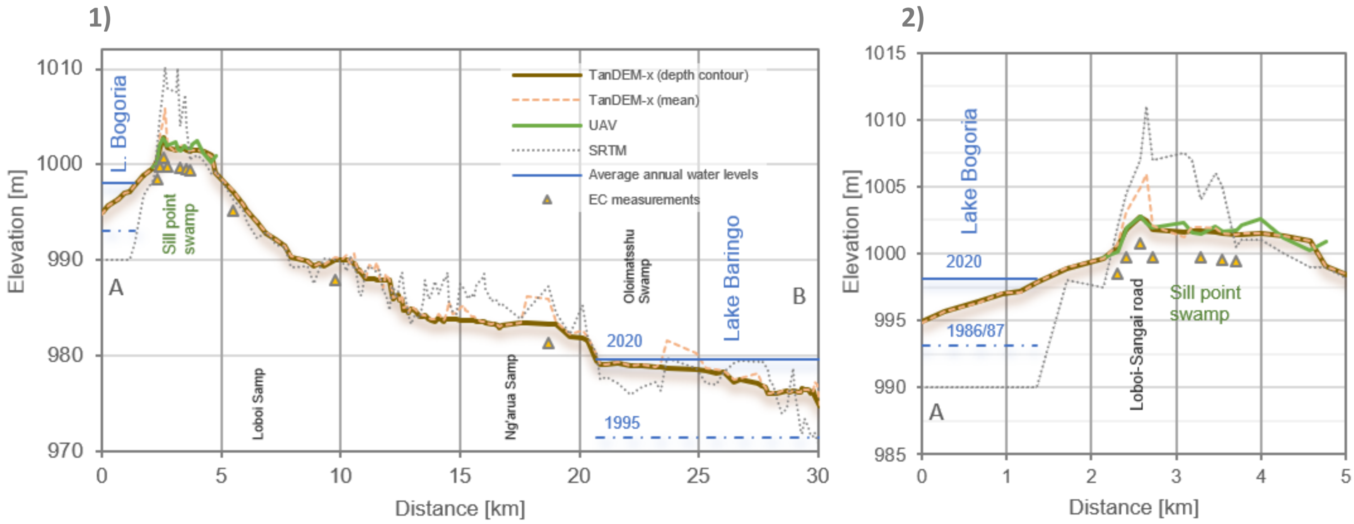

Figure 18: Visualisation of the (1) topography between Lake Bogoria and Lake Baringo, (2) Lake Bogoria's northern topography with the study lakes water levels. The elevation information stems from different DEMs, with different vertical datums. The elevation information stems from different DEMSs, with different vertical datums. The elevation values were therefore transformed into EGM96. (Based on work by Herrnegger: personal communication 2023b)

Once the sill point is reached no physical barrier between the study lakes prevents a cross-contamination (Figure 18). The topographical situation allows the water to flow from the sill point at Lake Bogoria downwards to Lake Baringo. Although Figure 18 is based on SRTM and not TanDEM-X elevation data, the sill point remains the only obstacle for a potential water flow between the study lakes. All the calculations performed in this paper are based on the used TanDEM-X based horizontal and vertical datum. The same analysis would yield different results regarding elevation if it was performed on a DEM using another reference system. The impact of various reference systems also becomes evident in the case of Lake Bogoria's sill point value of 986.74 m, despite the fact that, according to Herrnegger et al. (2021), the lake has already reached a water level of 994 m. The values are per se not wrong, but simply differ because they use different vertical datums.

In Figure 17, the relationship between rainfall occurring from 1984-2020 and the necessary rainfall rate for different sustained flow scenarios of the BoBa stream is displayed, providing insight into the rainfall variability of the last three decades of the study region. The required water quantity to create a sustained flow scenario of 10 L/s was accumulated by the rainfall records of various years during the measurement period, with pronounced inter-yearly variability of the rainfall resulting in substantial yearly rainfall differences ranging from <500 mm to nearly 1600 mm. Over the last 30 years, the overall rainfall trend increased, and high water level stands from one year with abundant precipitation can be sustained with more moderate rainfall, as noted by Nicholson and Yin (2001). Similarly, the volume change of the study lakes can be influenced by hydrological years experiencing very high rainfall followed by lower annual rainfall rates. According to GOK and UNDP (2021), the main reason for lake level changes in the study area can be attributed to climate change, due to the increased rainfall observations at the local gauging stations.

