Research article

Geospatial Analysis of Wetland Dynamics on Lake Abaya-Chamo, The Main Rift Valley of Ethiopia

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ABSTRACT

Wetlands worldwide and in Ethiopia have long been subject to severe degradation due to anthropogenic factors. This study was aimed at analyzing the impact of land use/land cover dynamics on Lake Abaya-Chamo wetland from 1990–2019. Data were acquired via Landsat TM of 1990, ETM+ of 2000, and OLI of 2010 and 2019 images plus using interview. Supervised classifications (via ERDAS14 and ArcGIS10.5) were applied to detect land use/land cover classes. Change matrix model and Kappa coefficients were used for analysis of the land use/land cover dynamics in the lake-wetland. It was found that forest; water body, shrub land, agricultural land, settlement and swamp area were the main land use/land cover classes. Wetland/swamp area has continuously declined throughout 1990–2000, 2000–2010 and 2010–2019 where its magnitude of shrinkage in the respective periods was 11.4 % (700 ha), 16 % (867 ha) and 31.3 % (1,424 ha). While ‘settlement’ and ‘water body’ of the lake-wetland increased at progressively increasing magnitudes of changes in three periods within 1990–2019, ‘shrub land’ and wetland/swamp declined at progressively increasing magnitudes of loss in the same periods. Siltation, rapid population growth-led expansion of settlement and irrigation-based farming were the main drivers of the land use/land cover dynamics and degradation of the lake-wetland. Thus, consistent mapping and integrated actions should be taken to curb the threats on the sustainability of the lake-wetland in Southern Ethiopia. To reduce the impact of LULC dynamics on wetlands, the regime should: advance a clear political, institutional and legal framework for wetland management.

1. Introduction

Land Use/Land Cover (LULC) changes affect aquatic and inland ecosystems including wetlands across the globe. Technically, the concept of ‘land use’ is different from that of ‘land cover’. ‘Land use’ is the purpose for which land is exploited by people; whereas, ‘land cover’ is the biophysical or inherent state of land above the lithosphere (Lambin et al., 2003). On the other hand, a ‘wetland,’ roughly upon the Ramsar Convention, is a natural or manmade swamp, ‘fen or peatland’ … having soft, spongy soil/land saturated with draining or stagnant, fresh, brackish or salty water including marine with a depth (at low tide) of less than 6 m (RCS, 2016). Inland (natural) wetlands are endowed with diverse species of flora usually dominated by dense growth of annual and perennial grasses, and herbaceous plants (in some cases, mixed with trees of variable densities) as well as with various species of fauna and microorganisms (Schuyt, 2005). Inland wetlands, being formed often on flat to plain landscapes, depressions (surrounded by uplands), banks and deltas of rivers (Ballanti et al., 2017), along margins of lakes, and where clayey/sticky soils are dominant, have vital economic and environmental values (Clarkson et al., 2014; CBD, 2015). Well managed inland wetlands provide myriads of benefits (services) with an estimated value of about US$ 44,000 per/ha/year (TEEB, 2013).

Wetland ecosystems provide numerous services, which range from provisioning (fish, rice production, animal fodder and fossil fuels) through supportive (e.g. habitat, breeding ground of birds and crop farming) and regulatory (carbon sink, climate control and regulate hydrological cycle) to cultural (e.g. recreation and aesthetic) services (MEA, 2005; Díse, 2009; Erwin, 2009; Davidson, 2014; Clarkson et al., 2014; CBD, 2015). Huge proportion of the wetlands (marine and inland) in the world undergoes complete and/or partial degradation or loss in response to the impact of natural and human factors (Schuyt, 2005; Zedler and Kercher, 2005). Climate change, sea-level rise, sediment load into wetlands, volcanism, earthquake and drought are among the main natural causes of degradation of wetlands (Morris et al., 2002; Parry et al., 2007; Ballanti et al., 2017; Galatowitsch, 2018). But the world experienced loss of about 50% (Clarkson et al., 2014) to 64% (CBD, 2015) of the total

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wetlands due to largely anthropogenic factors-induced LULC dynamics, underlain by rapid population growth (CBD, 2015). Expansion of farming, urban built-up area and infrastructures, air and water pollution, runoff-induced increasing fertilizers, eutrophication, invasive exotic plant species, diversion of wetland tributaries, construction of dams and irrigation canals, and intensive exploitation of resources are among the major manmade driving forces of LULC changes and degradation/loss of wetlands worldwide (Zedler and Kercher, 2005; UNEP, 2012; CBD, 2015; Giweta and Worku, 2018; Galatowitsch, 2018).

