

Review

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Review

The Shrinking and Expanding Eastern Africa Rift Valley Lakes: The Case of Ethiopian and Kenyan Rift Valley Lakes: Review

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Abstract: Morphological study of lakes defines the sensitivity of their watershed. Moreover, it plays important role in safeguarding the lake's ecosystem services through proper planning and utilization of the lakes' resources. In the last few decades, the morphology of lakes in Ethiopian and Kenyan Rift (EKR) valley are experiencing contradicting morphological changes. Being in the same system, some are shrinking and others are expanding beyond their natural boundaries. The objective of this review is to shed light on the trends in spatio-temporal water level fluctuation and their contributing factors for lakes to the academia and decision makers. Peer reviewed article journals, conference proceedings, thesis, and book chapters collected from online sources and supplied by authors on request formed a database of 346 documents where 226 are critically assessed. The review indicated that lakes in Ethiopian rift are shrinking and expanding, while Kenyan lakes are expanding. The endorheic lakes suffered the most fluctuations due to anthropogenic factors at the expense of loss of forest and woodlands in their watershed. While the lakes' water quality related to the morphological changes are given less attention, the predicted 12 m drop of Lake Turkana due to projects in the Omo catchment did not materialize.

Keywords: east Africa rift; size of lakes; lake expansion; shrinking of lakes

1. Introduction

The East Africa Rift (EAR) is the most extensive and densely faulted rift that extends from the Middle East southward to African continent transecting Ethiopia, Kenya, Uganda, Rwanda, Burundi, Zambia, Tanzania, Malawi, and Mozambique [1]. It is home to over 30 volcanic and tectonic lakes that are characterized by their oldest, deepest, largest by-area and by-volume lakes termed as the Rift Valley Lakes [2]. These lakes and their environments are important ecosystems supporting a wide-ranging socio-economic and ecosystem services.

The EAR system in its EKR portion is characterized by a chain of lakes-nested in echelon fashion; stream and wetlands-of various sizes and ecological settings [3]. It consists of Abaya, Chamo, Shala, Ziway, Langano, Abijata, Chitu, Beseka, Afdera, Chew Bahir, Hawassa and group of Afambo-Abhe Lakes in Ethiopia. Conversely, Kenya is home to Lakes Elementaita, Nakuru, Bogoria, Baringo, Logipi, Turkana, Magadi, Naivasha, and Solai in its rift valley portion.

In Ethiopia, the rift valley lakes are physically arranged in a NE-SW direction from the Danakil Depression to Chew Bahir, bisecting the Ethiopian highlands into two. Some of these lakes are freshwater eco-regions of great biodiversity, while others are saline-alkaline "soda lakes" supporting highly specialized and a wide variety of flora and fauna.

The Ethiopian rift valley is divided into three geographic zones owing to their structural features as the northern, the central, and the southern rift valley portions. The Northern Rift System in Ethiopia ranges from Afar to Adama (consisting of the Afar triangle up to Lake Beseka). The Central Rift Valley (CRV) system ranges from Adama to Hawassa that is characterized by a tectonically controlled endorheic basin features consisting of a chain of four hydrologically interconnected lakes;

Lake Ziway, Lake Abijata, Lake Langano and Lake Shala. Finally, the Southern Rift System ranges from Hawassa to Chew Bahir encompassing the Hawassa, Abaya, Chamo, and Chew-Bahir Lakes.

Similarly, according to [4], the Kenyan rift system consists of three distinct basin areas. The first one is the Turkana basin that consists of Lake Turkana and Lake Logipi. The second section is the Kenya Dome basins containing Lakes Naivasha, Oloidien, Elmenteita, Nakuru, Bogoria, Baringo, Solai, and Ol' Bolossat. It is bound by Sattima–MarmanetLaikipia Escarpment on the east and Mau Escarpment on the west. The last portion is the Lake Magadi basin containing Lake Magadi and Ewaso Narok South Wetland swamp.

With the exception of the small crater lakes, the alkalinity of the lakes in Ethiopia increases as one goes from south to north. In fact terminal lakes without surface water outlets such as Lake Abijata and Lake Shala in Ethiopia and Lake Bogoria and Lake Nakuru in Kenya have very high alkalinity so that they can be used for abstraction of salts. The lakes in Afar depression have very high salinity and were used for the abstraction of salts for centuries [5].

The EKR valley lakes form an important migration route for Arctic birds [5] and Palaearctic birds [4,6] during the winter season in the northern hemisphere. For instance, the muddy shore of Lake Abijata and Lake Baringo supports a wealth of bird life unequalled over perhaps the whole of Africa.

The Ethiopian CRV hosts the Abijata–Shala Lakes National Park, one of the biodiversity hotspot that is submitted by the Ethiopian government to the Ramsar convention on wetlands in order to be recognized as international Ramsar site for resident and migratory birds [7]. Moreover, the Bird Life International has identified the area as one of the important bird habitats in the world [8]. Conversely, the Kenyan rift valley hosts the Lake Baringo, the Lake Bogoria, and the Lake Nakuru gazette Ramsar sites.

Recently, the lakes located within the EAR system are revealing contradicting lake water level fluctuations. Some of the Ethiopian rift valley lakes, especially located in a terminal position, have undergone significant lake level changes since the late 1960s and early 1970s [9]. Similarly, major water level fluctuations are noted in the Kenyan rift lakes since 2010 [10]. Thus, in the last fifty years, the EKR valley lakes and the land resources have been under diverse interdependent and interrelated natural and anthropogenic stresses. This region is thus considered endangered due to anthropogenic environmental and climatic changes [11]. Voluminous publications on the status of water level fluctuation and the spatial and temporal pattern of rift valley lakes morphology exist but not organized, not focused, and even some publications contradict the existing facts, despite the fact that the lakes rapidly changing over time [12].

This situation calls for a comprehensive actions to ensure the sustainable utilization of the rift valley lakes and their watersheds. Thus, it is important to compile the trend in water level fluctuation using up-to-date data on the spatio-temporal coverage of the lakes that are experiencing remarkable changes in their size and the driving forces.

This review attempts to integrate the vast majority of literatures on the trend in the fluctuation of water level of selected EKR valley lakes with the aim to shed light to the academia, policy designers, decision-makers and planners. In this review, research articles related to the lake level fluctuations, LULC change, and their concomitant impacts on the spatio-temporal trend of Lake water level changes were collected, assessed, and compiled.

2. Materials and Methods

Most of the published articles used in this review work were collected from online sources such as Google Search, Semantic Scholar, Google Scholar, Research-Gate, and Science Citation Index Expanded (SCIE) bibliographic database. Some of the articles that were not available online were supplied by authors on request.

A search strategy consisting of three ways were used to develop collection of documents. While the first strategy involves searching for articles based on their study area, the second and third strategies encompass thematic relevance and the names of renowned authors, respectively. Search terms including "East African Rift," "Ethiopian Rift Valley Lakes," "Kenyan Rift Valley Lakes," "Central Rift Valley Lakes," "Main Ethiopian Rift," "Climate Change in the Rift Valley Lakes Areas,"

and “LULC change in the Rift Valley Lakes Areas,” and names of lake in the rift system were used to locate publications related to the topics under consideration.

Until the last search date 31 July 2023 a total of 346 journal articles, book chapters, reports and PhD thesis were collected, to establish our database out of which 226 are analyzed. Available publications were checked for their originality and published in reputable peer-reviewed journals to minimize bias. The articles were carefully read, compared, interpreted, and checked for their complementarity. Finally, results were discussed and narrated.

3. Results

Climate of the EKR

The Ethiopian Rift Valley has a complex structural pattern composed of southern, central, and northern segments characterized by climatic condition that varies markedly with altitude [7]. The climate in the rift is diverse and ranges from hot and arid to cool and humid with distinct wet and dry seasons that varies markedly with altitude. It is sub-humid and semi-arid close to the Kenyan border and arid in Afar. The Dalol Depression, one of the hottest places on Earth, has an average annual temperature of around 50°C [5].

The climate of Kenyan rift valley lakes area varies from arid (around Lake Turkana and Lake Magadi) to sub-humid and a semi-arid as in Lake Baringo, Nakuru, Naivasha and Elementaita. While Lake Turkana is located in the northwest of Kenya, the eastern branch of the rift valley in western Kenya is home for Lakes Baringo, Bogoria, Nakuru and Elementaita [13].

The climate of the rift area supports savanna vegetation complex characterized by open Acacia scrubland but with denser tree cover at higher elevations, and along streams [14]. Rainfall is low in the rift floor where it annually averages about 700 mm but is mostly greater than 2500 mm in the adjacent highlands[13].

Overview of Lake Level Variation in Selected Rift Valley Lakes of Kenyan

The lakes found in Kenya’s Rift Valley are tectonic in origin where water is tapped in the down faulted valleys. The Lakes Baringo, Bogoria, Nakuru and Naivasha lie within the arid and semi-arid northern part of the central rift valley in Kenya and are vulnerable to climatic variability with particular challenges related to water resources [15].

Though, Kenya is known for the utilization of its rift valley lakes for diverse socio-economic purposes, recently these lakes have been experiencing extraordinary rises in their water levels since 2010 [20,31,34]. The increases in lake level areas and consequent inundations of the riparian areas have had significant negative impacts on the socio-economic activities including tourism infrastructure [10].

The rises in water levels of the lakes in Kenya are not new [16]. Previous records of lake levels in Kenya show a significant rise in the levels and flooding of the mudflats and ring of acacia forest around the lakes in 1901 and 1963 [15]. The current flooding being witnessed suggests a return of a 50-year cyclic climatic event. Recently, significant scientific considerations have started to be given to lake levels, including the detailed long-term metaphors of the negative socio-economic consequences was given considerations lately [17].

