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Impacts of Land Use/Land cover change on wetland Ecosystem Services of Lakes Abaya-Chamo Wetland

Tariku Zekarias[a], Vanum Govindu[b], Yechale Kebede[c], Abren Gelaw[d]

[abcd] Department of Geography & Environmental Studies, Arba Minch University, Ethiopia,
Corresponding author; Tariku Zekarias. Tarezekarias@gmail.com

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Abstract

Although wetlands in Ethiopia provide multiple ecosystem services, they are extremely affected because of human pressure and limited policy attention. We aimed this study at analyzing the ecological services and drivers of the degradation of the Abaya-Chamo lake-wetland. We gathered data using a questionnaire survey of 304 HH (selected via systematic sampling), interviews, and satellite images. Normalized difference vegetation, water, and turbidity indices were used for satellite image interpretation via ArcGIS. Mean, standard deviation, correlation, and regression were used for data analyses. Abaya-Chamo lake-wetland offers fish, timber, firewood, fodder, irrigation, farmland, rainfall, habitat, tourism, aesthetics, recreation, carbon sink, air quality, and climate control services. The area showed siltation-led raising turbidity and a loss of 48.9% of its swamp area from 1990 to 2019. Farm expansion, siltation, irrigation, invasive plants, open access and overuse of resources, lack of legal framework, and rapid population growth were the main drivers of wetland degradation. Land degradation is anticipated adjacent to the lake-wetland in the next few decades because of irrigation. Invasive plants result in dwindling aquatic resources, economic, and tour benefits, and changes in local climate depleting water, and the dissolved O_2 and CO_2 sink capacity of the lake-wetland rapidly. Thus, the government should plan a clear policy and legal framework for the sustainable management of wetlands.

Keywords: *wetland degradation, ecosystem service, sedimentation, turbidity, Abaya-Chamo.*

1. Introduction

Wetlands are among the planet's most biologically productive ecosystems, which are rich in species diversity. Human activities pose threats to the sustenance of wetlands (Bjerstedt, 2011). A '*wetland*,' roughly, is a natural or artificial swamp/marsh, 'fen or peat land' having soft, spongy soil/land saturated with draining or stagnant, fresh, brackish or salty water including marine with a shallow depth (at low tide) of not more than 6 meters (RCS, 2016). It can be marine, riverine, lacustrine, estuarine and palustrine in its origin. Wetlands are often perceived to have little, or no value compared to other potential uses of land that enable the production of immediate economic benefits. But wetlands, constituting only 1.5% of the area of the earth, render about two-fifth (40%) of the ecosystem services globally (Zedler & Kercher, 2005). An inland wetland ecosystem provides services with an estimated average value of US$ 25,681 per/ha/year (Clarkson et al., 2014; TEEB, 2013). This is so because, wetlands offer provisions (fish, fodder, timber, medicines, and oil,), support farming, flora and fauna (wildlife habitat), store carbon, maintain air and water quality and supply, and the hydrological and biogeochemical cycles, regulate climate, stabilize shorelines, curb flood hazard, treat liquid waste, and render cultural, recreational and aesthetic services (Barbier, 2013; CBD, 2015; Clarkson et al., 2014; Dise, 2009; Egoh et al., 2012; MEA, 2005).

Wetlands undergo loss and/or degradation primarily due to human pressure. '*Wetland loss*' is the complete conversion of a wetland to land uses/covers different from it for various reasons; whereas '*wetland degradation*' is the human actions-induced depletion and impairment of wetland functions providing goods and services (Bjerstedt, 2011). That is, the 'degradation' aspect indicates diminishing quality, quantity, and pace of wetland ecosystem processes yielding benefits. Natural and human factors lead to wetland degradation or loss, depletion of its ecological services, and loss of livelihood sources of people nearby wetlands (Ramsar, 2018). The world experienced the loss of half (50 %) of the original wetlands although the loss varies from a low proportion in boreal nations to over nine-tenths in parts of Europe (Clarkson et al., 2014; Mitsch & Gosselink, 2000a).

Conversion to cropland, urban built-up areas and infrastructures, air, and water pollution, increasing nutrient concentration, eutrophication, invasive plants, diversion of wetland tributaries, building dams and irrigation canals, use of chemical farm inputs, drought, intensive exploitation, and unsustainable management are among the major artificial driving forces (causes) of loss/degradation of wetlands worldwide (CBD, 2015; Davidson, 2014; Galatowitsch, 2018; Heathwaite et al., 2012; Trinh et al., 2003; UNEP, 2012; Zedler and Kercher, 2005). These direct causes of wetland degradation are rooted in indirect drivers like population growth, lack of clear policy, climate change, globalization, and policy and governance structural changes (CBD, 2015; Davidson, 2014; Ramsar, 2018; RCS, 2016). Wetlands have been severely degraded in some recent decades-past due to the impact of human factors at large (Davidson, 2014). But all the factors (pointed out above) could not be equally significant in impairing the functions and services of wetlands, and the lives of people (whose livelihoods are linked to wetlands) everywhere globally (MEA, 2005; MEA, 2005b).

Wetland ecosystems, being rich in diversity of flora and fauna, are vital in supporting the livelihoods of local people in Africa (CBD, 2015). Increasing population, food insecurity, and rural poverty in Africa have already threatened wetland ecosystems in the continent (MEA, 2005; Rebelo et al., 2010). The diverse tangible and intangible products and services of wetland functions such as fodder, fish, fuel-wood, non-timber forest products, water, eco-tourism, and flood control have been sources of income and livelihood means for people in Sub-Sahara Africa (MEA, 2005; Egoh et al., 2012; Barbier, 2013). However, human pressure has threatened the flow rates of such ecosystem services and the welfare of people (Clarkson et al., 2014; MEA, 2005).