Nicholson and Kim (1997) state that the inter-annual rainfall variability in Eastern Africa is among others dependent on the Pacific El Niño-Southern Oscillation (ENSO). The rainfall magnitude of certain years is very pronounced, while the assessment of those fluctuations suggests that a periodic mechanism acts every 5-6 years, which is also the time range for ENSO years and sea surface temperature (SST) variations in the Indian Ocean (Nicholson & Kim 1997). The author further stresses that the rainfall tends to be above average during El-Niño years, although drought is more pronounced during La Niña years. Thus, local rainfall fluctuations are a response linked to local SST anomalies of the Indian Ocean, which are caused by the ENSO (Nicholson & Kim 1997). In the context of the potential cross-contamination between the study lakes, the ENSO years can explain the excessive rainfall during certain years and the big difference between the rainfall magnitude. Nevertheless, it is noted that especially the short-rain season during October-December that shows greatest variability according to the ENSO, while it is highlighted that the association with ENSO is stronger for wet than dry years (Nicholson 2017). However, even though ENSO is perceived as the primary driver of inter-annual rainfall variability, many factors contribute to the phenomena and their relationships are non-stationary (Nicholson 2017). Some of the most important are the ITCZ, zonal winds, Walker circulation and spatial changes due to topography and urbanisation (Koskei et al. 2018, Nicholson 2017).

Although seasonal climate variations are dependent on ENSO and SST, Ngaira (2006) claims that global climate patterns underwent strong variations during the last half century and that the most affected weather elements among others is rainfall. Therefore, climate change made the rainfall variability unpredictable in the study area. This is also supported by the fact that approximately 20 years ago, Aloo (2002) claimed that the Lake Baringo might desiccate periodically, even though the study region is currently struggling with extreme flooding.

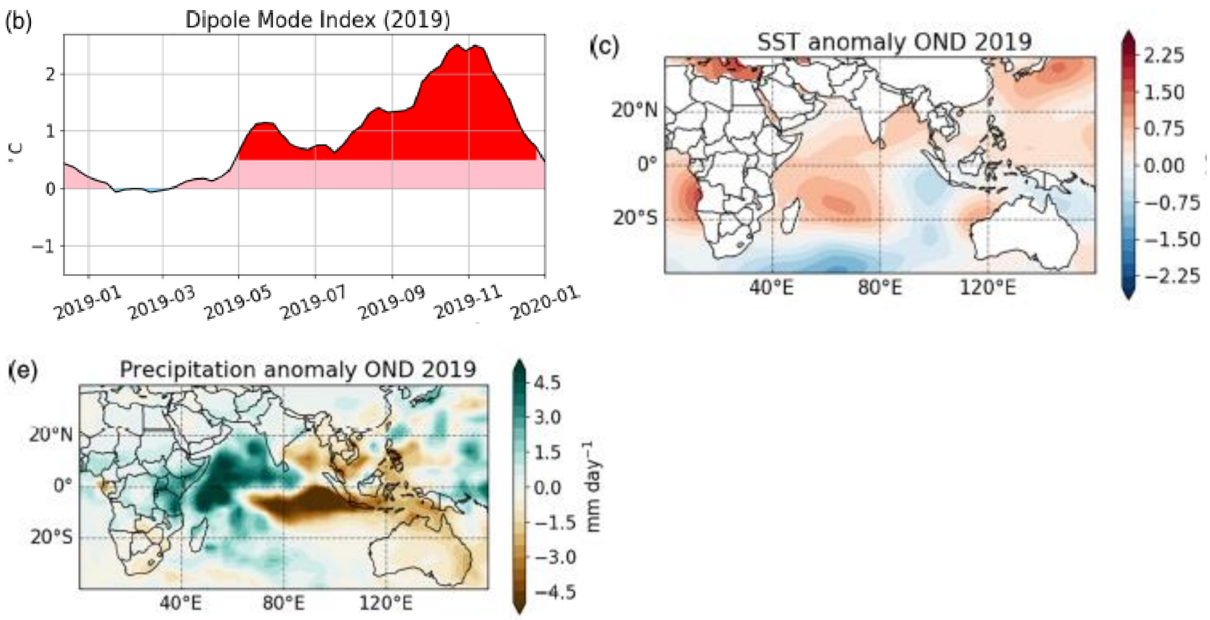

Figure 19: Illustration adapted from Wainwright et al. (2021) *showcasing the interrelation of the Dipole Mode Index (measuring the IOD) the SST anomalies and the precipitation anomaly during the short rain season October-November-December (OND)*