Intense country-wide media coverage due to increases in the water levels have provoked public debates on the potential causes, with expert opinions divided along potential geological, anthropogenic and hydro-climatic influences [17]. According to the assumption of the potential geological process, it is argued that the affected Rift Valley lakes are located in a geologically active zone and lie in closed basin without surface outlets. Consequently, recent movement of tectonic plates in the region could have caused decreases in underground permeability, thereby decreasing subterranean outflow or seepage [17].

On the other hand, the anthropogenic pushing factors such as LULC change and degradation of the catchment areas are considered as possible causes for the lake level rise. Under this assumption, it is argued that the lower permeability of the subterranean pathways may have been worsened in

one way or another by the potential sealing and clogging of the underground water paths as a result of amassed sediment loads from the nearby degraded catchments as a result of LULC changes.

In general, less infiltration and higher surface runoff are the results of LULC changes, thereby accelerating surface runoff and peak discharges on shorter time scales formulates the hydrological phenomenon [18]. This in turn affects the overall water balance on a longer time scale through decreased actual evapotranspiration.

Due to the fact that precipitation and actual evapotranspiration determine the atmospheric boundary conditions, they are important hydro-climatic drivers and elements of the water balance. Rising water levels can therefore also be explained by a deviation of inflow and on-lake precipitation and/or actual evapotranspiration from a magnitude that would result in equilibrium in the lake water levels. Larger values in rainfall and/or lower actual evapotranspiration compared to the mean values, if the lake surfaces are in equilibrium, would be the rational.

Variations in lake volume are an integral response to potential changes, not only in the catchment, but also in the lake water balance. Whatever the cause for the lake water level changes is – [14] argue that all the above can potentially play a role in the lake level fluctuations – a quantifiable magnitude can be derived by analyzing changes in lake volume, since they constitute an integrated catchment response. Changes in lake volume reflect potential influences due to deviations from an equilibrium regarding inflow and outflow, LULC changes, or hydro-climatic changes.

This section aims to examine the nature of lake level changes during the recent past and to explore the potential impacts of these changes. The lake water level change of Lakes Baringo, Bogoria, Nakuru, and Turkana is discussed in details since these lakes are ecologically significant because they provide habitats for bird wildlife and are important economically for the fishing industry, drinking and irrigation water and as major tourist attractions.

Lake Baringo

Lake Baringo is Kenya's tropical third largest freshwater lake despite lack of surface outlet, shallow depth and high net evaporation. It is located at 0°30'N to 0°45'N latitude, and 36°00'E to 36°10'E longitude approximately 60 km north of the equator at an altitude of 975 m a.s.l [15]. The total catchment area of the lake is 6,820 km² that includes a large part of the western escarpment of the Kenyan Rift Valley, where most of the water is derived from.

Lake Baringo is Endorheic and Holomictic Lake (have a uniform temperature and density from surface to bottom at a specific time during the year, which allows the lake waters to mix in the absence of stratification). It occupies the eastern end of a half-graben depression in the central Kenya Rift Valley [36,37]. The lake is believed to have an underground seepage that maintains its freshness by losing approximately 108 m³/year [21].

The lake is fed by Ol Arabel, Mukutan, Endao and Chemeron seasonal streams and Molo and Perkerra perennial rivers. The perennial rivers reach the lake directly through surface recharge and bringing in a large amount of sediments load. Molo River collects water from the Mau Escarpment as far south as Elburgon Forest, and is structurally controlled, following the troughs between the fault scarps or the base of the fault scarps in its flow northward [17, 33, 39]. In the recent past, while the Molo River displayed drying up towards the lake during the dry spell of each year due to a number of upstream impoundments to supply irrigation water, the down flow of Endau stream is seriously affected by upstream construction of the Kiriandich Dam [23].

Lake Baringo is rich in biodiversity. It is home to seven freshwater fish large populations of hippos, snake, crocodiles, and the over 500 avifaunal species that makes it a wetland of international importance and gazette as a Ramsar site in the year 2002 [17,41]. The Lake Baringo's Ramsar-designated water body has been facing myriad environmental challenges attributable to anthropogenic activities, thereby being an ecosystem under perturbation [23].

While Lake Baringo is located in a semi-arid climatic zone, its catchment covers a range of climatic zones, from semi-arid through semi-humid and sub-humid, to a small portion in the humid zone [25], with unpredictable timing of dry and wet seasonality [43, 44]. The day time temperatures vary 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 and October [16]. The dry season usually extends from September to February while wet season occurs between March and August [28].

Though the majority of catchment of Lake Baringo is comprised of vast plains and steep slopes, making it highly susceptible to erosion and sedimentation [29], it is home to native variety of acacias and foreign species, including *Prosopis juliflora* [28]. Thus, the watershed has been suffering from soil erosion, water pollution, and the invasive *Prosopis juliflora* [17, 41, 45]. This condition favors the characterization of the lake by its high turbidity that is caused due to erosion of fine volcanic soils as a result of the anthropogenic activities associated with land and water use rights in the upper catchments in the basin [27].

While seven islands are located in the lake, the largest being the volcanic Kokwa Island, from which a number of hot springs discharge into the lake [30], the lake is a source of water and provides livelihoods (mainly fishing) for the Iccamus, Tugen, Pokot and Turkana communities, among others [23].

The lake has a shallow varying bathymetry which has reportedly declined since 1972 due to observable impacts of siltation, evaporation and diversion of inflowing rivers [45, 48]. Thus, Lake Baringo has a long history of water level fluctuation as a result of unpredictable rainfall patterns [26], and because of marked increases in anthropogenic activities (river impoundment, sand harvesting and irrigation for flower farms and personal farms) in its catchments [40,49,50]. The lake has initially been characterized as a very shallow water body with an average depth of 2.5 m [34] until approximately the year 2010, when the depth changes commenced [23].

According to the analysis of records by [28] indicate that between 1969 and 1972, the average depth of the Lake Baringo was 8 m, while in early 2003, before the onset of the long rains, the average depth was 1.7 m. The average depth in 2006 increased to 2.5 m, with the deepest end of the lake being 3.5 m, where the increase in water depth was the result of the prolonged long rains during 2003, especially in the humid upper catchments [28].

Due to heavy rains experienced since 2011 in the eastern African region, the lake water surface increased dramatically from nearly 135 km² in 2010 [27] to 193 km² in 2016 [20,34] and then to more than 250 km² in 2020 [23] as shown in Table 1 below.

Table 1. Mean surface area of Lake Baringo between 1970 and 2020 [14, 17, 35].

Year	Area (km ²)	Δ (km ²)	Remark
1970	153.00	–	The water level of Lake Baringo showed enormous drop in size between 1970 and 2010. The total drop in the size of the lake throughout this period is 18.26 km ² , though little increase is reported between 2000 and 2010. During this period the rate of the decline in size is 0.46 km ² each year.
1973	148.00	–5.00	
1984	147.31	–0.69	
1989	132.35	–14.96	
1995	118.31	–14.04	
2000	124.95	6.64	In just five year time between 2010 and 2015, the size of the lake unceasingly grew to reach to 192.99 km ² an increase by 58.25 km ² . In general, Lake Baringo inundated a total of 97.18 km ² area since 1970.
2005	125.79	0.84	
2010	134.74	8.95	
2015	192.99	58.25	
2020	250.18	57.19	The lake expanded at an average rate of 1.94 km ² per year between 1970 and 2020, although there was a declining lake level trend between 1970 and 2010.
Overall increase: 97.18 km ²			

This rising water level of the Lake Baringo is accompanied by improved lake depth from an average of 2.5 m in 2003 to 10.5 m in 2020 and lake water clarity [23]. According to [23] this increase in lake volume and depth and decreased turbidity might be due to the rehabilitation of degraded watershed of Lake Baringo.

The water levels of Lake Baringo submersed the fringe vegetation and most buildings around the lake [29]. There is a direct nexus between rising lake levels and flooding witnessed in Lake Baringo catchment which increases the lake surface area and has negatively impacted the riparian communities [29]. As a result of its geomorphic structure, Lake Baringo's neighborhood is the worst

affected area in the rift valley lakes than all the lakes showing similar trends in terms of the size of affected human population and the loss of infrastructure such as schools, settlements, dispensaries and the size of the area under water [17,33,34].

The Lake Baringo's catchment is threatened by increasing pressure from climate change and rapid population growth [24]. According to [15], the natural forest cover of Lake Baringo that regulates rainfall patterns, sediment regime, flooding and sustains the ground water recharge decreased from 829 km² to 417 km² within the period of 30 years from 1976 to 2006.

Similarly, the report on the assessment of land cover conducted between 2000 and 2018 by the [4] revealed that forest cover that was 563.7 km² in 2000 increased to 769.6 km² in 2014 that finally declined to 513.9 km² in 2018. Conversely, between 2000 and 2018 cropland increased from 1652.6 km² to 2175.3 km² in 2018. An increase in cropland indicates that more vegetation is converted to farmland and the increase in wetland signifies the increase in water levels of the lakes within the catchment.

Lake Bogoria

Lake Bogoria is a narrow, saline and alkaline closed basin lake that occupies deep half-graben depression and extends from 0°10'N to 0°20'N and 36°04'E to 36°26'E, at an elevation of 992 m a.s.l. It is located some 20 km due south of Lake Baringo separated by the Lobo plain which constitutes a drainage divide that rises to about 1000 m a.s.l. [10]. It is located in the Kenyan CRV fed partly by ~ 200 hot alkaline springs located in three groups along its margins [36].

The lake is lying in a trough formed between a fault fragmented, eastward sloping Kipngatip plateau of phonolite lava to its west, and Lake Bogoria fault scarp immediately to its east [15]. The endorheic basin of Lake Bogoria influences its salinity and alkalinity that is exacerbated by inflow from saline hot springs and high evaporation rates that far exceed precipitation. Lake Bogoria has the highest concentration of geysers in Africa [37].

In 1970, Lake Bogoria was first declared a national reserve because of its scenery, hydrologic features and biodiversity (large number of bird species, buffalo, baboon, and caracal, cheetah, spotted hyena, warthog, impala, zebra, and etc.) [15]. The status was later changed to a National Park in 1990 and subsequently designated as a Wetland of International Importance under the Ramsar Convention in 2001 [38]. At present, the catchment of Lake Bogoria is around 1060 km² that lies within Lake Bogoria National Park.