The production of food from wetlands in Africa should be reconciled with the protection of natural resources. Maximizing the agricultural benefits of wetlands needs to be balanced with minimizing its adverse effects on other ecosystem services, which is the main dilemma of current policies and management of wetlands (Rebelo et al., 2010). Policymakers hardly appreciated the interlinkage between wetland ecosystems and the livelihood of people in many African nations (CBD, 2015; MEA, 2005a; Rebelo et al., 2010). Formulating sound policy and management strategies on wetlands requires a holistic understanding of how wetland ecosystem functions are affected by anthropogenic factors, how people make decisions on resource exploitation, and how wetland degradation influences the lives of people (Boyd, 2012; MEA, 2005b; Ramsar, 2018; Rebelo et al., 2010;).

Ethiopia is said to have about 58 riverine, lacustrine and other categories of wetlands although such resources are said to have not been fully documented (EPA, 2003). Wetlands, with an area extent of 18,597 km^2, account for about 1.5 – 2 % of the area of the country (EPA, 2003; Giweta and Worku, 2018). Assessment of the threats and opportunities (Teklu & Kassahun, 2017; Zinabu, 2002), hydrogeochemical and water level changes (Tamru et al., 2006), and local people to wetland interaction (Tesfau et al., 2018) in the Rift-Valley lakes (Central Ethiopia), sustainable management (Wood & Dixon, 2002) and hydrologic dynamics of wetlands (Legesse, 2007) in Illubabor area (Western Ethiopia), ecosystem services of Tana lake-wetland (Northwestern Ethiopia) (Ayalew, 2018), the status of natural lakes of Ethiopia (Tenalem, 2009) and reversing the degradation of Ethiopian wetlands (Giweta & Worku, 2018) were among the wetland-related studies in Ethiopia. But studies that came up with concrete (empirical) evidence on detailed benefits of wetlands, spatiotemporal changes in turbidity/siltation level and associated swamps, and the impacts on wetland ecosystem services have been limited in the country (EPA, 2003).

Land use/land cover dynamics-led increasing erosion over the highlands of Ethiopia and the resulting sedimentation elsewhere has significantly threatened the hydrology of lake-wetlands in the country (Feoli & Zerihun, 2000; Tesfau et al., 2018). Soil degradation, declining farm size, and raising rainfall variability-led decline in crop yield in the highlands of Ethiopia resulted in the shift of many farmers from uplands to wetlands in lowland areas (Giweta & Worku, 2018). Based on the authors' observation, depletion of vegetation adjacent to wetlands, raising sedimentation and turbidity levels, dropping water quality and depth of lakes, shrinkage of lakes and associated swamps, and depletion of aquatic and wetland ecosystem services could be among the key indicators of degradation of lake-wetlands in Ethiopia. Some studies indicate that wetlands in Ethiopia have been impacted by cropland expansion, overgrazing, open access and overuse of resources diverting streams, withdrawing water from lakes, runoff from croplands, frequent siltation, pollution by farm inputs, and eutrophication, underlain by rapid population growth (Ayenew, 2004; Giweta & Worku, 2018; Teklu & Kassahun, 2017; Tenalem, 2009; Tesfau et al., 2018; Ayalew, 2018.) However, the impacts of these factors on wetlands vary in space due to dynamics in socioeconomic and environmental circumstances across the country.

Abaya-Chamo lake-wetland, being in the Ethiopian Rift Valley, provides diverse goods and services to the local people even if its resources have been severely impacted by anthropogenic factors. Water and siltation level of Abaya Lake (Schütt et al., 2002), ecology and wetland vegetation composition (Dikaso, 2013) and limnological changes (Teffera et al., 2017) of Abaya-Chamo lake-wetland, land use/cover dynamics in Nech-Sar National Park (Fetene et al., 2015) and the impact of land use/cover dynamics on the landscape of Abaya-Chamo lakes sub-basin (Wolde-Yohannes et al., 2018) were among the main studies related to the lake-wetland where this study is made. But none of these studies analyzed the detailed ecological benefits, spatiotemporal changes in turbidity/siltation level, water extent and swamp area dynamics plus its impacts, and the main drivers of degradation of Abaya-Chamo lake-wetland. Assessing the ecological services and degradation of wetlands, and the direct and root causes of degradation is valuable to formulate sound policy and sustainable management options for wetlands (Boyd, 2012; CBD, 2015). This study was targeted to: (1) assess the main goods and services of Abaya-Chamo lake-wetland; (2) analyze the impact of turbidity/siltation level, water area, and ‘swamp’ area dynamics (1990 – 2019) on the sustenance of the lake-wetland; and (3) explain the main driving forces of degradation of the wetland in Abaya-Chamo wetlands.

2. Study Area and Research Methods

2.1 Description of Study Area

Abaya-Chamo lake-wetland is located within 5°43'19"N - 6°38'51"N latitude and 37°21'55"E — 38°15’05"E longitude in Southern Rift-Valley of Ethiopia (Figure 1). It comprised the larger Abaya Lake, North of Nech-Sar National Park, the smaller Chamo lake (South of this Park), and the associated swamps (Figure 1). Abaya and Chamo lakes are often connected by an overflow of Abaya Lake to the Kulfo River that joins Chamo lake but the lakes were disconnected between 1980 - 2013 (Teffera et al., 2017). Its area is about 242,615 ha. The mean annual temperature of Abaya-Chamo wetland (1987 – 2018) was about 24 ^{0}C; its mean monthly temperature is the highest in March (26

^{0}C) and the lowest in July (23^{0}C), November (23.1 ^{0}C), and December (23.1 ^{0}C) (NMA, 2019). The wetland receives low rainfall where the mean total annual (1982 - 2018) was 870.9 mm. The study area has two rainfall seasons: that is, Spring (March-May) with total rainfall of 362.9 mm is the main rainy season when rainfall is the highest in April (153.7 mm). Autumn (September - November) with a total rainfall amount of 265.6 mm is the second rainy season where it peaks in October (115 mm) (NMA, 2019).

