

# **A call to action: strong long-term limnological changes in the two largest Ethiopian Rift Valley lakes, Abaya and Chamo**

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## **Abstract**

The 2 largest Ethiopian Rift Valley lakes, Abaya and Chamo, are dominant socioecological systems with important potential for ecotourism because of their attractive setting with Nechisar National Park. We report on changes in water quality in these lakes during recent decades. We integrated data on key limnological variables during the last 55 years by supplementing historical literature data with our own field measurements. Our analyses provide strong evidence for a steady increase in nutrient concentrations and decrease in water transparency. Total phosphorus and total nitrogen concentrations in both lakes over the study period increased 5- and 7-fold, respectively. Similarly, water transparency decreased,

especially in Lake Chamo, which used to have clear water but is now becoming a sediment-loaded lake similar to Lake Abaya. We reconstructed fertilizer use and land use changes in the region during the past decades. The combined data suggest that the dramatic eutrophication we observed in the lakes is likely associated with increased fertilizer use or other activities related to intensified agricultural practices, and the decline in water transparency is probably associated with low tree cover due to deforestation. The profound changes in the ecology of both lakes may jeopardize the delivery of ecosystem services in the region, including water supply, fisheries, and ecotourism. Our results stress the urgent need for measures that prevent further environmental deterioration of the unique heritage provided by the Ethiopian Rift Valley lakes.

**Keywords:** deforestation, ecological deterioration, Ethiopian Rift Valley Lakes, nutrient enrichment,

## **Introduction**

The chain of 8 lakes (north to south: Koka, Ziway, Abijatta, Langano, Shala, Hawassa, Abaya, and Chamo) that comprise the Ethiopian Rift Valley are key ecological determinants of the region and have high societal importance (Alemayehu et al. 2006, Ayenew and Legesse 2007). Among these, Lake Abaya and Lake Chamo are the first and second largest in area (Baxter 2002, Golubtsov and Habteselassie 2010). They provide vital ecosystem services and are widely recognized for their outstanding biological diversity.

Ethiopia is a country in full transition (PIF 2010) and is experiencing rapid human population growth, and the expansion of agricultural activities in the Ethiopian Rift Valley has rapidly increased pressure on its natural resources (Ayenew and Legesse 2007, Meshesha et al. 2012). The conversion of large parts of the natural vegetation to cropland during the last

decades (Hengsdijk and Jansen 2006, Meshesha et al. 2012) and the sharp increase in inorganic fertilizer application after the introduction of the Sasakawa Global 2000 agricultural program in 1993 to improve food security in Ethiopia by increasing agricultural productivity (Seyoum et al. 1998, Belay and Abebaw 2004) have resulted in enhanced soil erosion and increased nutrient run-off, respectively (Ayenew and Legesse 2007). As a consequence, the majority of the Ethiopian Rift Valley lakes currently suffer from massive sediment input and severe eutrophication. Additional concern arises from the expansion of large-scale intensive horticulture in the Rift Valley, which further increases nutrient levels (Hengsdijk and Jansen 2006, Scholten 2007). For example, phosphate, nitrate, and silicate concentrations of Lake Ziway have reportedly increased in recent years (Ayenew and Legesse 2007). Intense cyanobacteria blooms and the occurrence of cyanobacteria toxins (microcystin) have been reported in multiple Rift lakes, including in Koka, Chamo, Langano and Ziway (Willén et al. 2011). The microcystin concentration in Lake Koka is the highest reported in African lakes to date ( $45\text{--}51\text{ }\mu\text{g L}^{-1}$ ) and exceeds levels that represent health risks for humans, livestock, and wildlife (Willén et al. 2011).

Likewise, the catchment areas of Lake Abaya and Lake Chamo have experienced profound land use changes. Agricultural intensification and large-scale forest clearance began in the lowlands of the Lake Abaya and Lake Chamo catchments in the 1960s, when the town of Arba Minch was established and both cash crop farming and mechanized agriculture expanded in the region (EPA 2005, Assefa and Bork 2014, Kassa 2015). Cultivated land in the study area increased by 39% during 1973–2006, and 37% of the natural grasslands in the highlands has currently been converted into cropland (Assefa and Bork 2014). The catchment areas of Lake Abaya and Lake Chamo are currently severely threatened by land degradation due to water erosion and poor land use practices (Makin et al. 1975, Schütt et al. 2002, Schütt and Thiemann 2006, Gebremariam 2007, Kassawmar et al. 2011).