The terrestrial vegetation around Lake Bogoria is mainly thorny bushland, dominated by species of Acacia, Balanites and Commiphora, with patches of riverine woodland containing Ficus capensis, Acacia xanthophloea and A. tortilis. The hydrology of Lake Bogoria is primarily influenced by the inflows from a number of springs, most of which emerge along the N-S fissures at the shores of the lake.

The springs include the Sandai, Lobo, Waseges, and Emsoss River flowing in from the north of the lake during the wet season (April to August), discharges from the lake floor, and from approximately 200 alkaline hot springs nearby. Emsoss warm spring flows in from the south through fissures in the Emsoss escarpment [15]. The larger part of the Bogoria drainage area, 1075.5 km², is occupied by Waseges river [10].

Lake Bogoria has no known surface outlet and is located on a semi-arid belt within a region receiving approximately 50 mm of rainfall per month and a precipitation of 400–600 mm per year with high rates of evapotranspiration at 1500 mm per day. Temperatures range from 18°C to 35°C during wet and dry seasons, respectively [38]. During the April to August wet season, the increased flow from the catchment coupled with geysers along the banks of Lake Bogoria raise the water level which subsequently declines through December to March.

Lake Bogoria is a major tourist destination. The lake is famous for its boiling springs and millions of flamingos. With the rising water levels, however, most of the hot springs has been submerged and all geysers have been suppressed [4]. Hence, there is renewed concern that the alkaline lake will overflow and merge with the freshwater Lake Baringo located about 20 km to the North, thereby causing severe cross-contamination [39].

The report prepared by the [4] revealed that the land cover of Lake Bogoria catchment between 2000 and 2018 showed increasing trend in forest cover from 26.5 km² to 38.7 km²; cropland from 361.9 km² to 416.5 km²; and water body and wetland from 39.1 km² to 49.4 km² as shown in Table 2 below. The increase in wetland is an indication that the water levels of Lake Bogoria have steadily increased during this period.

Table 2. Mean surface area of Lake Bogoria from 1984 to 2020 [4, 17].

Year	Area (km ²)	Δ (km ²)	Remark
1984	32.14	–	The surface area of the lake increased to 40.50 km ² in 2015 and remained mostly above 34 km ² since 2010. The overall increase in the size of Lake Bogoria between 1984 and 2020 is 11.11 km ² . The suppressed increase in Lake Bogoria's surface area is related to the steeper topography of the surrounding area, when compared to the other lakes. The lake occupies a deep and, somewhat, narrow depression which experienced a rise in lake level but was accompanied by limited expansion in surface area when compared to the shallow depressions occupied by the other lakes [17].
1989	33.11	0.97	
1995	31.89	–1.22	
2000	33.78	1.89	
2005	32.41	–1.37	
2010	34.35	1.94	
2015	40.50	6.01	
2020	43.25	2.75	
Overall increase: 11.11 km ²			

Lake Nakuru

Lake Nakuru is a shallow, alkaline and saline lake that extends from 0°18’S to 0°24’S and 36°03’E to 36° 07’E. It is located within an endorheic basin characterized by its hyper-salinity [10]. The lake is located 53 km from the southern edge of Lake Bogoria at an elevation of 1754 m a.s.l.

Lake Nakuru lies in a graben between Lion Hill fracture zone in the east and a series of east downthrown step-fault scarps leading to the Mau Escarpment to the west [17, 33]. Its catchment covers a total area of 1471 km² with daily temperatures that range between 9.4°C during the cold months and 26.8°C during the warmer months [16]. The wet season in the region fall between April and August, while the dry season occurs between October and March with mean annual rainfall is 95.1 mm [38].

In addition to precipitation, Lake Nakuru is fed by effluent of the nearby Nakuru City sewerage treatment system, Baharini spring on its eastern shoreline, and seasonal surface streams Njoro, Nderit, Makalia, Enderit, and Lamudhiak, originating from the Eastern Mau Forest [54,56]. The rest of the drainages rising from Eburru, Bahati and the rest of the Mau escarpment, carry runoff only during prolonged rainfall, but never reach the lake by means of surface recharge.

Lake Nakuru is part of Lake Nakuru National Park known for its highest biodiversity in Kenya. It is home for large population of Lesser Flamingos described as “the world’s greatest ornithological spectacle” with over 450 species of birds, 50 species of mammals and 300 species of plants and 70 species of waterfowl and water-related birds [4]. Each year the resident bird life of the park is enriched by the presence of several species of Palearctic waders that use the lake as a staging ground during their winter migration down the Rift Valley fly way. The lake has faced major ecological restructuring as a result of flooding.

The area of Lake Nakuru is a protected area under the Ramsar Convention on wetlands. The area has been designated as a Bird Sanctuary since 1960, declared a National Park in 1968, as well as the first rhino sanctuary and the first Ramsar Site in Kenya in 1987 and 1990, respectively [4]. It was identified as an Important Bird Area in 1999, and lastly in 2011, it was designated as a World Heritage Site by UNESCO [38].

Since this is a shallow lake it shows rapid fluctuation in size/area where its water is greatly reduced during prolonged drought that will be fed only from sewage water from the Nakuru sewage treatment works and perennial small springs off Lion Hill [17,33].

Lake Nakuru undergoes major fluctuations, sometimes drying up completely in 1995 and 1996, resulting in most birds disappearing and tourism being greatly diminished [57,58]. Following extreme El Niño-driven flooding in 1997 and 1998, the lake levels rebounded [42] and has shown an increase in water levels since 2011 [10]. This resulted in an increase in its flood area from a low area

of 31.8 km² in January 2010 to a high of 54.67 km² in September 2013, corresponding to a 22.87 km² increase in area.

Lake Nakuru is the first of Kenyan rift valley lakes to burst its bank since the short rains of September 2010 [10]. The lake has swollen submerging old buildings, grazing and farm lands, and the Nakuru sewerage treatment works. The rising levels of the lake coincide with the increase in rainfall in the catchment areas, with sharp increases in the surface area observed in 2014 and 2020 [4].

Apart from the impact on the livelihoods of multitudes of local community members, there are reports of risks of attacks by snakes and crocodiles and high risk of contracting waterborne diseases due to the submersion of public utilities like sewage treatment plants, transport infrastructure in the park, the tourism, the park main gate and other sanitation units.

According to the report of the [4], the land cover change trend within the catchment of Lake Nakuru between the year 2000 and 2018 depicts that forest cover decreased from 192.5 km² to 174.8 km², while cropland and wetland increased from 803.7 km² and 58.73 km² to 1059.5 km² and 75.16 km² respectively as shown in Table 3. The decrease in forest cover may be attributed to conversion of forest to cropland which is evinced by steady increase in cropland. The increase in wetland conversely is an indication of rising levels of water in Lake Nakuru.

Table 3. Mean surface area of Lake Nakuru between 1984 and 2021 [17].

Year	Area (km ²)	Δ (km ²)	Remark
1984	41.00	–	In just 11 years, between 1984 and 1995 the size of Lake Nakuru decreased by 7.90 km ² and remained low until after 2010 when it increased from 38.86 km ² to 54.40 km ² in 2015.
1989	35.75	-5.25	
1995	33.10	-2.65	
2000	37.19	4.09	In 1995, the lake showed its lowest areal extent of 33.10 km ² . Between 1995 and 2021, the lake showed an increase in size by 34.90 km ² . While changes in lake water levels between 2010 and 2021 depict overflows submerging an estimated area of 29.14 km ² , the lake experienced an overall increase in size of 27.00 km ² between 1984 and 2021. Thus, 27.00 km ² neighboring area of Lake Nakuru is inundated by the rising water level.
2005	36.51	-0.68	
2010	38.86	2.35	
2015	54.40	15.54	
2020	62.26	7.86	
2021	68.00	5.74	
Overall increase: 27.00 km ²			

Lake Turkana

Lake Turkana is the fourth largest lake in Africa, the world’s largest alkaline lake, the world largest desert lake, and the largest endorheic lake located in the arid region of EAR with unique ecosystem [59,60,61]. It loses water mainly through strong evaporation rate estimated to be around 7 mm/day [61,62]. It is located in the arid northwestern part of Kenya at about 4°39'13.55" N and 36°10'12.20" E. Most part of the lake lies in Kenya, but part of the Omo River that supplies water to the lake delta lies in southwestern part of Ethiopia [47].

Lake Turkana is characterized by an elongated shape oriented north–south, with a distance between the north shore and the south shore of about 200 km and maximum width of about 40 km. The lake surface area is about 7000 km² and the catchment area is 131,000 km² [48]. The wet season in the Lake Turkana basin is from April to October, with peak rainfall typically seen in April [49]. However, it should be noted that rainfall patterns differ substantially across the basin from the tropical, humid climate in the Ethiopian highlands in the north to the hot, arid semi-desert climate in the south.

Despite being a key stop-over site for birds on passage, Lake Turkana is home for 84 water-bird species, including 34 Palearctic migrants and breeding ground for at least 23 species of birds [4]. Thus, the lake is a unique ecosystem in the northern portion of Kenyan rift valley.

The catchment of Lake Turkana covers arid region and is fed by Turkwel and Kerio Rivers from the South–West, and the Omo River from the North. Turkwel and Kerio rivers have their sources in the Cherangany Hills forest reserves. Omo River (acts as the Turkana’s “umbilical cord”) provides about 90% of the lake inflow emanating from Ethiopian highlands with plentiful rainfall [61,65,66].

As a result, the lake's water level fluctuations are almost entirely caused by variations in rainfall over the Ethiopian highlands. Omo River forms an inlet delta at the mouth of Lake Turkana on the Ethiopian/Kenyan border that has been in a constant state of change in response to natural hydrological cycles, including lake level change [52].