The present geomorphic feature of Lake Abaya-Chamo wetland, being within the Ethiopian Rift Valley, is the combined effect of natural processes such as divergent tectonic movement (between the African Plate-westward and the Somalia Plate-eastward), faulting, volcanism, and alluvial and lacustrine deposition. The faulting, volcanic, and deposition processes resulted in the formation of graben, volcanic hills (islands), and shallowness of the lakes' (Abaya and Chamo) depth, respectively. The western edges of the Abaya-Chamo lake-wetland are covered by alluvial and lacustrine deposits, and swamps. Rivers like Bilate, Gelana, Gidabo, Shife, Basso, and Hare flow into Abaya Lake. Kulfo, Sile, and Elgo streams drain into Chamo Lake. Fluvisols, being the result of alluvial and lacustrine deposits, dominate the adjacent plains of the Abaya-Chamo Lake-wetland (Engidawork, 2001; Abren, 2007). The fertile luvisols, having good agricultural potential, covered the eastern side of Chamo lake. The soils are intensively used for agricultural production (Abren, 2019; Yechale, 2012).

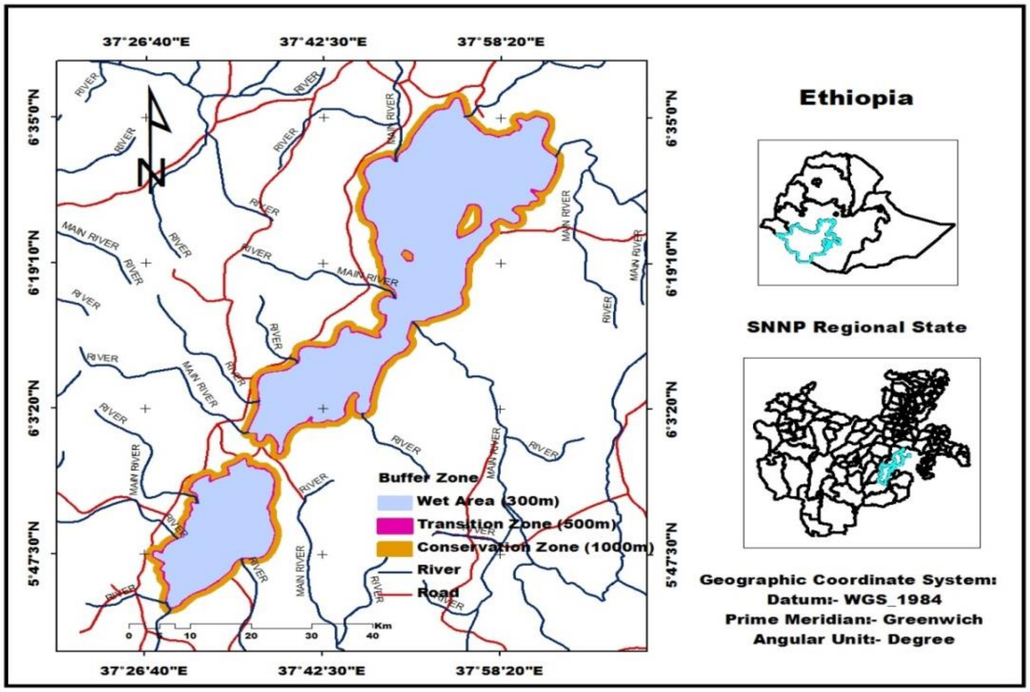

Figure 1. Location of Abaya-Chamo Lake-Wetland (**Source:** Own Design via ArcGIS, 2021)

Agroforestry and livestock rearing are the main activities on the plain western shores of Abaya-Chamo Lake-wetland, where crop farming is practiced using rain-fed and irrigation. Fruits (e.g., banana, mango, avocado, papaya, tomato, etc.,), cereals (e.g., maize), vegetables (e.g., cabbage, pepper, etc.), tuber and root crops (cassava, onion, carrot, etc.), and cotton are cultivated on fertile soils (Abren, 2007, 2019; Yechale, 2012).

The 2020 population, projected with a 2.8 % growth rate of the 2015 population (165,680) of Arba-Minch *Zuria Woreda* (CSA, 2015), was 188,875 where 44.2 % (83,483) of the *Woreda* population lives adjacent to Abaya-Chamo Lake-wetland. The 2020 population of Arba-Minch Town, is projected to have a 2.4 % growth rate of the town's 2007 population (74,879) (CSA, 2008), which was 113,816. This makes the population living in adjacent areas of the lake-wetland to be 197,299; of whom, males were 51.5 % and females were 48.5 %.

2.2 Research Methods

Both primary and secondary data were used for the study. Primary data about human activities, ecosystem goods and services, and challenges on Abaya-Chamo Lake-wetland were collected through questionnaire, Focus Group Discussions (FGD), Key Informant Interviews (KII), and field observation. The questionnaire, having close-ended and open-ended questions was used to gather data via household survey. FGD and KII were also used to collect data about change drivers, benefits, and threats on the Abaya-Chamo wetland. Landsat TM of 1990, ETM+ of 2000, and OLI of 2010 and 2019 of Abaya-Chamo lake-wetland, having a spatial resolution of 30 m and downloaded from the website (https://earthexplorer.usgs.gov/) was used to acquire data about the turbidity level dynamics of Abaya-Chamo Lake, and the water and wet/swamp area changes of the lake-wetland in three decades (1990 – 2019). Secondary data were obtained from books, journals/articles, research, and statistical reports of the Fishery Cooperatives, Meteorological Agencies, and so forth.

2.2.1 Sampling Techniques

Six (6) sample *Kebele* (*Kebele*–the smallest administrative unit in Ethiopia) next to Abaya-Chamo Lake-wetland were identified using purposive sampling. Considering inferences at 95% confidence level, sample size of households was determined using: $n = \frac{z^2pqN}{e^2(N-1)+z^2pq}$, (Kothari, 2004).