Further studies reveal also positive IOD (Indian Ocean Dipole) correlations between the rainfall variability in East Africa and SST anomalies (Figure 19). Generally, the IOD is the difference in SSTs between the east and west Indian Ocean, whereas warmer SST in the western Indian Ocean are responsible for enhanced short rain season in the study area (Nicholson et al. 2019, Wainwright et al. 2021). The influence of SST anomalies and their correlation to precipitation changes is also represented in Figure (19). The short rainy season during October-December 2019 was one of the wettest in decades and during the same time the IOD was strongly positive with abnormal enhanced SST of the western Indian Ocean, which is adjacent to East Africa (Wainwright et al. 2021). This shows that not only climatic phenomenon influences the rainfall variability between different years, but also within the same year.

The inter-seasonal variability is an important factor to understand the upsurges of the study lakes. The main rain season contributes disproportionally to most of the annual rainfall (Nicholson & Kim 1997), but it is important to consider the short rain season as well, as they have also led to substantial water level changes in 2019 (Wrainright et al. 2021). Especially concerning current and future climate change, climate models predict that rainfall variability throughout the year will be more pronounced by increased rainfall intensity during the short season with a higher frequency of climate extremes (Wainwright et al. 2021). It is also stated by Nicholson (2017), that the ENSO affects mainly the short rain season.

The inter-seasonal variability of the climate is also important to consider regarding flash-flood events. As mentioned before the LULCC homogenized the landscape through intensified cattle herding, resulted in soil degradation, compaction and enhanced erosion and sedimentation rates (Odada et al. 2006). The water recharge area of the study region is located mainly in steep hillslopes and with increasing erratic precipitation patterns, the LULCC plays a significant role in intensifying the flood events, as the buffer capacity of the watershed area is strongly compromised by the human activities in the study area (Odada et al. 2006). In combination with the alternating wet and dry seasons throughout the year, the infiltration capacity of the study site's clayey soils (Walumona et al. 2022) is reduced during the dry season, due to typical shrinkage and lower water retention of clay soils (Lu & Dong, 2017). Thus an erratic rainfall after a dry season can quickly result in a flash-flood, since the soils are quickly oversaturated in the study area and enhanced surface overflow occurs. Past intensive deforestation enhances also the intensity of flash floods in the region, which is evident by the fact that forested areas have decreased by 50% since 1976 (Odada et al. 2006). The missing forest reduces the groundwater recharge of the study area, which is a very important input for streams and lakes during the dry seasons. Furthermore, the LULCC changes might also result in faster upsurges of the study lakes water levels due to higher clogging of underground waterways, since higher erosion and sedimentation rates into lakes and streams are a by-product of the pastoralist local communities and the enhanced erratic rainfall patterns (Odada et al. 2006, Kiage & Liu 2009). In addition, the higher sedimentation can cause a rise of the lake bed that contributes also to higher water levels. Kiage and Douglas (2020) underline the sensitivity of watersheds to LULCC changes, as it can impact inflow and sediment yields. Thus, the LULCC contributes to the lake surface area changes of the study lakes, due to the disruption of the equilibrium between infiltration and run-off, resulting in alterations to surface hydrological processes (Kiage and Douglas 2020).

Although the LULCCs have already degraded the catchment area of the study lakes, the cumulative effects of the above discussed factors worsen the ecological impact from a potential cross-contamination. The study lake ecosystems are fragile and their resilience is strongly compromised through the climatic and anthropological impacts and a further big stressor might cause the biodiverse valuable region to finally collapse. More than a decade ago, Kiage and Liu (2009) stressed the importance to put effort in corrective measures, as the ecological changes affect also local population that evolved around those lakes and became dependent of the ecological goods provided by the study lakes. Koskei et al. (2018) underline also the vulnerability of a society that is determined by poverty, where weather extreme events restrict accessibility to resources and exclusion from decision making and missing social security occurs. The authors continue that the resilience capacity is weak in many places throughout Africa, where existential developmental challenges and limited access to capital, markets, technology and infrastructure; conflicts; and degradation occur (Koskei et al. 2018). This highlights the importance of measurements that support also the livelihoods of the locals, which are otherwise exposed to the climatic and hydrological changes that occur in the study area.