Due to its restricted basin character, arid surroundings, and heavy reliance on the Omo River for its intake, Lake Turkana is a highly pulsed, changeable system despite its large size [19]. As a result, the lake is occasionally referred to as an "amplifier lake," that is, it "amplifies" climatic variations.

The hydrological characteristics of the basin's river discharge into Lake Turkana have long been progressively changing with increasing anthropogenic pressure [53]. Since 2015, the lake inflow cycles have been permanently altered by the upstream developments on the Omo River [52]. Thus, the dynamics in the watershed of Lake Turkana have been modified in the last decades by the construction of cascade of dams within the Omo basin [46].

According to the prediction of [61,62,69], the development efforts in the Omo–Gibe basin is accompanied by a drop in the water level of Lake Turkana by 20 m. The filling of the Gibe III reservoir (located more than 380 km away from the lake) alone would cause a 2 m drop in Lake Turkana's surface level. Apart from this drop in water level, since the dam's completion in 2015, there have been reports that the regulation of flow from the dam has "eliminated the annual flood pulses of the Omo River" [55].

There are conflicting reports concerning this drop in the lake water level of Lake Turkana and the development efforts in the upper most catchment of the lake in Ethiopia. On the one hand, although [56] reported that the filling process of the Gibe III dam was accompanied by drop of the water level of Lake Turkana by 1.7 m, historical lake level studies reveal contradicting results. According to [57], reported that the historical lake level studies conducted between 1973 and 1989 indicating around 10 m drop in the water level of the lake. This drop allowed the formation of a large wetland and an estuary at the lake inlet.

According to the findings of [58], a decreasing and an increasing water surface elevation was noted for Lake Turkana between 2000 and 2014. The decreasing trend was recorded between 2000 and 2006 where the water surface elevation decreased from an annual average of 364.05 m in 2000 to an annual average of 361.83 m in 2006. On the other hand, the increasing water surface elevation was observed from 2006 to 2014 where the annual average increased from 361.83 m to an annual average of 364.51 m in 2014.

Before filling of the Gibe III reservoir commenced, these data show a pattern of annual peak lake surface elevations between September and November for most years. Exceptions include 2002 and 2009, which saw negligible peaks during these months. During the filling of the reservoir, there was a cessation of annual peaks and a general decline in lake surface elevation from early 2015 to mid-2017 [58]. From mid-2017 through 2018, lake levels were on the rise, and began to display annual peaks, albeit less pronounced than pre-dam conditions.

The 18-year change in lake volume variations for Lake Turkana sums to +1.06 km³, indicating the lake has had a net increase in volume since 2000. Between the years 2000 to 2014 (prior to the filling of Gibe III reservoir) there was an overall increase of volume of Lake Turkana by 1.36 km³ [58]. Moreover, during reservoir filling period (2015 to 2018), Lake Turkana experienced an overall decrease of 0.30 km³ in volume. The years 2007, 2010, and 2013, are noted with a volume increase of 9.46 km³, 6.81 km³, and 5.60 km³, respectively, since these are the wettest years [58]. The three driest years were 2002, 2009, and 2015, with a volume decrease of 7.65 km³, 9.54 km³, and 10.37 km³, respectively [58].

The effects of Gibe III Dam construction on Lake Turkana that was assessed by [58] revealed that the magnitude of seasonal floods used to occur from August to October before construction of the dam is reduced by half and occurred approximately four months earlier. Likewise, periods of negative volume variation were also smaller in magnitude, indicating the dam had a moderating effect on Lake Turkana water levels.

In general, the trends in the water level fluctuation of Lake Turkana contradicts the forecasted negative impacts of the ongoing water resources projects being carried along the Omo River in Ethiopia, which is considered the main water source for the lake [52]. The substantial increases in water levels is affecting the local communities [19]. The size of Lake Turkana between 2010 and 2020 is displayed in Table 4 below.

Table 4. Mean surface area of Lake Turkana from 2010 and 2020 [4].

Year	Area (km ²)	Δ (km ²)	Remark
2010	7,485.48	–	The water levels recorded of 2020 is the highest Lake Turkana has ever registered in recent years. The flooding submerged approximately 779.6 km ² of land around the lake. This has resulted in loss of properties and displacement of a large population. The lake expanded at a rate of 779.58 km ² per year between 2010 and 2020.
2014	8,064.09	578.61	
2020	8,265.07	200.98	
Overall increase: 779.59 km ²			

When it comes to the assessment of land cover change of the watershed of Lake Turkana between 2000 and 2018, the report compiled by the [4] demonstrates that forest cover slight decreased while cropland and wetland steady increase. Forest cover decreased from 3762.6 km² in 2000 to 3272.9 km² in 2018 and cropland steady increase from 256.5 km² in 2000 to 978.3 km² in 2018. Wetland also increased from 7358.43 km² to 7431.45 km². This signifies that there was conversion of forest to cropland and that the lakes within the catchment expanded hence decreasing the size of grassland.

Overview of Lake Level Variation in Selected Ethiopian Rift Valley Lakes

The complex tectonic and volcanic processes in the Ethiopian rift valley have resulted in the formation of volcano-tectonic structural depressions that became sites for many rift valley lakes [59]. These rift valley lakes exhibit a very large morphometric variation due to the difference in geomorphological setting resulting from volcano-tectonic processes. The hydrological exchange characteristics of the watershed, geographic location & climate, retention time of water, morphometric characteristics, processes taking place in the lakes, and the biogeochemical processes that occur on the land and influent streams determine the state of a lake [75,76].

Changes in lakes can be manifested in surface area, volume or water quality depending on the dynamics in the contributing area, the size and shape of the water body, and the geologic formation [62]. This variation affects nearly all the physical, chemical, and biological parameters of the lakes. The geomorphological setting is highly controlled by different episodes of volcano-tectonic activity that shaped the region in the Cenozoic era, with the influence continuing till the present day [63].

According to [64], the present-day rift lakes are remnants of large lakes evolved into separate systems as they receded through time. During the Early–Mid Holocene and the Late Pleistocene wet periods, lakes Ziway, Langan, Abijata and Shala were united, forming one large freshwater lake which overflowed to the Awash river to the north [64]. Sediments of these large lakes mainly consist of thick diatomites which outcrop today in the basin and are intensively eroded by surface runoff and wind deflation [65].

The closed lakes in this rift are saline, while the open lakes are freshwater lakes. The deepest lake in Ethiopian is Shala (266 m), while the shallowest is Ziway, if we do not consider Chew Bahir, which used to be a vast lake when it was discovered in 1888 by Samuel Teleki, and now is partly a swamp and for the most part a muddy salt plain [63]. Some of the Ethiopian Rift lakes, particularly those located in a terminal position, have undergone significant lake level changes since the 1970s [66].

The water level of a lake fluctuates within its normal amplitudes naturally in response to climatic variability and hydrological exchange (including precipitation and evaporation) characteristics within the lake’s watershed [67]. This natural seasonal and annual water level fluctuation is a common phenomenon in every lake. These natural fluctuations are inherent feature of lake ecosystems and essential for the survival and well-being of many species that have evolved to suit

their life cycle to those fluctuations [68]. Unlike these natural fluctuation situations, different observations might be recorded when the issue of anthropogenic factors comes into the picture.

The precipitation trend within the watersheds of Ethiopian rift lakes is characterized by no significant discernible increasing or declining pattern for the past half a century except for the inter-annual and seasonal variations [12,84]. In line with this observation, the water level of certain lakes remains almost constant with little or no change, while certain other lakes in the rift region behaved differently either by increasing or decreasing size in their lake level trends [10, 12, 85, 86].

Recently, the lakes that are situated in terminal positions in the Ethiopian rift, have witnessed major lake water level fluctuations. For instance, until the mid-1970s before irrigation activities started in the Ziway area, Lake Ziway remained to maintain its natural fluctuation pattern. Similarly, before the establishment of the Abijata Soda Ash Factory in the mid-1980s, Lake Abijata was able to maintain a natural balance between inflow and evaporation without any human interference [78, 87].

Due to anthropogenic economic activities such as expansion of irrigation agriculture, industrial lake water use, land degradation, and neo-tectonic movements, the lakes' water level has been rapidly declining in some of the rift valley lakes [5]. On the contrary, the irrigation return flows have been blamed for the observed booming expansion of Lake Beseka [73] since the late 1960s.

The case of Lake Abijata is serious as the lake has been decreasing even more dramatically, and many researchers predict that, if business continues as usual in the CRV, this lake could dry up completely in the next 20 – 50 years [7]. In similar trend data collected between 1977 to 2007 on the level of Lake Ziway revealed that the lake has been gradually decreasing [7].

The study of lake morphology is important not only to understand spatial change in the shape and size of the lake, but also to comprehend its hydrologic and limnologic characteristics [74]. Thus, monitoring lakes for temporal and spatial alterations has become a valuable indicator of environmental change and for providing insight into the similarity or dissimilarity of the variability among the lakes in the basin. The following sub-section describes the extent of change observed in selected rift valley lakes that exhibit significant fluctuation in their water levels.

Lake Abijata

Lake Abijata is an alkaline and saline closed-basin terminal lake that is located at 7°35' N, 38°35' E. The main water inputs into the lake come from Horakelo and Bulbula rivers, direct precipitation, and groundwater recharges. Owing to its terminal position in the drainage area and its shallow depth, Lake Abijata is especially susceptible to changes in climate and LULC changes in its catchment[81,90].

Since the mid-1980s Lake Abijata's water levels have been in almost constant decline, which is not explainable through the pattern of rainfall record, indicating that water abstractions are the main cause of the decline [66]. The fluctuation of water level of Lake Abijata follows the same trend as Lake Ziway, with an average lag time of about 20 days [76]. Thus, decrease in water level of Lake Ziway is accompanied by decrease in outflow into Bulbula River that obviously causes decrease in the inflow of water into Lake Abijata [11, 21].