Where: 'n' is sample size, 'e' is standard error margin (0.05), 'z' is a standard value of the desired confidence level (95%, which is 1.96), 'p' is the desired sample proportion (0.5), 'q' is 1–p (1 - 0.5 = 0.5), and N is population.

Table 1 Total Household Heads (HH) and Sample Size of HH

N0	*Kebele*/Village Name	Total HH	Sample HH			
			Males	Females	Total	Percent (%)
1	Chano Mille	255	38	15	53	17.4
2	Lante	280	51	7	58	19.1
3	Ganta Kanchama	265	49	6	55	18.1
4	Elgo	210	40	4	44	14.5
5	Shara	295	56	5	61	20.1
6	Omo Lante	160	30	3	33	10.9
	Total	**1,465**	**264**	**40**	**304**	**100.0**

Source: Office of Arba-Minch *Zuria Woreda*, 2019

The total sample household heads became 304; of who, 86.8 % were male-headed and 13.2 % were female-headed. Sample size based on *Kebele* and gender class was determined via proportionate sampling (Table 1). The target sample household heads were identified using systematic random sampling, that is, starting randomly every 5^{th} household head was picked (from HH lists of the sample *Kebele*) until all the 304 were acquired. Besides, four groups (each having 8 - 10 persons) were used for FGD, where the participants were selected purposively. Each group consisted of elders, development agents, women, and youth. Sixteen (16) key informants (4 members of Fishery Cooperatives, 4 experts in Natural Resources Protection, 2 development agents, and 6 elders/farmers) were selected purposively upon their experience with Abaya-Chamo lake-wetland.

2.2.2. Data Analysis Methods

GIS-based LULC change detection was conducted to assess 'water body' and 'swamp' area dynamics, and degradation of the Abaya-Chamo Lake-wetland from 1990 to 2019. Normalized Difference Vegetation Index (NDVI) was used to evaluate the changes in 'water surface' and 'non-water surface' areas, and Normalized Difference Water Index (NDWI) was used to recognize the dynamics in 'water body/surface' and 'swamp' area of the lake-wetland. The magnitude of area change of each land cover class in each period was calculated as $M = (A_2 – A_1)/A_1 * 100$, where M is the magnitude of area change of a land cover class in a period, A_1 is an area (ha) of the land cover class in the initial/earlier year, and A_2 is an area (ha) of the same land cover class in the recent year. Kappa coefficients were used to confirm the accuracy of the classification of the lake-wetland into 'water' versus 'non-water' surface, and 'water body' versus 'swamp' area. Normalized Difference Turbidity Index (NDTI) was also used to analyze the change in the turbidity level of Abaya-Chamo Lake in 1990–2019 and its impacts on the lake-wetland. *Turbidity (NDTI)* is a measure of the degree of concentration of clay, silt, inorganic and organic matter, algae, pollutants, microbes, and others in the water, and it is estimated (Somvanshi et al., 2011): $NDTI = \frac{Red - Green}{Red + Green}$

The mean and standard deviation of the NDTI were extracted from multispectral Landsat TM of 1990, ETM+ of 2000, and OLI of 2010 and 2019 to rate/classify the turbidity classes of the lake in 1990, 2000, 2010, and 2019.

Table 2. NDTI Intervals Used to Map the Turbidity Classes of Abaya-Chamo Lake within 1990 - 2019

N0	Turbidity Class	NDTI Ranges/Intervals in Four Periods			
		1990	2000	2010	2019
1	Low turbidity	-0.286 – 0.262	-0.264 – 0.232	-0.290 – 0.256	-0.148 – 0.005
2	Medium turbidity	0.262 – 0.810	0.232 – 0.728	0.256 – 0.802	0.005 – 0.158
3	High turbidity	> 0.810	> 0.728	> 0.802	> 0.158

Source: Own Extraction Via ArcGIS 10.5

The turbidity level of the lake water was rated as 'high turbidity', 'medium turbidity', and 'low turbidity' classes based on the mean and standard deviation of the NDTI (Table 2). In Table 2, the 'low turbidity class's interval ranges from the 'mean minus standard deviation' to the 'mean,' the 'medium turbidity class's interval ranges from the 'mean' to 'mean plus standard deviation' and the 'high turbidity class's interval is greater than the 'mean plus standard deviation' (Somvanshi et al., 2011). The water area (ha) of each turbidity class in 1990, 2000, 2010, and 2019 were measured via NDTI and mapped using ArcGIS 10.5. The temporal changes (1990 – 2019) in the turbidity level of Abaya-Chamo Lake were also assessed. That is, the changes in the turbidity level, the polluted water area, and the impacts on the lake-wetland were evaluated.The correlation was used to measure the association between 'area change by turbidity/siltation level' and 'water surface area change' of the lake in 1990 – 2019. Simple linear regression analysis was used to evaluate whether the impact of 'area change by turbidity/siltation level' (predictor) on the 'water surface area' (dependent variable) was significantly assuming that 'area change (of Abaya-Chamo Lake) by turbidity level' is a surrogate of the 'change in sediment load' 'into the lake over time. Questionnaire data were entered into SPSS and excel. Percent and mean were used for analysis. The study results were presented in tables and figures.

3. Results

3.1 Ecosystem Goods and Services of Abaya-Chamo Lake-Wetland

Degradation/loss of the Abaya-Chamo wetland emanated largely from the impact of anthropogenic factors, where peoples' livelihood is partly or fully linked to the lake wetland. The main ecosystem goods and services got from the Abaya-Chamo lake-wetland were organized based on evidence gained from the perception and experiences of households, and through field observation of the wetland ecosystem (Table 3).