During the past decades, the nutrient status of Lake Abaya and Lake Chamo has been sporadically measured, and local residents and fishermen have reported the degree of change in these lakes, including strongly decreased fisheries yields in Lake Chamo during the last 15 years (Ward and Wakayo 2011). The objective of this study was to identify the long-term trends in water quality characteristics in Lake Abaya and Lake Chamo over the past decades and to evaluate the link between these trends and land use change and changing agricultural practices such as fertilizer use.

## **Study Site**

The 2 largest Ethiopian Rift Valley lakes, Abaya ( $6^{\circ}5'14''\text{N}$ ,  $37^{\circ}41'20''\text{E}$ ) and Chamo ( $5^{\circ}50'59''\text{N}$ ,  $37^{\circ}33'54''\text{E}$ ) are located in the Southern Nations, Nationalities, and People's Regional State of Ethiopia (Fig. 1). These lakes are known for their outstanding biological diversity and their high socioeconomic importance. Lake Abaya and Lake Chamo are separated by only a 5 km wide ridge with a vertical offset of ~60 m (Awulachew 2006a, Belete et al. 2015). The surface area of Lake Abaya is much larger than that of Lake Chamo (Table 1; Awulachew 2006a). Both lakes are relatively shallow and polymictic throughout the year (Gebermariam 2007).

Lake Abaya and Lake Chamo do not share a catchment. The catchment of Lake Abaya is considerably larger than that of Lake Chamo, but they both have largely undergone the same socioeconomic developments during recent decades with regard to deforestation, agricultural practices, and human population density (EPA 2005, Awulachew 2006b, Kassawmar et al. 2011). The major difference between the 2 catchments is that land degradation in one of the key catchments of Lake Abaya (Belate basin) occurred earlier than that of the typical catchments in Lake Chamo (Kulfo basin; M. Mekie, Nechisar National

Park, 2012, pers. comm.); however, land degradation also was extensive in the catchment of Lake Chamo in recent decades (EPA 2005, Schütt and Thiemann 2006, Kassawmar et al. 2011).

The 2 lakes have a complex history of being interconnected or disconnected from each other. Lake Abaya and Lake Chamo have been interconnected in the past, with water from Abaya flowing into Chamo via the Kulfo River, but the lakes were disconnected from 1980 (Tekelemariam 2005) until recently, 2013, probably as a result of a decreased water level (and a subsequent increase that reestablished the connection in 2013). For most of the time considered in this study, the 2 lakes were therefore disconnected.

The catchments of both lakes are characterized by a humid to hot semiarid tropical climate with a bimodal rainfall pattern including 2 wet seasons (first from end-Mar to mid-Jun, second from mid-Sep to late Nov) and 2 dry seasons (first from Dec to mid-Mar, second from end-Jun to mid-Sep; Assefa and Bork 2014, Wagesho 2014).

Most of the alluvial soils around Lake Abaya and Lake Chamo are formed from materials recently deposited by rivers and lakes. The deltas and the flood plains are deep, fertile, and well suited for cultivation (especially banana plantation) and hence have been under extensive cultivation since the 1980s. As a result, a considerable load of sediment and nutrients enter from the inflows of the 2 lakes (Makin et al. 1975, EPA 2005, Tekelemariam 2005, Kassawmar et al. 2011).

## **Methods**

### ***Data collection and statistics***

We screened published scientific literature and official national and international reports from 1961 to 2015 for data on key limnological variables of both lakes. Our survey includes data on total nitrogen (TN) and total phosphorus (TP) concentration, conductivity, water

transparency, and phytoplankton biomass measured as chlorophyll *a* (Chl-*a*) concentration (Supplementary Table S1). To avoid seasonal variation between time points, all data were collected during the dry season except one datum point for TP and 2 data points for conductivity and 2 data points for Chl-*a* (see also Supplementary Table S1).

In addition to data on lake limnology, we retrieved data on the average annual national inorganic fertilizer use in Ethiopia from 1970 to 2013 from the Central Statistical Agency (CSA), the Food and Agriculture Organization (FAO), the International Fertilizer Development Center (IFDC), and the Winrock International Institute for Agricultural Development (WIIAD; Supplementary Table S1). We used national fertilizer use data because these data are available for a longer time period than catchment-specific data. Nevertheless, national fertilizer use data are representative of the fertilizer use in the catchment area of both lakes because fertilizer application has been uniform throughout the country (Belay and Abebaw 2004; Fig. 2e). Fertilizer in Ethiopia typically contains phosphorus in the form of diammonium phosphate (DAP) and additional nitrogen in the form of urea. The ratio of DAP to urea application in mass ( $\text{kg ha}^{-1} \text{ yr}^{-1}$ ) at country level is 2:1 (CSA 2008, FAO 2009). In the present study, fertilizer use is expressed in units of  $\text{kg ha}^{-1} \text{ yr}^{-1}$ , which refers to the total fertilizer (DAP + urea) used per hectare per year.