Since there is no clear declining trend in rainfall during the past 40 years, the reduction of the water level of Lake Abijata is the result of anthropogenic activities, rather than changes in rainfall patterns [77]. Studies conducted by [12, 16, 92, 93, 94] disclosed that the spatial cover of Lake Abijata has been decreasing rapidly over time due to the recent development schemes, such as pumping of water from the lake for soda extraction, and the utilization of water from feeder rivers and Lake Ziway for irrigation.

The rapid declining of the lake is correlated with the increase in salinity by more than 2.6 times (from 8.1 to 26 mg/L), the pH varied between 9.5 and 10.1, and alkalinity changed from 80 to 326 mg/L as reported by [59]. These results reveal that the increases in these values are the result of loss of water and increase in the concentration of the ionic species. In line with this finding, [66] reported that there was a considerable reduction in the volume of Lake Abijata in 1985 and 1990, amounting to about 425 Mm³, or 51% of its present volume.

According to [75] the size/area of Lake Abijata decreased from its 225 km² in 1970 to 115 km² in 1990. In similar development [81], reported that only between 2000 and 2006, the lake has lost 46% of its surface area. Hence, Lake Abijata has receded 3 km from pumping station and soda ash production has slowed down because of the loss of water in Lake Abijata.

On the other hand, [78] revealed that Lake Abijata has lost some 6.5 m height between 1985 and 2006, and 70% (~4.5 m) of the loss has been attributed to human-induced causes whereas the remaining 30% is related to natural climate variability. This means, the lake has lost approximately 65 km² (35%) of inundated area since 1985.

The estimated volume of water lost from Lake Abijata is approximately 830 Mm³ (1130 Mm³ from 1985 to 300 Mm³ in 2006), which is nearly 70% of the original 1985 lake volume. In the month of May, 2013 the estimated volume of Lake Abijata was ~530 Mm³ represents ~50% of the 1985 high-volume stage [78].

According to [69], the water level of Lake Abijata has decreased in size by 25% since the late 1980s due to decrease in the level of Lake Abijata and intensive withdrawal of water from Lake Abijata for soda ash production. According to [5], until 2007 the shoreline of Lake Abijata located closer to the soda ash plant has receded by 1.3 km from the 1980s position. The following Table 5 displays the areal extent/size of Lake Abijata reported by different scholars.

Although there are differences in the reported data by the researchers, there are some important overlaps of observations in the reported results. For instance, the size of the lake at the beginning of the 1970s (in 1972 and 1973) is roughly closer to 200 km². Moreover, continuous decline in the size of the lake has been reported by all researchers. The loss in the size of the lake between 1973 and 2018 is roughly 130.98 km².

Assessment conducted by [82] on the LULC dynamics from 1973 to 2016 and its impact on biodiversity resources in the Abijata–Shalla National Park, part of the CRV Lakes Region, revealed that cultivate land and grazing land increased by 14.89% and 14.1% respectively, while water bodies and the acacia woodland areas decreased by 15.51 %, 8.86% respectively.

Table 5. Changes in the size/area of Lake Abijata between 1973 and 2018 reported by different scholars.

Reference	Reporting year	Extent (km ²)	Remark
[7]	1973	194	Overall loss in size: -99 km ²
	1986	162	
	1999	163	
	2006	95	
[83]	1980	215	Overall loss in size: -126.82 km ²
	1993	162.7	
	1997	135	
	1999	134	
	2010	115	
	2014	88.18	
[84, 85]	1973	200.13	Overall loss in size: -130.98 km ²
	1986	165.22	
	2000	164.83	
	2005	94.69	
	2011	128.01	
	2015	131.94	
	2018	69.15	
[86]	1972	198.4	Overall loss in size: - 67.4 km ²
	1984	179.2	
	1994	150.6	
	2003	144.9	
	2015	131.8	

Lake Beseka

Lake Beseka is one of the volcanically dammed endorheic (closed-basin) lake located at 8051.5'N latitude, 39051.5'E longitude, some 955 m a.s.l. within the tectonically active Ethiopian northern rift portion near the Afar triangle in the middle of Awash Basin [12, 85, 97]. It has a high level of salinity, alkalinity, and fluoride concentration with no surface outflow until the 2007 intervention was launched due to its violent expansion over half a century [14, 98].

The topographic nature of the watershed is characterized by diverse relief displacement including undulating plateau, narrow valleys, and flat plains with elevation ranging from 940 m to 1872 m a.s.l. that falls within Kola (warm & semiarid) agro-climatic zone [90]. The lake area and its watershed are characterized by bimodal and erratic rainfall distribution pattern.

The major rainy season occurs from July to September and the minor, occasional rain occurring between February/ March to April [85,97]. During the main rainy season, the local hydrological cycle is sourced by moist air carried from the Atlantic and the Indian Ocean. During the minor rainy season, the catchment gains small precipitation being sourced by a southeasterly wind carrying moist air from the Indian Ocean [90].

Unlike other rift valley lake watersheds, the catchment of the Lake Beseka does not contain perennial river that drains into the lake, except seasonal floods in the wet season, in addition to excess irrigation drainage and groundwater inflow [89]. The lake was essentially a surface pond of about 2.7 km² total surface area in the late 1950's and early 1960's before the establishment of Metahara Sugar Estate [7,97]. Metahara Sugar Estate was made operational in the early years of the 1970's.

The total area of watershed of the lake is about 500 km² with variable elevation in the ranges of 950–1700 m [97, 100]. The Lake is situated on Metahara plain, surrounded by mountain chains of variable elevation, which are the extensions of Chercher highlands [91].

In contrast to many East African terminal lakes, despite the aridity of the rift valley, Lake Beseka is exceptionally the only lake that has extremely expanded at an alarming rate in surface area and volume over the last decades towards the south and the south-west directions, with minor expansion towards the west [97,101]. Although the starting time of expansion is not exactly known, most previous studies tend to agree that the problem was initiated in the late 1960 and early 1970s when the Metahara mechanized farm around the lake was started to be irrigated for cultivation of cotton and citric fruits which latter on shifted to sugarcane development [7,12,85, 97,98]. Furthermore, [89] reported that the water level of Lake Beseka started to rise from 1976 to 1978 as a result of poor irrigation water management practices of the newly introduced Abadir farm.

Although it is difficult to conclude that the source of the expansion of the lake is related to return of excess irrigation water, the time period of the late 1960 and early 1970s roughly overlapped with the initiation of commercial irrigation farms such as cotton farm in Abadir area, Metahara sugar estate, Abadir sugarcane farm, and Nura Hira irrigation scheme. Apart from this, it is also important to consider that the area is prone to different tectonic activities as it is situated in northern rift valley portion of the Ethiopian rift valley [12, 97, 102, 103, 104].

Lake Beseka expanded enormously between 1973 and 2010 comprising about 53% lake area and 46% of its volume [87]. During this period forested lands in the lake's watershed were changed to irrigated farmlands consuming significant quantities of water. Cognizant of the potential damaging effects of the rise in the level of the lake, the Ministry of Water Resources initiated the proportional mixing of the lake water with Awash River in 2004 [87].

The mixing was accompanied by minor calming of the lake level rise that did not bring about substantial lake level stabilization. The groundwater table under the towns of Metahara and Fantalle is very shallow (< 2 m), further illustrating the rising trends of surrounding groundwater levels following the lake's phreatic levels.

According to [94], despite small inter-annual variations between 1973 and 2002, the surface area of Lake Beseka risen from 11.1 km² to 39.5 km². Moreover, they indicated that the level of the lake rose by 4 m between 1976 and 1997. On the other hand, [96], estimated the total surface area of the lake in 2008 to be around 43 km².

Various hypotheses have been proposed to explain the aggressive expansion of Lake Beseka. While some scholars claim to relate the expansion of the lake with the establishment of irrigation schemes in the area and leakage from the Awash River favoring groundwater discharge, others argue that the hot springs around the lake and recharge from irrigation runoff or their combinations cause the lake's expansion [12, 97, 102, 103, 104]. Conversely, some focuses on the increased surface runoff, climate change, LULC change, geological changes happening in the Ethiopian Rift Valley, and etc. as causes for the expansion of the lake [102,105].

The main changes in the water balance of Lake Beseka come from groundwater inputs, which are related to the recent increment of recharge from the nearby irrigation fields and due to the rise of the Awash River level after the construction of the Koka dam located some 152 km upstream [7,12]. Prior to the construction of the Koka dam, the Awash River sometimes ran dry between December and March. However, after the construction of the dam there has been fairly steady flow of the river throughout the year. The sustained flow of the Awash throughout the year has become a source of continuous indirect recharge to the groundwater of the area, ultimately feeding Lake Beseka which is located at a relatively lower topographic position [6].

Apart from the issues related to irrigation return water and groundwater recharge, the LULC change analysis by [87] indicated that the watershed of Lake Beseka had experienced a drastic change in its LULC conditions over the last four to five decades because of the rapid increase in human settlement, deforestation, establishment of irrigation schemes, and etc.

Approximately, 189.24 km² of forest and 47.30 km² of grazing lands were devastated from 1973 to 2008; reducing the forest coverage from 42% in 1970s to only 6% in 2000s [87]. This phenomenon coincides with the time period where about 70% of the lake expansion was observed [91].

Moreover, [97], estimated the effect of LULC change on surface (direct) runoff for Lake Beseka catchment indicating about 86% of forest coverage and 46% of grasslands were lost between 1973–2015, which were shifted to open bushy woodlands, farms, lake water and wetlands.

Although different hypothesis were proposed to explain the expansion of Lake Beseka, it is finally confirmed by [98] through the research conducted by using dual Radon and isotope analysis that the main source of water responsible for the expansion of the lake is the excess irrigation water joining the lake through subsurface flows.

Different studies indicated that the expansion of the lake is challenging the socio-economics and environment of the region significantly [99]. Accordingly, [93], reported that the substantial growth in lake size along with its saline content of the water causes multiple challenges to the Rift Valley and the Awash Basin communities. Moreover, [70] described the situation as natural disaster for the ecosystem of the region because the lake's expansion has created an unstable transitional zone between the wetland and the nearby terrestrial ecosystem. The effort to protect further expansion of the lake through controlled draining it into Awash River is compounded by unprecedented consequences to the downstream communities.