During the last decade the impacts of climate change became more pronounced in the study area through droughts and floods, aggravating the situation in the study area. The rainfall magnitude, its seasonally and yearly distribution and variability are altered. Those changes are especially intense in semi-arid regions, due to the dependency of biogeochemical cycles of water availability and timing (Koskei et al. 2018). Walumona et al. (2022) claim that physico-chemical properties and the ecosystem productivity are affected by water level fluctuations. Kiage and Douglas (2020) stress also that drastic changes in hydrology in combination with natural and anthropogenic disturbances result in danger to biodiversity. According to GOK & UNDP (2021) the once thriving flamingo population of 1-1.5 million individuals has been strongly reduced in Lake Bogoria to tens of thousands, who frequently suffer injuries from submerged thorny vegetation in the process of finding wading areas. The composition, abundance and distribution of aquatic organism are defined by the water body’s physico-chemical properties and the interactions with its surroundings (Walumona et al. 2022). Thus, changes of fish diversity and in populations can be expected to occur, also in correlation with the higher turbidity levels that occur in the lake catchment areas (Walumona et al. 2022). This could be a big loss for Kampi ya Samaki, the main fishing village close to the shores of Lake Baringo, which has a population of ca. 1500 people that mainly depend on fish as food source (Aloo 2002). In case of a cross-contamination of the study lakes, the lake properties of both study lakes and the wetlands in-between will strongly be altered. As a consequence, further changes in the previous aquatic flora and fauna are highly likely, while the currently struggling species will be exposed to more severe disturbances. In order to protect the livelihood of the locals, the natural diversity of the study area and its prevailing aquatic environments, it is mandatory to come up with appropriate management plans.

6.1 Uncertainties

The interpretation of the study lake's water balance is a complex problem (Nicholson and Yin, 2001), which has been simplified due to lack of data and feasibility. The climatic interpretation of a lake requires an extensive understanding of the basin characteristics, due to regional-scale influences on the surrounding topography and lake geometry (Nicholson and Yin, 2001). For this assessment the boundary conditions of the catchment area are assumed to be constant, which make it possible to perform the ICR analysis or to interpolate the rainfall, allowing to identify the rainfall amount that is needed to create a sustained flow. The results of this analysis have to be interpreted carefully with the consideration that in real conditions the interactions between the rainfall rate and its contribution to the water level are more complicated. The approach of applying the ratio of AET/R or the ICR are based on lake Bogoria's catchment aggregated values. Storage changes, (groundwater) infiltration rates, interception and further hydrological processes are not quantified. The representation of the BoBa stream watercourse in Figure 18 shows that the flow path would cross several wetlands, which would also intercept a considerable water amount through transpiration. The study relies on few parameters as more processes can't be included in this work due to missing information. It is apparent that for these reasons the actual rainfall magnitudes to reach Lake Bogoria's sill point or the sustained flow of the BoBa stream can differ.

The data basis for this assessment has also uncertainties. Firstly, the used TanDEM-X provides absolute values, but as mentioned before the data provides mean elevation of 12 x 12 m grid cells and they are to be seen in relation to the used reference system and geodetic datum. Therefore, the resulting sill point value of 986.7 m is not an absolute threshold value, but more of an indicator of how much Lake Bogoria needs to rise to start the formation of the BoBa stream. Relative changes are at the same time more robust. This would mean that the BoBa stream could start to form once that lake Bogoria's water level rises approximately 3.85 m compared to its water level in the October of 2020.

Secondly, it is also important to note again that the orthophoto of Lake Bogoria's northern part (Figure 9), shows clearly that the water extent is bigger than measured by DAHITI. Although the orthophoto has been taken on the same date than DAHITI's lake surface area record, the extent of Lake Bogoria differs. The reason for the underestimation from the satellite product is the low water depth of the additional water area, while this area was falsely classified to land by the satellite product. Thus, Lake Bogoria has already reached a higher water level than the used reference height of 982.8 m that is used.

The needed water upsurges to reach the sill point are therefore also overestimated, which are according to Herrnegger (2023a) only 0.8 m, making a significant difference to the needed volume accumulations and needed ICR changes.