We retrieved historical data on changes in forest cover in the Abaya catchment (1967–2004) from Wagesho (2014) and Mengistu (2009), but these data are also largely representative of the catchment of Lake Chamo. The main difference is, in general, heavier and earlier deforestation in the catchment of Lake Abaya than in the catchment of Lake Chamo (M. Mekie, Nechisar National Park, 2012, pers. comm.), but the tendency of a decline in forest cover and the overall high level of deforestation is shared by both catchments (EPA 2005, Kassawmar et al. 2011).

Arbaminch daily wind run data and analysis are given in supplementary information (Appendix 1).

Finally, we supplemented the literature data with our observations on key limnological variables in the 2 lakes collected during the dry season of 4 consecutive years (Aug to mid-Sep 2012, Feb to mid-Mar 2013, Feb to mid-Mar 2014, and mid-Sep 2015). Water samples were collected at 4 pelagic locations along a transect from the inflow to the outflow. Phytoplankton biomass was estimated by *in situ* measurements of Chl-*a* concentrations on a pooled sample from the surface, middle, and near-bottom (taken by a SEBA Van Dorn) using a hand-held Fluorometer (AquaFluor, Turner Designs, Sunnyvale, CA). Samples for nutrient concentration (TN and TP) analyses were taken from the pooled water sample and kept cool in the dark in the field. In the laboratory, nutrient samples were kept frozen (−20 °C) until further analysis. Water transparency was measured using a Secchi disk (diameter: 0.3 m) with alternating black and white quadrants. TN and TP concentrations were analyzed using a HACH DR/900 photometer after alkaline persulphate digestion (Koroleff 1970). The results of the nutrient analyses were validated by a parallel analysis of a subset of the samples using a Technicon Auto analyzer II (Technicon) after alkaline persulphate digestion (analyses performed at KU Leuven, Belgium). Conductivity was measured from the pooled water sample at each sampling location using an electrode (HACH, HQ40D). The concentration of total suspended solids (TSS) in the water column was determined gravimetrically from the pooled water sample by filtering a known volume of lake water through a pre-weighed glass fiber filter (Whatman GF/C), drying the filter (105 °C, 24 h), and quantifying the difference in weight.

Nonparametric Mann-Kendall tests were used to assess the presence of a monotonic trend over time for the 7 investigated variables (TN, TP, Chl-*a*, water transparency, conductivity, fertilizer use, and forest cover). Mann-Kendall is well suited to test for

significant trends in skewed data with relatively few data points (Gilbert 1987) and is robust to abrupt breaks in nonhomogeneous time series (Tabari et al. 2011).

## Results

### *Limnology*

TP showed a significant increase over time in both lakes (Fig. 2a, Table 2). In Lake Chamo between 1978 and 2005, TP ranged from 0.14 to 0.45 mg L<sup>-1</sup>, whereas between 2012 and 2015 the range increased to 1.5–1.95 mg L<sup>-1</sup>. A similar trend was observed in Lake Abaya, where TP between 1961 and 1991 ranged from 0.24 to 0.29 mg L<sup>-1</sup>, whereas between 2012 and 2015 the range increased to 1.44–1.84 mg L<sup>-1</sup> (Fig. 2a).

In Lake Chamo, TN showed a significant increase over time (Fig. 2b, Table 2). Although TN in Lake Abaya seemed to increase over time (Fig. 2b), this trend was not significant (Table 2). Before 2005, TN in Lake Chamo was ~0.29 mg L<sup>-1</sup> and then in 2005 increased to 1.6 mg L<sup>-1</sup>. A significant increase was seen between 2012 and 2015, with annual averages ranging from 1.97 to 3.50 mg L<sup>-1</sup>. TN concentrations in Lake Abaya during 2012–2015 similarly ranged from 1.94 to 2.9 mg L<sup>-1</sup> (Fig. 2b).

Chl-*a* levels in Lake Chamo showed a significant decline over time, whereas this trend was not significant for Lake Abaya (Fig. 2c, Table 2). In Lake Chamo, Chl-*a* levels increased from ~90 µg L<sup>-1</sup> in 1966, approaching ~180 µg L<sup>-1</sup> in 1990. From 1990 onward, we observed a strong decline, with average values of ~12 µg L<sup>-1</sup> during 2012–2015. In Lake Abaya, Chl-*a* levels declined 93% from 1966 to 1991, and the current data (2012 to 2015) indicate that Chl-*a* has declined below 6 µg L<sup>-1</sup> (Fig. 2c).