Table 3. Goods and Services got from Abaya-Chamo Lake-Wetland Ecosystem

N0	Benefits/Services	N0 of HH	P (%)
1	Fish for food or cash	254	83.6
2	Water for livestock and domestic use	180	59.1
3	Timber (for making boats and benches) and firewood	101	33.3
4	Grazing and fodder/grass for livestock or cash	247	81.3
5	Irrigation for cash-crop farming (e.g. fruits, vegetables, tubers/roots)	234	77.1
6	Land (soil) for primary (e.g., crop) production	85	27.9
7	Natural (e.g. hippos) and managed (e.g. crocodile) home of animals	157	51.6
8	Recreation (e.g., swimming) and ceremonial (e.g., weddings, parties)	146	47.9
9	Tourism and aesthetic value	226	74.5
10	Regulation of local climate (e.g. temperature, rainfall, wind, etc.)	219	72.1
	Total	**304**	**100.0**

Source: Own Field Survey, 2019/20

As it is displayed in Table 3, over 80% of people harvest fish for food or cash (83.6 %) from Abaya and Chamo lakes, use the wetland for grazing and generating fodder/grass for livestock or cash (81.3 %) usually during dry conditions, exploit the lakes' water for livestock and domestic use (59.1 %), and generate timber from woodlands and patches of forests (e.g. *Sokie* tree) of the wetlands for making traditional boats (e.g. for fishing) and furniture (e.g. bench), and firewood (33.3 %). People, especially the poor, frequently harvest green grass from the lake wetland for cash. The mean annual fish catch (2013 – 2019) from Abaya and Chamo lakes by legal fishermen is too small (31,791.2 quintals) from the existing high fish yield potential; of this, 73.3 % (23,301.5 quintals) is from Chamo lake and 26.7% (9,918.2 quintals) is a catch by legal fishers in the west-south-west coast of Abaya Lake (see Table 6). Even if Abaya Lake has a high supply of fish (e.g., tilapia, Nile-perch, etc.), its share (%) of annual fish catch is small because of siltation-induced high turbidity of the lake water throughout the year (Teffera et al., 2017), which makes fishing risky because of crocodile attack.

The Abaya-Chamo lake-wetland also provides supportive services to the local people and people away from the wetland such as irrigation water (77.1 %) and fertile land/soil for primary (crop) production (27.9 %) (Table 3); meaning, the lakes' water and the neutral to alkaline land (soil) in the western part of Abaya-Chamo wetland (Abren, 2007) is being used for the production of fruits (e.g. banana, mango, tomato, pepper, etc.), vegetables (e.g. cabbage, salad, etc.), tuber and root crops (e.g. onion, carrot), tobacco, etc., using water pump motor-based irrigation by farmers and small scale investors. The lake-wetland offers a supportive service (51.6 %) since it has natural habitats (for fish, hippos, crocs, and birds like pelicans) and a managed habitat for crocs (known as 'Arba-Minch Crocodile Ranch' – located at the South-Southwestern tip of Abaya Lake) (see Table 3).

The Abaya-Chamo wetland also provides cultural services such as 'tourism and aesthetic values' (74.5 %), and 'recreational (e.g., swimming) and ceremonial (e.g., weddings, parties) services (47.9 %) (Table 3). The local people (especially the youth) frequently swim in Abaya and Chamo lakes. The *Arba-Minch* (Forty-Springs) cool their bodies and refresh their minds when the weather is too hot on the coasts of the two lakes. The *Arba-Minch* (Forty-Springs) frequently get crowded with participants in wedding ceremonies (during wedding periods in Ethiopia) and parties or special occasions on weekends. The Abaya-Chamo lake-wetland is among some of the most preferred tourist destinations for domestic and foreign tourists in the areas surrounding the wetland and Arba-Minch town in Ethiopia. This is so because, it has various tourist attractions such as the numerous small islands, hippopotamus, crocodiles, various bird species, the Arba-Minch Crocodile Ranch, the *Arba-Minch* (Forty-Springs), and *Azo-Gebeya* ("Crocodile Market"). Here, '*Arba-Minch*' refers to the 'Forty-Springs' which are situated in a dense tropical (gallery) forest between Abaya and Chamo lakes, from which the name of Arba-Minch Town was coined and the potable water supply service of the town's 113,816 population is generated. Again, *Azo-Gebeya* ('crocodile market'), being a beach in the northeastern part of Chamo Lake, is not a site where crocs are exchanged, but where crowds of crocodiles (like people in a market) are observed and visited. The lake-wetland is frequently visited by domestic and foreign tourists since Abaya and Chamo lakes are next to (and separated by) the Nech-Sar National Park of Ethiopia, which is endowed with diverse fauna species (e.g., Zebra, Swayne's hartebeest, Cheetah, Lion, Hyena, African Leopard) (Fetene et al., 2015). All these are valuable tourism-led sources of earnings to the government (via tourism and the export of skins of crocodiles), service providers, retailers, and tour guides. Moreover, the two lakes and the associated swamps of the Abaya-Chamo wetland, being surrounded by the western and eastern escarpments of the Ethiopian Rift Valley, have optimized the natural beauty of the environment around the wetland.