The future expansion of the highly saline lake may be concentrated towards the east and north-east direction due to the topography of the area which has the potential to displace Metahara town and impact the Metehara sugar plantation [11,109].

The Extent and Pattern of Expansion of Lake Beseka

Lake Beseka has been gauged since 1976, but some data between 1999 and 2001 were missing related to the damage at the station [89]. Since Lake Beseka's morphometric data were initially reported by Wood & Talling, (1988), many scholars have cited this value of 3.2 km² in different research articles, until very recently. For instance, [7,12,84,110] used this value as it is without considering the changes taking place through time.

Although [102] reported the size of the lake to be 3.2 km² in its 1988 article, [7] and Gulilat, 2000 as cited by [93] reported that the area of the lake was only 3 km² in 1957. The least reported size/area was 2.7 km² as indicated by [87] as initial area of the lake in 1960.

These reported sizes can be considered as starting values of Lake Beseka to evaluate its spatio-temporal expansion. In the so far assessment of published articles concerning the areal expansion of

Lake Beseka, [12,97, 98,112] extensively assessed and reported the spatio-temporal expansion of the lake from the late 1950s.

Surprisingly, [12], revealed that lake Beseka has expanded from an area of 3.0 km² to 40 km² between 1957 to 1998. On the other hand, the surface area of the lake increased from 2.7 km² in 1957 to more than 50 km² in 2015 [99] with the possible reason of increased groundwater inputs from percolated irrigation water as shown in Table 6 below.

Table 6. Changes in the size/area of Lake Beseka between 1957 and 1998 [6].

Year	Area (km ²)	Δ (km ²)	Remarks
1957	3.0	–	Between 1957 & 1972 the expansion of the lake was more or less normal. A record high expansion (17.1 km ²) of the lake was noted between 1972 & 1978, few years after the commencement of irrigation in the area. The time period between 1984 and 1998 is characterized by culmination of expansion. Generally, the lake expanded by 37.02 km ² between 1957 and 1998.
1972	12.8	9.8	
1978	29.9	17.1	
1984	36.1	6.2	
1996	39.7	3.6	
1998	40.02	0.32	
Overall change		37.02	

On the other hand, according to the investigation reported by [87], the average elevation of the lake that was ~944 m in 1975 that grew to ~952.4 m in 2010. Hence, the lake water level has increased by at least a depth of 8.4 m (~0.24 m/year) over the indicate period, with the average and maximum depth estimated to be 7.5 ± 0.5 and 13 ± 0.5 m (953–939.5 m), respectively resulted in flooding about 45.8 km² of the surrounding areas and an incremental lake volume of about 280 Mm³. Table 7 below displays Dinka's findings about the size of Lake Beseka between 1960 and 2010:

Table 7. Changes in the size/area of Lake Beseka between 1960 and 2010 [87].

Year	Area (km ²)	Δ (km ²)	Remarks
1960	2.7	–	Between 1960 & 1975, the expansion of the lake was more or less normal that is less than 7.5 km ² (0.5 km ² /year). A record high expansion (19.3 km ²) of the lake was noted between 1975 & 1986. The time period between 2000 & 2010 is characterized by more or less culmination of expansion of the lake 0.7 km ² /year. In general, the lake expanded by 45.8 km ² between 1960 and 2010.
1973	8.4	5.7	
1975	10.2	1.8	
1986	29.5	19.3	
2000	41.5	12.0	
2007	43.4	1.9	
2010	48.5	5.1	
Overall change: 45.8 km ²			

The findings of [12, 97] on the expansion of Lake Beseka demonstrate closer results. While [12] reported that a record high expansion (17.1 km²) of the lake was noted between 1972 and 1978, [87] disclosed that the lake showed violent expansion (19.3 km²) between 1975 and 1986.

This shows that Lake Beseka was aggressively mounting in the 1970s and 1980s. According to [6], the lake expanded by 37.02 km² between 1957 to 1998. This means the lake was expanding at 0.90 km² every year. On the other hand, according to [87], the lake expanded by 45.8 km² between 1960 to 2010 revealing expansion of 0.92 km² every year.

According to the findings of [87], this situation generally resulted in flooding of about 45.8 km² of surrounding areas and, an incremental lake volume of about 280 Mm³. This was about a 15-fold incremental area increase since 1960s accompanied by detrimental effects on the surrounding residential, ecological, hydrological, and infrastructural facilities (Ayenew & Tilahun, 2008).

Conversely, in its conference poster Shishaye, (2015), reported that the size of Lake Beseka raised to its highest level of 54 km² in 2015. On the other hand, Teffera et al., (2018) revealed that the lake area that was approximately 11.7 km² in 1972 rose to 41.1 km² in 2005 that finally reached 46.7 km² in 2017. According to this report the lake has shown a total areal increment of about 35 km² between 1972 and 2017 with expansion rate of 0.78 km² each year.

In another research, the change detection analysis conducted by Beyene, (2007) revealed that the lake size has increased by 3.53 km² between 1964 and 1973. Similarly, the lake size has increased by 25.00 km² between 1973 and 1986, and by 11.94 km² between 1986 and 2003. In general, Lake Beseka has expanded by about 40.47 km² between 1973 and 2003 as shown in Table 8 below.

Table 8. Changes in the size/area of Lake Beseka between 1964 and 2006 [103].

Year	Area (km ²)	Δ (km ²)	Remarks
1964	3.02	–	While there is relatively calm (0.39 km ² per year) situation between 1964 and 1973, there is a sharp rise (1.92 km ² per year) in the level of the lake between 1973 and 1986. Moreover, the time period between 1986 & 2003 is characterize by more or less calm situation with 0.70 km ² per year expansion. The overall finding indicates that the lake expanded by 40.47 km ² in just 39 years.
1973	6.55	3.53	
1986	31.55	25.00	
2003	43.49	11.94	
Overall change 40.47 km ²			

Very recently, Gichamo et al., (2022) extended the study on the extent of Lake Beseka between the years 2007 and 2013. According to the findings of this research, the surface area of the lake expanded to 54.49 km², which was approximately 18 times more than the 3 km² defined before 1960s, as shown in Table 9 below.

Table 9. Changes in the size/area of Lake Beseka between 2007 and 2013 [89].

Year	Area (km ²)	Δ (km ²)	Remarks
2007	45.63	–	This record shows that in only six years between 2007 and 2013 the overall change in the size of the lake was 8.86 km ² . Within these six years the spike in area of the lake was noted between 2009 and 2008.
2008	46.17	0.54	
2009	49.87	3.70	
2010	53.12	3.25	
2011	53.19	0.07	
2012	53.72	0.53	
2013	54.49	0.77	
Overall change: 8.86 km ²			

The studies conducted on the size of Lake Beseka by [12, 97, 98, 112], revealed similar increasing trend. These observations indicated the severity of the flooding problem in the area as a function of the rising lake level because of the flat topography of the area surrounding the lake. If this condition of the lake is left unchecked, the terminal Lake Beseka might become an open system lake just like Lake Ziway by joining Awash River through its overflow causing a calamity to all downstream irrigation developments in the Awash River basin.

Several studies have been conducted around Lake Beseka mainly focusing on the pattern of expansion of the lake and the LULC change on its watershed. According to [87], the LULC pattern of the watershed of Lake Beseka experienced drastic changes over the last 4–5 decades because of rapid increases in human settlement, deforestation, establishment of irrigation schemes and Awash National Park.

Approximately 189.24 km² of forest and 47.30 km² of grazing lands were devastated between 1973 and 2008 [87]. At the same time, there was a shift in land cover from forests/woodlands to open woodlands, shrub and grazing lands.

Recently, [97], stated that the catchment of Lake Beseka experienced a significant LULC change, where about 86% of forest coverage and 46% of grasslands were lost over the study period from 1973 to 2015, which were shifted to open bushy woodlands, farms, lake water and wetlands as shown in Table 10 below.

Table 10. LULC change of Lake Beseka watershed between 1973 and 2015 [97].

LULC class	Area (km ²)					Remarks
	1973	1986	2000	2007	2015	
Farm land	10.5	44.0	24.0	22.5	21.0	Farmland, lake area, wetland and bush land expand. Forest, grass land, and bushy woods declined. The loss of forest was very high. Lake area increased by 1.05 km ² each year reaching 51.0 km ² in 2015. Conversely, forest area declined by 4.52 km ² each year, reaching 21 km ² in 2015 from 211.0 km ² in 1973.
Forest	211.0	105.5	37.0	31.0	21.0	
Shrub land	123.5	116.0	122.0	115.5	128.5	
Grass land	91.5	63.0	49.5	46.0	43.5	
Bushy woods	53.0	136.5	213.0	225.0	218.5	
Wetland	3.5	7.0	14.5	16.0	8.5	
Lake Beseka	7.0	28.0	40.0	44.0	51.0	

Lake Ziway

Lake Ziway is an open lakes located in the most upstream portion of the Ethiopian CRV portion at 8001'N and 38047'E. The mean and maximum depths of the lake are about 2.5 m and 9 m, respectively. The main water inputs to Lake Ziway come from Katar River (from the western highlands) and Meki River (from the eastern mountains), and direct precipitation. According to [106], while the annual average inflow of Katar River is about 464 Mm³, the inflow from Meki River is about 276 Mm³.

On the other hand, the main outputs are evaporation, discharge via the Bulbula River and groundwater leakage through faults and paleo-channels. The annual discharge of water from the lake is around 170 Mm³ [116,117] into Lake Abijata via Bulbula River. According to [76], hydro-chemical and isotopic evidence revealed that there is a southward groundwater migration from Ziway to Abijata.