Water transparency changed significantly over time in both lakes (Fig. 2d, Table 2). Secchi depth was reduced 37% and 72% from 1984 to 2015 by in Lake Abaya and Lake



Chamo, respectively. Similarly, the concentration of TSS is high in both lakes (average 155 and 47 mg L<sup>-1</sup> in Abaya and Chamo during the dry season during 2012–2015, respectively).

Conductivity of both lakes showed a significant increase over time (Fig. 3, Table 2). In Lake Chamo, before its disconnection from Lake Abaya, conductivity ranged from 1034 – 1115  $\mu\text{S cm}^{-1}$  between 1938 and 1966. After the lake became disconnected from Abaya Lake, conductivity range increased to 1100–1910  $\mu\text{S cm}^{-1}$  between 1989 and 2005. In Abaya Lake, conductivity increased slightly but overall remained below 1146  $\mu\text{S cm}^{-1}$  (Fig 3).

### ***Fertilizer use and forest cover***

Fertilizer use in Ethiopia showed a significant increase over time (Fig. 2e, Table 2). In the 1970s and 1980s fertilizer use rates in Ethiopia were below the average level for Africa of 21 kg ha<sup>-1</sup> yr<sup>-1</sup> (Stepanek 1999). After the introduction of the Sasakawa Global 2000 agricultural program in 1993, however, the application rate steeply increase. Between 1993 and 2013 the application rate increased from 13 to 105 kg ha<sup>-1</sup> yr<sup>-1</sup> (Fig. 2e). Similarly, the average application of fertilizer in Abaya catchment increased from 94 kg ha<sup>-1</sup> yr<sup>-1</sup> in 2007 to 110 kg ha<sup>-1</sup> yr<sup>-1</sup> in 2013 (Fig. 2e). Forest cover in the Abaya catchment (Belate and Hare catchments) showed a significant and strong decline over time (Fig. 2f, Table 2). Forest cover was reduced 53% from 1967 to 2004.

Mean daily wind run trend analysis is given in supplementary information (Appendix 1 and Supplementary Fig. S1).

## **Discussion**

Our analysis showed a strong decrease in water quality in Lake Abaya and Lake Chamo, with a strong increase in nutrient concentrations and a consistent decrease in water transparency over the last decades. The increase in nutrient concentrations has been especially pronounced

in the last decade, whereas water transparency and Chl-*a* levels have been strongly decreasing during the last 30 and 20 years, respectively.

As a result of intensive inorganic fertilizer use, Ethiopia has witnessed a significant change in the agricultural sector, and the economy has been one of the world's fastest growing, with World Bank and IMF growth estimates >7% per annum in recent years (PIF 2010). Our results indicate that the strong increase in TP and TN concentration in Lake Abaya and Lake Chamo followed, with some 9 years delay, the sharp increase in fertilizer use. This finding suggests that the profound nutrient enrichment of both investigated lakes may to a large extent have been caused by the excessive use of inorganic fertilizers on agricultural lands in the catchment areas of these lakes. Other factors may also have been important, however, because the increase in fertilizer use is likely also related to other aspects of agricultural intensification, such as changes toward more intensive land use practices that promote erosion and increased agricultural activities close to the rivers and lake shores.

Lake Chamo showed a remarkable decline in water transparency over time. The Secchi disk depth was ~115 cm in 1980 but has steadily declined, and in 2012–2015 the average Secchi disk depth was <36 cm. Lake Abaya has long been a turbid lake (Kebede et al. 1994, Baxter 2002), and its Secchi disk depth has varied between 19 and 9 cm during the past 30 years. Although Lake Chamo is still considerably less turbid than Lake Abaya, its turbidity is rapidly converging to that of Abaya Lake. We are witnessing a rapid change from a clear-water lake to a sediment-loaded turbid lake. The strong decline in water transparency in both lakes is likely caused by increased soil erosion in the catchment area due to strong deforestation.

Although wind-induced sediment resuspension likely occurs in both lakes because of their relative shallow depth, this cannot explain the overall strong decline in water transparency over the last 40 years because the lakes have been consistently polymictic and

well-mixed (Gebremariam 2007). Strong changes in mixing regime during the past decades are unlikely given that the long-term mean daily wind run data (Supplementary Fig. S1) and temperature data (Fetene 2015) did not show clear directional changes over time.