Thirdly, the calculations performed in this work are primarily based on rainfall data, which values are derived from the CHIRPS satellite product. However, as pointed out by Herrnegger et al. (2021), the local gauging station at the Snake Farm on the shores of Lake Baringo inidcates higher interannual rainfall variability compared to CHIRPS. Given the study area location in a semi-arid valley surrounded by humid highlands, there's a significant climatic range with varying rainfall. For instance Lake Baringo receives an annual rainfall of 450-900 mm, while the humid hillslopes of the drainage basin have a varying rainfall between 1100-2700 mm (Odada et al. 2006). As a result, it is uncertain to what extent the CHIRPS satellite product is able to provide accurate rainfall records. Moreover, due to the lacking density of functioning gauging station in the area, the rainfall data from CHIRPS cannot be validated.

6.2 Recommendations

Further research is needed to enhance the accuracy of flooding prediction. Such information will be central, in order to avoid the construction of homes on the potential floodplain and to enhance the efficiency of future decision-making processes. This work has shown the influence of rainfall on the study lakes water levels, such as the importance to keep track on the rainfall developments in future management plans.

It is recommended to establish water retention programs, which improve the catchment water retention capacity (Herrnegger 2023b). This can occur by initiating re-afforestation projects, which focus on improving the soil quality of the study area and enhance its buffer capacity by increased groundwater recharge and reduced soil erosion. According to Aloo (2002), the water diversion projects in the region made the study lake and their hydrological balance vulnerable to disturbances, as their resilience capacity has been compromised. In order to ensure the success of afforestation programs, mitigate the degradation of the catchment through LULCC and to partially restore the resilience of the catchment, it important to implement protected zones for the forested areas and the watershed area. This measure could further fuel the conflict potential between pastoral communities, since they loose more land for their livestock through protected zones.

It is important to include not only pastoral communities, but also all the involved stakeholders in the decision-making process of planning protected zones. Compensation should be agreed upon in case that a party loses land, which represents an important economical income source for them.

Muia et al. (2021) mentions also flood adaptations measures and early warning systems to prepare affected areas and reduce the potential flooding damage. According to Herrnegger (2023b), society needs to be prepared in order to reduce human and economic losses, which can be achieved by making information accessible and understandable to the people. The author further emphasizes that the expansion of hydroclimatic on-site measurement stations, as well as the observation and assessment of their data, would provide an improved basis for planning and comprehending the lake upsurges. This would also benefit the creation of flood risks map that show endangered flooding zones, which range from riparian areas to critical infrastructure such as roads, hospitals or schools (Herrnegger (2023b). The author stresses that historic high stand of water levels should be considered in the flood risks maps, as it sets a reference to a potential worst-case scenario. When it comes to flood adaptations, the importance of technical and natural measures are underlined by the author, which could reduce flood peaks by improved infiltration of rainfall or surface runoff. Such measures not only mitigate the magnitude of flooding events, but they also benefit the landscape and ecosystem if a natural-based approach is taken (Herrnegger 2023b).

At last, it would also be important to assess the ecological potential changes that could occur in case of a potential cross-contamination, which is likely to occur according to the results of this study. With the current increasing rainfall trend, it is foreseeable that further habitats might be lost to the floodings and that alterations in aquatic habitats might occur. Since the study area provides different habitats for an abundant biodiversity and has international designated nature reserves and water bodies, it is crucial to assess how the cross-contamination and habitat losses through floodings might threaten certain species. Therefore, it is also recommended to assess with further studies, which species are mostly affected by a potential cross-contamination and how their respective threats can be reduced by mitigation measures.

7 Conclusion

Over the past decade, the Great Rift Valley in Kenya has experienced a continuous increase in water levels, resulting in a range of negative social, economic and ecological impacts. The local settlements around the Rift Valley Lakes have been particularly affected, with floods causing the loss of residential areas, essential infrastructure, agricultural fields and tourism facilities. The rising water levels have threatened internationally recognized biodiversity hotspots through habitat loss and degradation, and there is a growing concern that the potential merging of the alkaline Lake Bogoria and freshwater Lake Baringo could lead to an ecological disaster.

This study focuses on investigating the hydro-climatic factors driving the rise in water levels, as well as assessing the potential for cross-contamination between Lake Baringo and Lake Bogoria. The investigation involves the identification of Lake Bogoria's sill point, as the needed volume and rainfall changes that are required to achieve that level. At last, the potential merge between the study lakes is assessed by creating hypothetical flow scenarios and their respective calculations of required rainfall changes. The analysis relies on remotely sensed data, including the TanDEM-X for elevation information, DAHITI for lake surface area and time volume series, and CHIRPS for effective rainfall in the Bogoria catchment. By relying on this data, the study aims to provide a thorough understanding of the hydro-climatic influences behind the rising water levels and the likelihood of a catastrophic merge between the two lakes.