Since the early 1970s agricultural activities have massively intensified in the watershed of Lake Ziway where its natural vegetation (forests and woodlands) has been degraded leading to the subsequent siltation in lake [10, 26, 91,118, 119]. The intensification of large-scale irrigation in the watershed is achieved at the expense of water consumed from the lake and its two main feeder rivers [9].

The first reported size/area of Lake Ziway was 442 km² that came from [102]. Similar to that of the size of Lake Beseka, this reported value of size of Lake Ziway kept on appearing on scientific articles of [7, 110] until the second reported size/area of 440 km² came from [111]. Surprisingly enough, this reported size of Lake Ziway kept on appearing on scientific articles until 2016 as it was reported by [8,78]. According to [113], the size of Lake Ziway was 434 km² which is 8 km² less than the size reported in 1998.

The report by [114] revealed that the water level reduction of 40 cm/annum, surface area shrinkage of 0.08 km²/annum, and loss of water storage by about 20.4 Mm³/annum. As a result, since 2009 the lake has lost 12.75% of its water storage volume. Table 11 below displays the output of change in size of Lake Ziway between 1985 and 2015.

Table 11. Changes in the size/area of Lake Ziway between 1985 and 2015 [80] .

Year	Area (km ²)	Δ (km ²)	Remarks
1985	427.47	–	In just thirty years the size of the lake declined by 2.68 km ² . Each year the size of the lake declined by 9 ha between 1985 and 2015.
1995	425.40	–2.07	
2015	424.79	–0.61	
Overall change: –2.68 km ²			

The watershed of Lake Ziway is bounded between 7°20'54"N and 8°25'56"N latitudes and 38°13'02" E and 39°24'01"E longitudes that includes the rift floor, two escarpment areas, two major river inlets and one river outlet encompasses 7300 km² [12]. It is characterized by higher mountains

at the periphery (along the southeastern and northwestern ridge) and predominantly flat landform with elevations that range from 1601 to 4213 m a.s.l. [12].

The slope classes in the watershed are spatially distributed along with elevation. Eighty-nine percent of the total watershed areas consist of < 30% slopes, and the remaining > 30% slopes (steep to very steep hills and mountains). Thus, the watershed of Lake Ziway is characterized by rugged terrain and geological and structural complexities in which the principal features in the rift margin are dominated by chains of mountains, step faults, horst-graben structures and river channels [115].

The western and eastern parts of the watershed are mainly dominated by volcanic mountain chains and a series of step faults having more annual precipitation and lower annual temperatures than the rift floor areas. The rift center is characterized by gentle slope and flat land decorated by volcanic hills and closely spaced horst-graben structures. Despite the considerable changes in elevation, the bulk (60%) of the watershed area is on the rift floor, and the remaining 40% is on the escarpments that surround it on either side. The watershed has a tropical climate, with a minimum and maximum annual precipitation of 729.8 mm and 1227.7 mm, respectively [12].

The vegetation cover in the rift floor is characterized by *Acacia combretum* open woodland, with deciduous woodlands (composed of *Olea europaea*, *Celtis*, *Dodonaea viscosa*, and *Euclea*) on the escarpments. Change in the LULC of the watershed of Lake Ziway began in the early 1970s [116]. Thus, in the past fifty years the watershed of Lake Ziway has been under progressive and intensive LULC changes. According to [12], the major LULC changes in the Lake Ziway watershed between 1973 and 2018 is characterized by the expansion of cultivated land, agroforestry and settlement areas at the expense of woodlands as shown in Table 12 below.

Table 12. LULC change of Ziway-Shala sub-basin between 1986 and 2016 [12].

LULC class	Area (km ²)			Remarks
	1973	1989	2018	
Cultivated land	2546.97	2863.06	3692.24	Cultivated land gained a total of 1,145.27 km ² which shows an increase of 25.45 km ² each year. Agroforestry rose from 1,589.94 km ² to 1,763.15 km ² . The total increment in agroforestry is 173.21 km ² . The expansion of cultivated land and agroforestry is at the expense of woodland that declined from 1,909.68 km ² to 450.84 km ² . In general, the rate of loss of woodland is 32.42 km ² per annum.
Agroforestry	1589.94	1560.01	1763.15	
Woodlands	1909.68	1301.59	450.84	
Afro-alpine	672.33	984.04	775.36	
Water bodies	427.05	426.32	430.04	
Wetlands	91.98	88.33	88.25	
Settlement	24.82	27.74	59.91	
Plantation	37.23	48.91	40.22	

Study conducted by [117] on the LULC change in the Ziway–Shala sub–basin between 1986 and 2016 revealed that grass/grazing land, cultivated land, and bare-land have increased, while scattered acacia woodland, bush/shrub-land, and swampy/marshy land declined. The driving forces are population growth, fuelwood extraction, agricultural land expansion, charcoal making, climate change/recurrent drought, and overgrazing as shown in Table 13.

Table 13. LULC change of Ziway-Shala sub-basin between 1986 and 2016 [117].

LULC class	Area (km ²)			Remarks
	1986	2000	2016	
Agriculture land	450.06	627.40	640.86	While agriculture and grazing lands increased by 190.80 km ² and 444.13 km ² , respectively, bush land, acacia woodland and water bodies decreased by 193.11km ² , 380.78 km ² and 64.93 km ² , respectively. The rate of loss of
Acacia woodland	738.38	773.52	357.60	
Bare land	122.46	74.28	164.14	
Bushland	384.29	280.74	191.18	
Dense acacia woodland	79.97	98.71	71.97	
Grazing land	356.94	303.36	801.07	

Swampy land	96.48	76.71	66.69	acacia woodland and gain by agriculture land is 12.69 km ² and 6.36 km ² per annum.
Water body	999.82	993.68	934.89	

In a similar research conducted by [115] on LULC change of the watershed of Lake Ziway for the period between 1985 and 2020 depicted an increase in cultivated land from 2,598.07 km² to 3,588.68 km². Similarly, settlement increased from 365.00 km² in 1985 to 1,007.4 km² in 2020. According to this finding, cultivated land and settlement expanded by 27 km²/year and 1.8 km²/year, respectively. The expansion of cultivated land and settlement in the watershed is at the expense of woodland that diminished from 1,718.42 km² in 1985 to 219 km² in 2020 with negative annual rate change of 42.8 km² per year.

In another similar research conducted by [118] on LULC change in the Lake Ziway watershed for the time period from 1990 to 2020 revealed that cultivated land, settlement, and plantation lands have increased. Conversely, forest land, grazing land, water bodies and wetlands decreased as shown in the Table 14 below.

Table 14. LULC change of Lake Ziway watershed between 1990 and 2020 [118].

LULC class	Area (km ²)			Remarks
	1990	2005	2020	
Cultivated land	3,258.34	3,823.67	4,566.76	Cultivated land and settlement increased by 1,308.42 km ² and 80.00 km ² , respectively. This increment in the two land covers is observed at the expense of decline in forest land, wetland, grazing land, and water body by 1,201 km ² , 23.57 km ² , 168.85 km ² , and 40 km ² , respectively.
Grazing land	1065.00	975.00	896.15	
Forest land	2,189.64	1,677.11	988.64	
Plantation	75.00	98.00	120.00	
Wetland	122.02	111.22	98.45	
Settlement	130.00	165.00	210.00	
Water body	460.00	450.00	420.00	

The studies conducted on the watershed of Lake Ziway by [26,121,123,124] revealed similar increasing and decreasing trend in the identified land use types. The change in the land use pattern reported since 1973 confirmed that cultivated land, agroforestry and settlement areas increase at the expense of forest land, woodlands, grazing land, bush/shrub-land, and water bodies and wetlands.

Lake Hawassa

The Lake Hawassa basin represents a large collapsed caldera bordered by highlands to the north and east. The center of the caldera is occupied by Hawassa and Shallo (Cheleleka) lakes [63]. Lake Hawassa is an endorheic freshwater lake within the southern portion of Ethiopian rift located between 6059'3.91"-707'42.24"N latitude and 38023'17.8"-38028'52.9" E longitude. The elevation of the lake is 1,680 m a.s.l., representing the culmination of the Ethiopian Rift floor level occupied by lakes [63]. The floor of the caldera is faulted and dotted by volcanic hills [63].

The input comes from rivers, direct precipitation, and groundwater. Usually the overflow from Shallo/Cheleleka wetland that is located about 6 km east of Lake Hawassa is the only perennial water source that drains into Lake Hawassa via the Tikur Wuha (Black Water) river. Cheleleka wetland that receives water from Wedesa, Gomesho, Shenkora, Werka, Weshu, and Lango streams serve as a sediment trap and transports the water and sediment to Lake Hawassa through Tikur Wuha River. Seasonal streams may also terminate in wide-open fractures before reaching the lake [63].

Lake Hawassa and its feeder Cheleleka have been subjected to natural and anthropogenic alterations. Thus, different scholars reported their findings concerning the lake size/area and volume at different times. Unlike the other lakes, there is no substantial abstraction of water, except limited diversions for local irrigation from the Tikur-Wuha River. The water level of Lake Hawassa has been experiencing a progressive rise with an average rate of 4.9 cm/year between 1970 and 2010 [86,125] as shown in Table 15.

Table 15. Changes in the size/area of Lake Hawassa between 1976 and 2004 [71].

Year	Area (km ²)	Δ (km ²)	Remarks
1976	88	–	There is an increasing trend in the size of the lake. While the increase in the size of the lake is 0.5 km ² per year between 1976 and 1998, it is 1.0 km ² per year between 1998 and 2004.
1998	99	11	
2004	93	6	
Overall change			

According to [62], the surface area of Lake Hawassa increased by 7.5% in 1999 and 3.2% in 2011 from that of 1985, while the water volume decreased by 17% between 1999 and 2011. Moreover, silt accumulated over more than 50% of the bed surface that caused a 4% loss of the lake's storage capacity. The sedimentation patterns identified may have been strongly impacted by anthropogenic activities including urbanization and farming practices located on the northern, eastern and western sides of the lake watershed [62].