Lake Abaya is more turbid than Lake Chamo because (1) Lake Abaya is considerably larger than Lake Chamo, which makes it more prone to wind-induced sediment resuspension (Scheffer 2004); (2) the much larger catchment area of Lake Abaya compared to Lake Chamo likely results in higher sediment input per unit lake area (Ekholm et al. 2000, Hecky et al. 2003); and (3) land degradation in one of the main catchments of Lake Abaya has been extensive and has occurred earlier than land degradation in the catchment of Lake Chamo (M. Mekie, Nechisar National Park, 2012, pers. comm.). More specifically, the Belate basin of Lake Abaya is well known for its severe land degradation (Wagesho 2014). Note that the current turbid state of Lake Abaya is probably not its natural state. Although we found no formal reports, many local citizens indicated that the lake was more transparent several decades ago (M. Mekie, Nechisar National Park, 2012, pers. comm.). Because of the earlier land degradation history in its catchment, however, the lake had already shifted to a highly turbid state more than 4 decades ago. The key observation in our study is that Lake Chamo is also drastically changing and rapidly converging toward an unfavorable turbid state similar to that of Lake Abaya. Land degradation has drastically increased in the catchment of Lake Chamo (Schütt and Thiemann 2006, Kassawmar et al. 2011), and the use of inorganic fertilizer in the region has strongly increased in recent decades (Seyoum et al. 1998, Belay and Abebaw 2004). We argue that fertilizer use explains why nutrient concentrations in both lakes have increased, whereas land degradation explains why Lake Chamo especially is rapidly becoming more turbid (Lake Abaya was already turbid in the 1980s).

Although the disconnection between the 2 lakes in 1980 and their reconnection in 2013 reflect changes in water levels, no obvious relationship to climate exists given the

absence of any directional change in rainfall, wind intensity, and temperature in the region (Wagesho 2014, Fetene 2015). More likely, the change in water level may be related to tectonic activity in the region (Tudorancea and Taylor 2002). Furthermore, the water level in Lake Abaya has tended to increase during the last decade (Schütt et al. 2005, Tekelemariam 2005), so that the increased nutrient levels cannot be explained by lake water level changes.

The Ethiopian Rift Valley, including the Lake Abaya and Lake Chamo catchments, has witnessed pronounced land use changes since the 1960s (Ayenew and Legesse 2007, Meshesha et al. 2012, Assefa and Bork 2014, Wagesho 2014, Kassa 2015). Agricultural activities have resulted in forest clearance, which promotes erosion on slopes and marginal lands (Schütt et al. 2005, Awulachew 2006b, Wagesho 2014). The capacity of the land to absorb runoff decreased considerably, and the resulting erosion washed soil and nutrients into rivers and lakes (Schütt et al. 2002, Schütt and Thiemann 2006, Tekelemariam 2005).

The current nutrient concentrations in Lake Abaya and Lake Chamo are high, with TP  $>1.7 \text{ mg L}^{-1}$  and TN  $>2.6 \text{ mg L}^{-1}$  in both lakes. Unlike most hypertrophic lakes, Lake Abaya has no algal blooms. By contrast, Lake Chamo historically experienced periodic fish kills because of algal blooms (Belay and Wood 1982), and Chl-*a* levels peaked at high concentrations in the early 1990s. Although increasing nutrients are expected to increase phytoplankton densities, this is not what we observed in the 2 Rift Valley lakes during the last 2 decades. In Lake Abaya, Chl-*a* levels dropped over the last 40 years, whereas Chl-*a* levels in Lake Chamo showed a remarkable increase in the 1970s and 1980s followed by a dramatic decline since the early 1990s. We maintain that this decline in Chl-*a* concentration is likely caused by light limitation due to reduced water transparency.

The negative effect of water turbidity on primary production can influence higher trophic levels (Vijverberg et al. 2012) and is likely the major cause of the observed collapse of fisheries in Lake Chamo. The overall fish density declined rather than specific species or

functional groups targeted by fishermen, providing a strong argument for a general cause of the fish stock decline. The main argument is, however, that the changes in Lake Chamo as it becomes more turbid mirror the differences that we observed between very turbid Lake Abaya and less turbid Lake Chamo. Although nutrient concentrations in the 2 lakes are similar, we found that not only Chl-*a* levels (present study) but also zooplankton densities and fish abundances (Tefferu et al. unpubl.) are much lower in Lake Abaya than in Lake Chamo. Additional concern for the decline in fisheries likely arise from increased fishing pressure and habitat modification, especially to the shore lines, which provide important nursery habitat for the majority of fish species (EPA 2005, Golubtsov and Habteselassie 2010, Ward and Wakayo 2011). Although a reduction in fish can increase top-down control of phytoplankton by zooplankton (Scheffer 2004), the similar nutrient concentrations but much lower plankton and fish densities in Lake Abaya compared to Lake Chamo provide a strong argument that the observed changes in Chl-*a* concentration in both lakes are bottom-up controlled by light limitation.