Abaya-Chamo wetland is valuable in regulating the local climate (72.1 %) (Table 3). The lake-wetland, being in a semi-arid tropical environment, is useful in moderating the local climate; Where the lakes have a cooling effect during daytime in months of hot weather due to sea breeze (i.e., a cool air blowing from Abaya and Chamo lakes to the surrounding landmass during daytime) resulting from the air pressure differences between land and sea (the lakes) locally. The lake-wetland also regulates air quality by storing huge amounts of dissolved inorganic (sediment form) and organic CO_2 within its lakes and the surrounding swamps as the carbon sink capacity of warm lakes like Abaya and Chamo is high (Tranvik et al., 2009); this, in turn, implies that the wetland controls the level of land surface temperature by reducing the amount of greenhouse gas emission to the atmosphere (Clarkson et al., 2014; Egoh et al., 2012). The Abaya-Chamo lake-wetland is also a key source of rainfall to the local people (farmers) as the lakes are conducive surfaces for evaporation to take place; meaning, it facilitates the hydrological cycle, which is a supportive service for crop farming (MEA, 2005). Since the wetland is located in the semi-arid Ethiopian Rift-Valley depression, its rainfall supply is threatened by a 'rain-shadow location' on the leeward sides of the western escarpment (for moist winds from the west) and the eastern escarpment (for moist winds from the east) of the Rift-Valley. It is because of such landscape barriers that the Abaya-Chamo lake-wetland receives a mean total annual rainfall of about 870.9 mm only (NMA, 2019) although it is located almost in the tropical rainforest region (5^0 – 6^0 N) (Figure 1). The area usually receives a better rainfall amount when rainfall commences from Abaya and Chamo lakes and the associated swamps. The wetland is thought to have a high potential supply of hydrocarbons (e.g., petroleum).

3.2 Impact of Sediment Level, and Dynamics on the Lake-Wetland

Households and key informants indicated that Abaya-Chamo lake-wetland and its ecological benefits have been degraded due to the impact of anthropogenic factors. Results of the NDVI, NDWI and NDTI-based change detection about the lake-wetland well supported the perceived degradation of the lake-wetland in 1990 - 2019 (Table 4a, Table 4b, and Table 5). 'Water surface' expanded at the cost of 'non-water surface' with progressively increasing magnitude of change by 599 ha, 967 ha, and 1,443 ha in 1990 – 2000, 2000 – 2010, and 2010 – 2019, respectively (Table 4a); meaning, 'non-water surface' had shrunk at the equivalent magnitude of water surface change in three decades, respectively, due to sedimentation-led expansion of the lakes. The Abaya-Chamo Lake water has expanded by 3,009 ha (2.2. %) from 1990 – 2019 (Table 4a).

Table 4a. Magnitude (M) of Non-Water Surface (NWS) and Water Surface (WS) Area (ha) from 1990 – 2019 Using NDVI

Class	1990 (ha)	2000 (ha)	2010 (ha)	2019 (ha)	1990 –		2000 –		2010 –		1990 –	
					M	%	M	%	M	%	M	%
NWS	107907	107308	106341	104898	-599	-	-967	-	-1443	-	-3009	-
WS	134708	135307	136274	137717	599	0.4	967	0.7	1443	1.1	3009	2.2
Total	**242615**	**242615**	**242615**	**242615**	**0**	**0.0**	**0**	**0.0**	**0**	**0.0**	**0**	**0.0**

Source: Own Analysis Using Arc GIS, 2021

The sedimentation-induced lateral spread of water and decline in depth of the lakes, again, accelerates the rate of evaporation, the magnitude of water loss, and degradation of the lake-wetland since the evaporation rate in shallower water bodies is higher than that of deeper ones, especially in tropical areas like Abaya-Chamo lake-wetland where the mean annual temperature exceeds 24 ^{0}C (NMA, 2019). Results of the NDWI also confirm that increasing siltation-led expansion of the 'water surface' has resulted in the shrinkage of the 'swamp/wet' area of the lake-wetland (Table 4b).

Table 4b. Water Body (WS) and Wetland Area (A) Changes from 1990 – 2019 Using NDWI

LULC Class	1990 (ha)	2000 (ha)	2010 (ha)	2019 (ha)	1990 –		2000 –		2010 –		1990 –	
					A	%	A	%	A	%	A	%
WS	134708	135307	136274	137717	599	0.4	967	0.7	1443	1.1	3009	2.2
Swamp	6116	5416	4549	3125	-	-	-	-	-	-	-	-
Total	**140824**	**140723**	**140823**	**140842**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**

Source: Own Analysis Using ArcGIS, 2021

The ‘swamp/wet’ area of the lake-wetland had declined at progressively increasing magnitude of loss by 11.5 % (700 ha), 16 % (867 ha), and 31.3 % (1,424 ha) in 1990 – 2000, 2000 – 2010 and 2010 – 2019), respectively, largely due to siltation-led lateral spread of Abaya and Chamo lakes; hence, the swamp area revealed a net loss by 48.9 % (2,991 ha) in the three decades (1990 – 2019) studied (Table 4b). Based on the 2007 international value of US$, provisioning [e.g. food ($614), water ($408), raw materials (timber, fodder) ($425), medicinal ($99) and ornamental ($114)] services, regulatory [e.g. climate regulation ($488), moderating extreme events ($2986), controlling water-flow ($5606), waste treatment ($3015), erosion prevention ($2607), maintaining soil fertility ($1713) and biological control ($918)] services, supportive or habitat [e.g. maintaining lifecycle ($1287) and gene pool protection ($1168)] services and cultural [e.g. aesthetics ($1292), recreation/tourism ($2211) and art-architectural design ($700)] services of 'swamp' areas like Abaya-Chamo lake-wetland are estimated to have a value of US$ 25,681 per/ha/year (TEEB, 2013). Here, the 2,991 ha 'swamp' area loss in 1990 – 2019 implies that the lake-wetland exhibited a gross total service value loss of US$ 76,811,871 in three decades. Meaning, the annual average gross value loss via the swamp area shrinkage of Abaya-Chamo lake-wetland (in 30 years) was about US$ 2,560,395.7.

Results on the spatiotemporal dynamics of the NDTI of Abaya-Chamo Lake in 1990 - 2019 also revealed that the turbidity (sedimentation) and pollution level of the lakes was increasing, where deterioration of aquatic and wetland ecosystems, and their services became the main consequences.