The results show that over a long-term period, small rainfall changes in the catchment can cause big effects on the lake water level. Based on the assumption that DAHITI provides an accurate water surface area of Lake Bogoria, the sill point can be reached if the water level rises additionally 3.85 m. The respective volume and rainfall changes assessment revealed that over a time period of 10 years, only a 7% increase in rainfall in comparison to the reference rainfall period 2010-2020 is enough to accumulate the needed water volume to reach the sill point. The further analysis reveals that once Lake Bogoria overflows, a stream of smaller magnitude between the study lakes is very likely to occur, due to the fact that most hydrological years from 1984-2020 accumulated enough rainfall to create a flow scenario of 10 L/s. It has been successfully demonstrated that increasing rainfall contributes significantly to the water level rises of the study lakes, even though the catchment's boundary conditions were assumed to be stable. With the current climatic trend, it is foreseeable that Lake Bogoria may soon merge with Lake Baringo. This is particularly concerning since lake Bogoria is closer to the sill point than assumed by the DAHITI dataset, missing only 0.8 m water level rises to overflow.

The findings of this study have contributed to the actual understanding of upsurging water rises from Lake Bogoria and Lake Baringo. This work has also provided new insights by demonstrating the differing water extent of Lake Bogoria in the orthophoto and the DAHITI product, both of which were recorded on the 24th October 2020. The latter is especially important for further research, as overestimations in the calculations performed in this work can serve as a basis for more accurate impact assessments that carefully consider the initial water extent of Lake Bogoria. Consequently, urgent action may be required to prevent further damages, as the sill point and potential cross-contamination could occur earlier with the current increasing rainfall trend.

Important future work should include further studies and mitigation measures to reduce the potential damages in the study area. This will require a multifaceted approach that considers social and ecological factors, which include social preparedness, anticipatory flooding risk maps, improvements of the catchment buffer capacity through afforestation initiatives and studies on the behalf of ecological implications. The contribution of these efforts would allow to prevent or mitigate the consequences resulting from of the rising water levels of Lake Bogoria and Lake Baringo. At last, they could also serve as important basis for decision-making processes in similar cases that may occur in the future due to climate change.

8 References

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9 Appendix

Table 4: Data basis used for the calculations performed in this work. Adapted from Herrnegger et al. (2021). Lake Bogoria's catchment rainfall [mm] is retrieved from CHIRPS, while mean annual lake level [m] and lake volume variation [km²] stem from the DAHITI dataset.

Year	Catchment rainfall [mm]	Mean annual lake level [m]	Lake volume variation [km²]
1984	541.84	993.3	0.008
1985	925.05	993.2197	0.005
1986	936.86	993.1	0.002
1987	785.34	993.1	0.002
1988	1091.84	993.3585	0.009
1989	1092.59	993.6	0.016
1990	957.05	993.58056	0.01267
1991	873.85	993.57711	0.00933
1992	913.65	993.3	0.006
1993	840.67	993.28775	0.0065
1994	911.1	993.3	0.007
1995	954.5	993.3	0.006
1996	1012.63	993.25202	0.01175
1997	1248.22	993.25371	0.01750
1998	1126.48	993.25540	0.02325
1999	727.11	994.0	0.029
2000	707.05	993.8	0.023
2001	1162.66	993.7	0.022
2002	972.88	993.6	0.018
2003	1047.84	993.6	0.016
2004	934.15	993.6	0.017
2005	931.02	993.4	0.01
2006	1038.86	993.2	0.003
2007	1250.36	993.6	0.017
2008	848.61	993.9	0.025
2009	757.64	993.7	0.019
2010	1270.91	993.9	0.027
2011	1206.44	994.2	0.036
2012	1329.42	994.5	0.048
2013	1486.47	995.7	0.092
2014	882.37	996.6	0.13
2015	842.67	996.1	0.109
2016	970.23	996.2	0.112
2017	1159.54	995.8	0.095
2018	1554.91	996.9	0.134
2019	1211.57	996.9	0.141
2020	1588.2	998.1	0.19