Lake Abaya and Lake Chamo have been subjected to increased conductivity during the past 70 years. Lake Abaya has had a moderate increase in water conductivity, whereas the increase has been high and relatively fast in Lake Chamo. We believe the observed changes in conductivity in both lakes are closely related to their connectivity. Before their disconnection, the conductivity of the 2 lakes was relatively stable but higher in Lake Chamo than in Lake Abaya, likely because Lake Chamo to some extent is a closed basin with no functional outflow. When Lake Abaya stopped overflowing into Lake Chamo, the conductivity in Lake Chamo started to increase, likely because of the lack of dilution. Conductivity in Lake Abaya also started to increase after its disconnection with Lake Chamo, possibly because Lake Abaya then became a closed lake. The rather moderate increase in conductivity in Abaya compared to Lake Chamo may be related to its large catchment area

and large water mass but may also have been caused by its slow increase in water level (Schütt et al. 2002, 2005), which finally resulted in a reconnection with Lake Chamo in 2013. Given the lack of clear changes in rainfall, temperature, and wind intensity in the region, climatological conditions cannot explain the observed increase in conductivity (Fetene 2015; Supplementary Fig. S1).

## ***Conclusions***

The present study indicates that the water quality in the 2 large Ethiopian Rift Valley lakes, Abaya and Chamo, has deteriorated dramatically during the last decades because of a steady increase in nutrient concentrations and a strong decline in water transparency. This process can have detrimental long-term effects on multiple ecosystem services and can severely affect human livelihoods in the region. Despite their prominent role in the maintenance of biological diversity and economic sustainability, little has or is being done to protect the Ethiopian Rift Valley lakes in general, and Lake Abaya and Lake Chamo in particular, from further degradation. Our study stresses the urgent need for adequate land restoration measures to prevent further ecological degradation of these 2 important Rift Valley lakes. Restoration programs should focus on reducing soil erosion and developing guidelines for fertilizer application on poorly managed degraded marginal lands. In addition, the lakes and their surroundings and catchments need more effective protection.

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**Figure 1.** Ethiopian lakes, including Lake Abaya and Lake Chamo (shapefile downloaded from [www.maplibrary.org](http://www.maplibrary.org)). The dotted line and arrow indicates the water flow from Lake Abaya to Chamo.

**Figure 2.** Changes in Lakes Abaya and Chamo from 1961 to 2015: (a) total phosphorus (TP), (b) total nitrogen (TN), (c) Chl-*a* concentration, (d) water transparency (Secchi depth), (e) average fertilizer use in Ethiopia and Abaya catchment, and (f) forest cover in Abaya catchment. Note that the smoothening lines for fertilizer use and forest cover were added to visualize the overall change of each variable but do not imply that the data can be interpolated as such.

**Figure 3.** Conductivity in Lake Abaya and Lake Chamo during the past 70 years. Arrows indicate the moment of hydrological disconnection between the 2 lakes in 1980 and their reconnection in 2013. Smoothening lines were added to visualize the overall change but do not imply that the data can be interpolated as such.