On the other hand, [120] investigated and reported the changes in surface area of Lake Hawassa over a period of 46 years (1973–2019). According to this report there was a gradual increase in surface area of the lake from 1973 to 2002, accompanied by declining of surface area up to 2015, and finally, a drastic increase up to 2019 as shown in Table 16 below.

Table 16. Changes in the size/area of Lake Hawassa between 1973 and 2019 [120].

Year	Area (km ²)	Δ (km ²)	Remarks
1973	83.98	–	The surface area of the lake showed an expansion by about 7.89 km ² in 29 years between 2002 and 1973.
2002	91.87	7.89	
2009	90.65	–1.22	Similarly, the lake spread out by 2.8 km ² in 9 years.
2019	93.45	2.8	According to this result, the surface area of the lake increased by 11.28 % over 46 years.
Overall change: 9.47 km ²			

The discharge from Tikur-Wuha River along with the sediment into Lake Hawassa is the culprit for the increased surface area of the Lake as well as the cause for reduction in the lake depth [120].

The watershed of Lake Hawassa that consists of important ecosystems is about 1435.61 km² located in an old caldera in a closed drainage system, approximately between 6045'N and 7015'N Latitude and 38015'E and 38045'E Longitude. The formation of the watershed is attributed to intensive tectonic activity which is related to the formation of the main Ethiopian rift system [121].

The dominant landscapes characterizing the watershed are the volcanic mountains forming the surrounding escarpments and fat plains lying at the foothills of the mountains. In terms of elevation, the watershed ranges from 1680 to 2970 m a.s.l. Thus, the topographical characteristics include inter alia, flat plains, gentle slopes to dissected escarpments, mountainous regions, and hilly surfaces.

The central part of the watershed is characterized by low-lying plains. The area between the low-lying plains and the top of the escarpments is characterized by steep slopes. There are a number of urban centers in the watershed, with Hawassa city being one of the biggest. The dominant economic activity in the watershed was agriculture, which was characterized by subsistence level mixed cropping with some commercial farming and livestock production [122].

The vegetation type in the watershed is influenced by altitude and rainfall. The eastern part of the watershed is a "Moist Woina Dega" (moist mid-highland), and montane forest composed of *Podocarpus falcatus* and *Juniperus procera* is dominant [121]. The western part of the "Dry Woina Dega" (dry mid-highland) harbors shrubs and acacia woodland [123].

The rainfall within the watershed amount differ between the drier western escarpments, which receive 900 mm a year, and the wetter eastern escarpments, which receive 1200 mm. The mean annual temperature in the foothills varies from 17 to 19 °C [121] as shown in Table 17 below. In general, the LULC change studies depict that cultivated land, agroforestry, and built area are expanding, while other land uses generally decline in the Hawassa watershed.

Table 17. LULC change of Lake Hawassa watershed between 1972 and 2017 [121].

LULC class	Area (km ²)			Remarks
	1972	1992	2017	
Cultivated land	136.05	221.36	391.73	Cultivated land, agroforestry, and built area expanded from a total of 347.58 km ² in 1972 to a total of 892.25 km ² in 2017. This expansion is the result of declining in all other land uses.
Agroforestry	209.94	299.28	491.88	
Bare land	1.59	4.40	8.64	
Shrub land	405.48	243.12	96.68	In general, during the study area shrub-land, woodland, forest, wetland, grassland, and lake exhibited decline by 76.2%, 61.2%, 59.8%, 42.7%, 9.9%, and 6.4%, respectively. Predominant decline was noted in shrub-land.
Woodland	247.03	222.12	95.14	
Grazing land	99.658	125.09	89.824	
Wetland	76.33	78.85	43.77	
Lake area	101.646	99.04	95.13	
Built area	1.59	4.39	8.64	
Forest	142.92	119.52	57.46	

LULC Change in the CRV Watershed of Ethiopian Rift Valley

LULC change in the Ethiopian rift system is taking place due to the enhanced socio-economic development, population increase and human pressures on agricultural lands [12]. LULC change and climate change studies in many African countries indicate an increase in settlement and cultivated land areas at the expense of woodlands, dense forest, and wetland vegetation [130,131]. For instance, a few decades ago, the CRV basin is known for its dense acacia woodlands that have now been transformed into agricultural and grazing lands [126]. These have serious ecological consequences apart from their social and economic improvement.

LULC change detection at a local scale is an important topic of study for resource management and environmental change monitoring system [133,134]. In the rift valley region, socio-economic development, population growth and human pressures on agricultural lands have become the main drivers of LULC changes [12]

Less is known about the exact trend and extent of LULC changes in Ethiopia in general and the Ethiopian rift system in particular, except the widely scattered studies that indicates the expansion of cultivated lands into ecologically sensitive areas at an alarming rate and lake water drop [135,136,137]. For instance, [80] conducted an overall assessment of LULC change in the CRV for 30 years period from 1985 to 2015 and revealed that settlement area increased by 223.77 km², while large scale farming expanded by 203.31 km², and open woodland and forest decreased by 335.42 km².

On the other hand, [132] reported that farmlands, bare lands, and settlement areas showed positive changes, while forest, grasslands, shrub-lands and waterbodies showed negative changes between 1973 and 2020. According to this finding, the expansion of agricultural lands has occurred at the expense of grassland (where 2044.91 km², or 87.2% of grassland was converted to farmland), forestland (5,568.34 km², 65.9%), and shrub-land (2,614.12 km², 78.3%). The expansion of bare-land occurred mainly at the expense of waterbodies (77.22 km², 6.0%) as displayed in Table 18 below.

Table 18. LULC change in the CRV between 1973 and 2020 [132].

LULC class	Area (km ²)				Remarks
	1973	1990	2005	2020	
Farmland	2,846.66	3,617.90	7,118.84	12,813.30	Between 1973 and 2020 forestland, grassland, shrub-land, and water body declined by 68.0%, 68.8%, 82.3 & 8.5, respectively.
Forestland	8,452.50	5,472.40	5,232.32	2,702.84	
Bare land	5.78	1.012	19.29	110.64	
Grassland	2,344.86	1,584.90	314.95	730.46	Conversely, farmland, bare land, & settlement increased by 350.1%, 1,813.5%, & 696.8% respectively.
Settlement	21.27	29.49	56.40	169.49	
Shrub land	3,338.29	6,376.91	4,299.49	591.13	
Water body	1,275.31	1,202.07	1,243.40	1,166.80	

In similar track record, the research conducted by [133] on LULC change in the CRV from 1989 to 2019 using Landsat images and historical climate data involving machine learning revealed that the areal percentage of agricultural land increased by 27.5%, settlement by 0.8%, and barren land 0.4% while the natural vegetation, wetland, water body, and grass land decreased by 24.5%, 1.6%, 0.5%, and 2.1%, respectively. The land use dynamics have been stronger in the first decade of the study period.

In similar development, [134] reported their findings of the LULC change observed between 1985 and 2015. According to their finding, small-scale farming occupied 44.34% of the area in 1985, which was followed by mixed cultivated/acacia (21.89%), open woodland (11.96%), and waterbodies (9.77%). The details of the observed changes are indicated in the Table 19 below.

Table 19. LULC change in the CRV between 1985 and 2015[134].

LULC class	Area (km ²)			Remarks
	1985	1995	2015	
Water body	1,241.66	1,202.40	1,097.97	During the study period settlement, largescale farming, and mixed cultivated/acacia land increased by 70.84%, 33.65%, and 46.20% at the expense of decline in water bodies, small-scale farming, open woodland, grazing land, forest and degraded savannah.
Small scale farmland	5,637.17	4,549.89	4,600.93	
Settlement	315.90	384.84	539.67	
Open Woodland	1,520.23	833.46	1,238.43	
Open grazing land	137.39	186.38	11.81	
Mixed cultivated/acacia	2,782.45	3,760.02	4067.99	
Large scale farming	604.12	1,138.71	807.44	
Forestland	180.45	189.89	126.84	

4. Discussion

According to the assessments of the published literature, the water levels of Lakes Abijata and Ziway in Ethiopia are dropping while those of Beseka and Hawassa Lakes in Ethiopia and Baringo and Bogoria Lakes in Kenya are rising at worrisome rates. [18,19]. On the account of expansion of the lakes, the surrounding areas of the lakes are submerged, disrupting livelihoods, causing property damage, and uprooting thousands of people. Conversely, the shrinking in the size of the lakes is also accompanied by loss of important ecosystem services [14]. This is a good indication that the health of the rift region lakes has been under immense influence from extensive anthropogenic (land use land cover /LULC/ changes) and natural (climate change and geological) influences.

According to [76] there are little evidences on the geothermal activity in Ethiopian rift that has slight influence on the levels of the lakes. On the other hand, the effects of climate change and land use change on the water cycle are the major concerns in water resources management within the rift system [136].

In Ethiopia, over recent years, the CRV has become the focus area for large and small-scale irrigation developments and other human activities that withdraw considerable amount of water from the lakes and their tributary rivers [137]. Studies on the rift valley lakes region have shown that water abstraction and LULC change within the rift system are frequently carried out without a fundamental understanding of the intricate hydrological, hydrogeological features and the fragile nature of the rift valley’s ecosystem [12,18,24]. These anthropogenic forces contributed for the fluctuations in the lake water levels, hydrodynamics, and increased salinity [112].

5. Conclusions

The unprecedented increases in water levels fluctuation in EKR valley lakes that inundated entire villages are major causes of problems that are affecting communities and their livelihoods, inundating infrastructures such as roads and building, and damaging sewers, grazing areas, and destroy diverse biodiversity. This review contributes to knowledge by documenting spatio-temporal changes in lake levels.

Despite the fluctuations in the water level of Lake Beseka, Ziway, Baringo, etc. there are no sufficient accounts of how these fluctuations have affected their water quality parameters and ecological functions. This is the high time to halt and think about the health of EKR valley lakes by the academia and decision makers and get prepared for the currently observed and “would be” materialized consequences of the shrinking or expanding water level fluctuation of lakes.

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