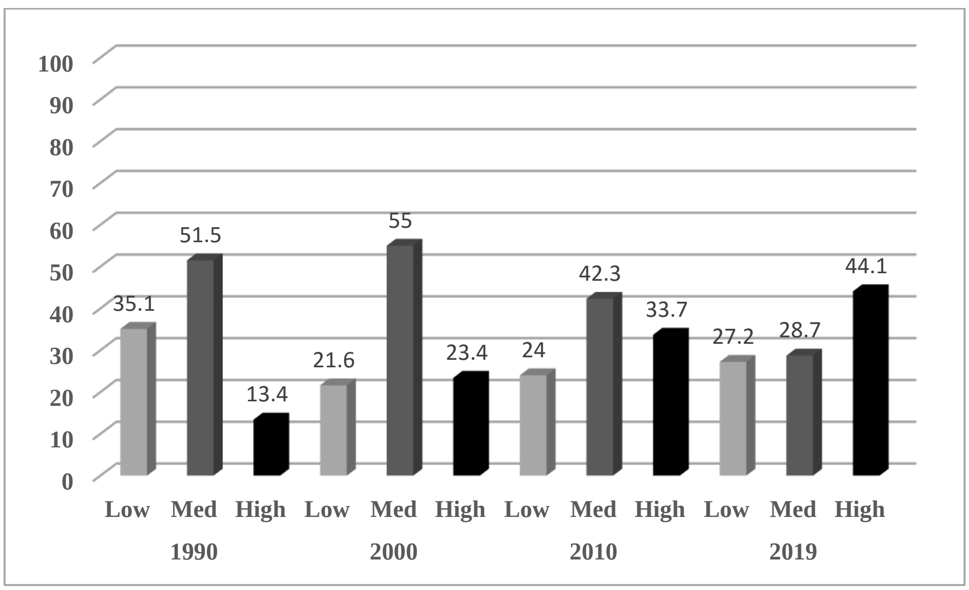

Figure 2. Area (ha) (%) of the Low, Medium, and High Turbidity Classes of Abaya-Chamo Lake-Water in Four Periods (1990, 2000, 2010, and 2019) (Note: Med = Medium)

As we display in Figure 2 above, based on NDTI, the pollution level of Abaya-Chamo Lake water for the years 1990, 2000, and 2010, and we rated 2019 as a low, medium, and high turbidity class. The deep-dark bars in Figure 2 above show that the area (ha) of the lake water with 'high turbidity class' increased from 13.4% (18051 ha) in 1990 through 23.4% (31662 ha) in 2000 and 33.7% (45924 ha) in 2010 to 44.1% (60733 ha) in 2019 (see Figure 2 and Table 5). The moderately dark bars show a decline in proportion (%) of water-area (ha) with ‘medium turbidity class’ from 1990 to 2019. The area of the 'low turbidity class' also declined from 35.1% in 1990 to 27.2% in 2019. The result of the NDTI proves that pollution of the lake water increased progressively from 1990 to 2019 since the high and increasing area of turbidity class implies high pollution and increasing sediment load into Abaya and Chamo lakes.

Again, the 'area change by turbidity/siltation level' was correlated with the 'water surface area change' of Abaya-Chamo Lake for four periods between 199 and 019 to confirm whether the association between 'sediment load' and 'lateral spread of the lake area' was important. The result revealed that there was a strong positive association (0.956*) between increasing 'turbidity/siltation level' and 'water surface' area change (lateral spread/shrinkage of the lake area) at a 95% confidence level (Table 7).

Table 5. Water Area (A) (ha) by Turbidity/NDTI Level of Abaya-Chamo Lake in 1990–2019

NDTI Level	**1990 (ha)**	**2000 (ha)**	**2010 (ha)**	**2019 (ha)**	**1990 - 2000**		**2000 - 2010**		**2010 – 2019**		**1990 - 2019**	
					A (ha)	**%**	**A (ha)**	**%**	**A (ha)**	**%**	**A (ha)**	**%**
Low	47282	29226	32706	37459	-18056	-38.2	3480	11.9	4753	14.5	-9823	-20.8
Medium	69375	74419	57644	39525	5044	7.3	-16775	-22.5	-18119	-31.4	-29850	-43.0
High	18051	31662	45924	60733	13611	75.4	14262	45.0	14809	32.2	42682	236.5
Total	**134708**	**135307**	**136274**	**137717**	**599**	**0.5**	**967**	**0.7**	**1443**	**1.1**	**3009**	**2.2**

Source: Own Computation, 2021

The regression analysis also revealed that about 91.4 % of the ‘water surface area (ha)’ change/increase of Abaya-Chamo Lake in 1990 - 2019 was significantly predicted by the variation in ‘turbidity/siltation level’ at a 95 % confidence level. The high F-statistic (21.4) and the low significance value (0.04) confirmed that the variation in (or increasing) 'turbidity/siltation level' significantly contributed to the increase in 'water surface area' of the lakes in the three decades (1990 – 2019) studied (Table 8).

3.3 Driving Forces (Causes) of Degradation/Loss of Abaya-Chamo Lake-Wetland

The degradation/loss of Abaya-Chamo lake-wetland is the combined effect of various anthropogenic factors. Degradation of the lake-wetland and its benefits has been driven by crop farming expansion (60.2 %), use of the lakes' water for irrigation (65.6 %), sedimentation (44 %), overgrazing, or frequent use of the wetland for livestock grazing (59.6 %), invasion of the two lakes by exotic plant species (e.g. *water hyacinth*) (50.8 %) and overfishing (40.7 %) underlain by rapid population growth (53.1 %), open access (69.3 %) to and low protection (61.7 %) of the wetland resources. A shortage of farmland (Assefa and Bork, 2016) induced farm expansion towards the wetland and marginal areas) and overgrazing was because of the shrinkage of grazing land in the areas next to the study site (Assefa & Bork, 2016; Kebede, 2012). The tendency to generate more services from wetlands and the likelihood of degrading wetlands is higher for households with large family sizes; this is because of the involvement of more members of HH with larger family sizes in deriving products from the wetlands (Giweta & Worku, 2018). Discussants of the FGD also confirmed that the expansion of farming (to the extent the wetland lost its buffer zone), intensive grazing, and the frequent harvest of fish (by legal and illegal fishers) have resulted in the degradation of Abaya-Chamo lake-wetland.