**Figures**

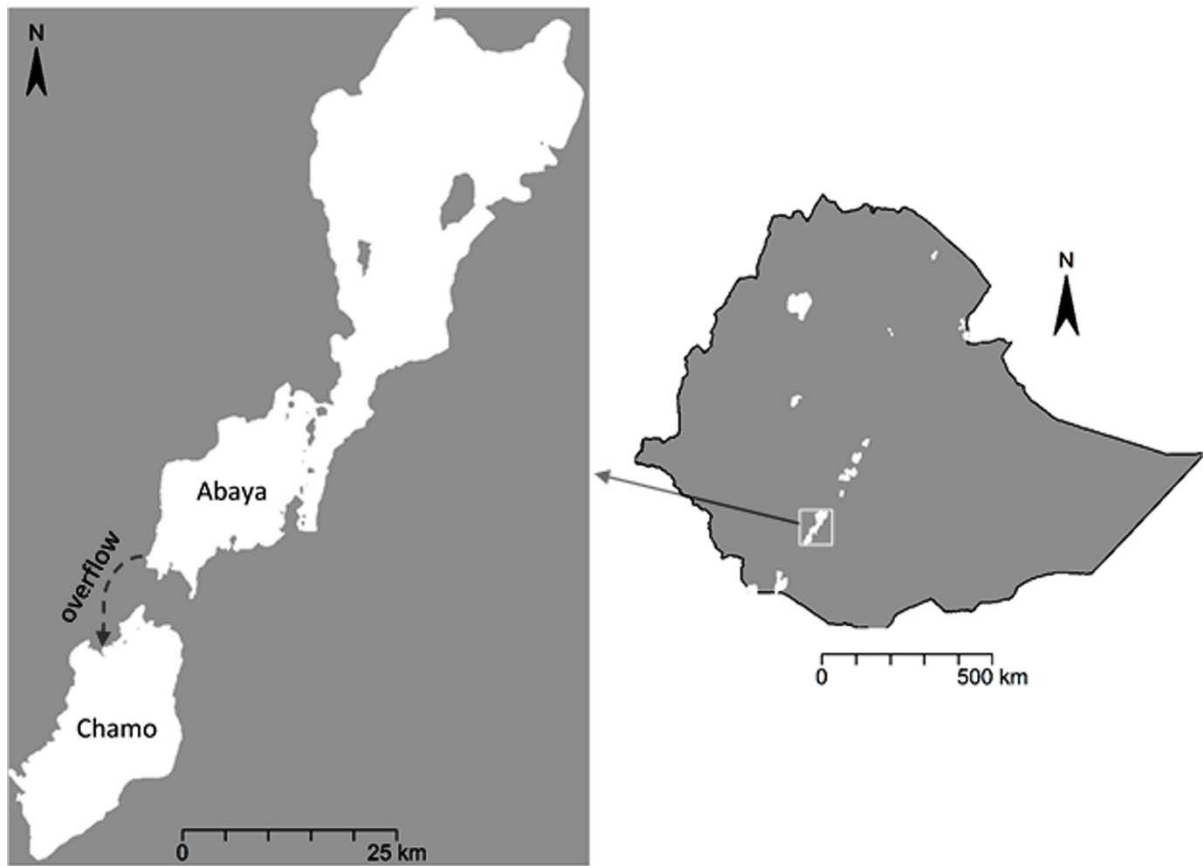


Figure 1

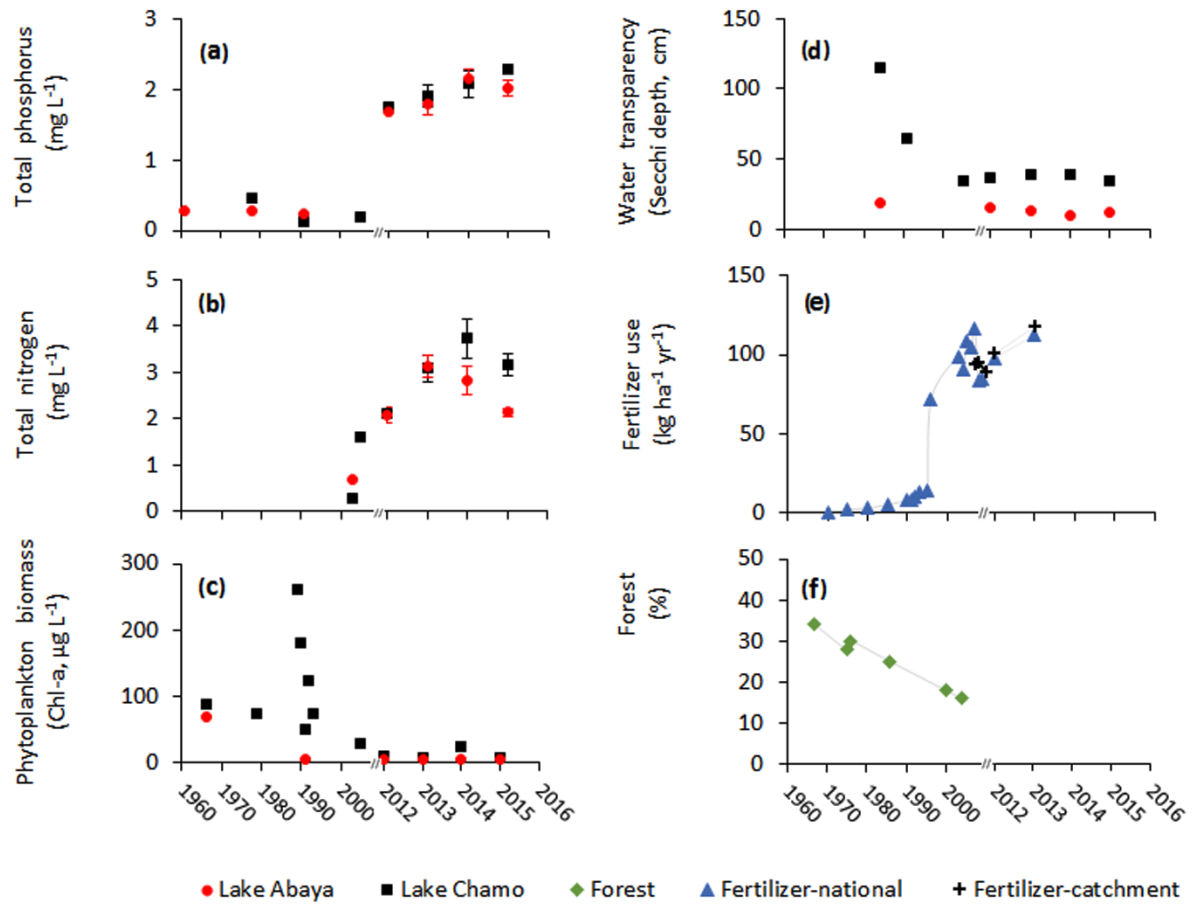


Figure 2

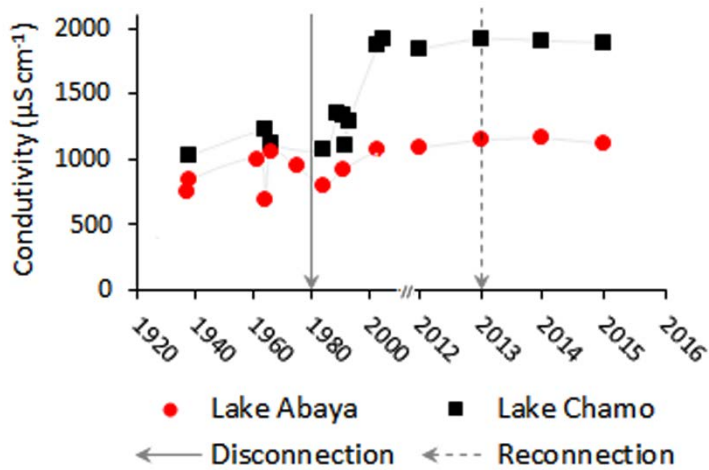


Figure 3

**Table 1.** Morphometric characteristics of Lake Abaya and Lake Chamo, following Awulachew (2006a).

Parameter	Lake Abaya	Lake Chamo
Altitude (m)	1169	1110
Basin area, including lakes (km <sup>2</sup> )	16 328.5	2271.3
Lake surface including Islands (km <sup>2</sup> )	1139.8	316.72
Mean depth (m)	8.6	10.2
Maximum width (km)	27.1	15.5
Shoreline length (km)	268.78	108.1
Volume (m <sup>3</sup> )	9.81 × 10 <sup>9</sup>	3.24 × 10 <sup>9</sup>

**Table 2.** Results of Mann-Kendall analyses testing for trends in changes over time in total phosphorus, total nitrogen, Secchi depth, conductivity, chlorophyll *a*, forest cover, and fertilizer use. *S* = Mann-Kendall statistic, *Z* = the standard normal variable. Significant trends (*P* < 0.05) are shown in bold.