The irrigation, of the tributaries of Abaya and Chamo lakes, seems not a critical threat to the sustainability of the lake-wetland. Irrigation, farm expansion, and sedimentation became real challenges to the sustainability of the wetland resources, especially since the onset of the 21st C–a turning point for the beginning of extensive use of the salty water of Abaya and Chamo lakes for irrigation-based cash crop production in the western coast of the wetland by the local farmers and small-scale investors. It is carried out (as it was observed on-site) using large motors that pump the lake water through plastic pipes to the cultivated field where cash crops such as banana, papaya, onion, tomato, pepper, cabbage, tobacco, spinach, lettuce, and others are grown.

Factors such as farm expansion, irrigation, sedimentation, and overgrazing together with the depletion of vegetation cover adjacent to the lakes and in the uplands (ridges of the Rift-Valley) have contributed to the degradation of Abaya-Chamo lake-wetland in at least five ways: *first*, expansion of farming has resulted in the removal of natural vegetation (e.g. woodland, grassland, forest, and bush) nearby the coasts of the lakes (which was used as a buffer zone of the lakes) and loss of its biodiversity. *Second*, the destruction of the natural vegetation adjacent to the lakes aggravated the magnitude of sedimentation and the entrance of chemical pollutants (e.g. nitrate, phosphate, etc.,) into Abaya and Chamo lakes. *Third*, applying the lakes' salty water for crop farming in coastal lands where evapotranspiration is so high results in an increase in alkalinity (sodic toxicity) of the soil and chemical degradation of land nearby the lakes. *Fourth*, the chemical fertilizers and pesticides used for cash-crop farming by farmers and investors (plus the fertilizer used in the surrounding highlands) are aggravating the pollution of the lakes because of sedimentation by runoff from uplands. *Fifth*, events pointed out in # 1–4 above have resulted in *eutrophication*, which is a dense growth of a strange plant, locally known as water hyacinth in Abaya and Chamo lakes because of the rising concentration of nutrients (e.g., nitrate) in the lakes. We highly pronounced expansion of the water hyacinth plant in parts of the water where the main tributary streams are empty to the lakes; this proves that pollution and eutrophication erosion of nutrients causes problems of the lake-wetland by runoff from farmlands in the sub-catchments of tributaries of the lakes. This again is degrading the biodiversity (fish, flora, and fauna) and sustenance of the wetland ecology since the thick-leafed and deep green water hyacinth plant consumes water at a faster rate – where shrinkage of the lakes, dwindling supply of dissolved O_2, decline storage of CO_2, loss of aquatic biotas, climate change and disruption of the overall ecological balance of the lake-wetland become resultants of the invasive plant (CBD, 2015; Davidson, 2014; Erwin, 2009; MEA, 2005; Ramsar, 2018).

An informant (development agent), age 37, stated that the degradation of Abaya-Chamo wetland is exacerbated due to the lack of clear regulations and legal frameworks on the exploitation and protection of resources of the lake-wetland, and the measures to be enforced on those who abuse the wetland resources (e.g. illegal fishermen, farmers who encroach to the wetland,), and limited commitment of concerned bodies in natural resources protection. The rapid population growth, as a root cause of the wetland degradation, is the combined effect of high natural increase locally and high magnitude of in-migration from Gamo highlands and Wolaita areas due to push factors such as population pressure, declined farm size, severe soil erosion and low yield, and pull-factors such as availability of fertile land, the gradual development of infrastructures, the provision of health services, improvement of malaria treatment and the progressive control of tsetse-fly (vector of livestock disease) in the tropical (low-lying) wetland by the government of Ethiopia (Abren, 2019).

4. Conclusion and Management Options

Abaya-Chamo lake-wetland supports the livelihood of people by providing multiple benefits such as provisions (e.g., fish, timber, firewood, water, fodder), supportive services (e.g., for primary production like irrigation water, farmland, rainfall, balanced hydrological cycle, and wildlife habitat), cultural services (e.g., recreation, tourism, aesthetics), and regulatory services (e.g., carbon sink, air quality, and climate regulation). The lake-wetland revealed a rapid increase in turbidity/pollution level, and significant loss in the 'swamp area' and its services in 1990 – 2019, where 91.4 % of the area loss was significantly impacted by sedimentation-led lateral expansion of the lakes at a 95 % confidence level. Farm expansion, sedimentation, irrigation, invasive plant (e.g., *water hyacinth*), overgrazing, pollution, and resource overuse (*the tragedy of the commons scenario*) were the main direct drivers of the wetland degradation, which were rooted in rapid population growth, open access, limited protection, and response. This is so because, the invasive deep green water hyacinth plant leads to dwindling aquatic resources, loss of economic and tourism benefits, and change in local climate dehydrating the lake water and depleting the dissolved O_2 and CO_2 storage capacity of the lakes rapidly.

To curb the problems of the lake-wetland, the government should: (i) formulate clear policy, institutional and legal framework on the management of wetlands; (ii) coordinate the local people for a campaign-based removal (control) of water hyacinth plant from Abaya and Chamo lakes; (iii) intervene biophysical measures on the uplands of Abaya-Chamo basin; (iv) demarcate clear buffer zone to limit the encroachment of people to the lake-wetland; and (v) integrate wetland management objectives with other development goals (e.g. improving income, poverty reduction, employment creation and ensuring food security) to make the interventions effective.

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No potential conflict of interest was reported by the authors.

Availability of Data

All data used are included in the article and supplementary material.

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