Location	Variable	Time period	Observation (n)	Kendall's tau	<i>S</i>	<i>Z</i>	<i>P</i> -value
Chamo	Total phosphorus	1978–2015	7	0.81	17	2.4	<b>0.008</b>
Abaya	Total phosphorus	1961–2015	7	0.68	14	1.95	<b>0.024</b>
Chamo	Total nitrogen	2003–2015	6	0.87	13	2.25	<b>0.012</b>
Abaya	Total nitrogen	2003–2015	5	0.4	4	0.73	0.242
Chamo	Secchi depth	1984–2015	7	–0.62	–13	–1.8	<b>0.035</b>
Abaya	Secchi depth	1984–2015	6	–0.8	–8	–1.72	<b>0.043</b>
Chamo	Chlorophyll <i>a</i>	1966–2015	12	–0.66	–44	–2.95	<b>0.001</b>
Abaya	Chlorophyll <i>a</i>	1966–2015	6	–0.33	–5	–0.75	0.235
Chamo	Conductivity	1938–2015	14	0.58	53	2.85	<b>0.002</b>
Abaya	Conductivity	1937–2015	13	0.62	48	2.87	<b>0.002</b>
Ethiopia	Fertilizer use	1970–2013	20	0.73	139	4.06	<b>&lt;0.001</b>
Abaya basin	Forest cover	1967–2004	6	–0.87	–13	–2.25	<b>0.012</b>