Studies reveal that most of the riverine and lacustrine wetlands of Ethiopia have been critically threatened due to the impact of LULC changes (Feoli and Zerihun, 2000; Giweta and Worku, 2018). Numerous studies were made about various issues of wetlands in different parts of Ethiopia. Investigations about the threats and opportunities (Zinabu, 2002; Teklu and Kassahun, 2017) and hydrogeochemical and water level changes (Alemaechu et al., 2006) of Rift-Valley lake-wetlands, sustainable management (Wood and Dixon, 2002) and wetland ecosystem dynamics (Legesse, 2007) in Illubabor Zone, status of natural lakes of Ethiopia (Tenalem, 2009), ecology and wetland vegetation composition (Unbushe, 2013) and limnological changes (Teffera et al., 2017) of Lake Abaya-Chamo wetland, ecosystem services of Tana lake-wetland in Northwestern Ethiopia (Wondie, 2018), and reversing wetland degradation in Ethiopia (Giweta and Worku, 2018) were among the main wetland-related studies in Ethiopia. Most of these studies were conducted not via GIS and remote sensing-based geospatial analyses of the dynamics of the wetlands in the respective areas of Ethiopia overtime largely due to the views and thematic-area interests of the studies. It is ambiguous to understand the accurate spatiotemporal magnitudes of LULC (e.g. forest, water, swamp) changes (gains/losses) of wetlands from results of studies made without the application of GIS and remote sensing (satellite images) techniques (Lillesand et al., 2004; Ballanti et al., 2017).

Several studies have been conducted about the causes of LULC dynamics and degradation of wetlands in Ethiopia (Wood and Dixon, 2002; Tenalem, 2009; Simane et al., 2013; Teklu and Kassahun, 2017; Wondie, 2018; Giweta and Worku, 2018). Persistently high population growth led to conversion of wetlands to croplands (Simane et al., 2013) and urban (built-up) areas, open access to and overuse of common (natural) resources (use of wetland trees for timber and fuel, intensive and inefficient water use for irrigation and overgrazing) (Tenalem, 2009; Teklu and Kassahun, 2017), lack of regulations about use and abuse of resources, absence of service costs (i.e. the free riders/tragedy of the commons’ scenario), draining wetlands, dam construction, intensification of farming, infrastructure expansion and diversion of water flowing to wetlands (Zinabu, 2002; Wood and Dixon, 2002; Wondie, 2018), poor catchment management, sedimentation, eutrophication and pollution by chemical farm-inputs (Giweta and Worku, 2018) were among the major drivers of LULC dynamics and wetland degradation in different parts of Ethiopia. But all the causes (shown above) cannot be equally significant in inducing LULC changes and threatening wetlands everywhere as the drivers and their impacts vary in space and time depending on variations in circumstances across the different specific areas of the country (Giweta and Worku, 2018).

GIS and satellite image-based studies about the dynamics and threats of wetlands in Ethiopia were limited. Dynamics of Dawda Chefa Wetland in North central part (Hussien, 2014), characterizing wetlands and their dynamics in Central Highlands (Dubeau, 2016), and the impact of LULC changes on the landscape of Abaya-Chamo wetland (Wolde-Yohannes et al., 2018) were among the few GIS and remote sensing-based studies made in Ethiopia in the recent past. Studies made through integrated application of different data acquisitions (GIS and satellite images, ground survey and interview) techniques for addressing the dynamics and threats of wetlands were rare in and around Lake Abaya-Chamo wetland (Southern Rift-Valley of Ethiopia) where this study is conducted. Remote sensing-based mapping and analyses of the dynamics of biophysical status of wetland (upon multispectral Landsat images) is useful to develop bases for detecting and monitoring changes (degradation) of the wetland, and to respond for its restoration (Baker et al., 2007; Klemas, 2011; Ballanti et al., 2017). This is so because, GIS and remote sensing techniques, by providing synoptic coverage and repeatability of spatial information, enable to get accurate results about wetland dynamics and are more cost-effective for monitoring the changes overtime (Ballanti et al., 2017). This study was aimed to: (1) quantify the magnitude and rate of LULC dynamics of Lake Abaya-Chamo wetland within 1990–2019; (2) explain the trends of LULC changes in three decades; (3) analyze the driving forces and impacts of the LULC dynamics on the sustenance of the lake Abaya-Chamo wetland.

2. Materials and methods

2.1. Study area

Lake Abaya-Chamo wetland is located in 5° 43’19”N - 6° 38’51”N latitude and 37° 21’55”E - 38° 15’05”E longitude (Figure 1). In Figure 1, the large Northeastern water body is Abaya Lake and the smaller Southwestern one is Chamo Lake. The area of Abaya-Chamo lake-wetland is 242,615 ha (Figure 1). Abaya and Chamo lakes, being Rift-Valley lakes in Southern Ethiopia, lie on a gravem (depression) created by faulting due to divergent movement along the boundary of the Africa plate (westward) and the Somali plate (eastward). The Western part of the lake-wetland is largely plain, where some dome shape and conical volcanic hills, and elevated spur are observed.

The fans, deltas and flood plains around lakes Abaya-Chamo are built-up from materials recently deposited by rivers and lakes. The rift valley floor near lakes Abaya-Chamo is filled with alluvial sediments. Perennial and intermittent rivers drain into the two lakes. Soil fertility, structure and drainage are generally favorable for agriculture provided that there is enough moisture (EPA, 2006). The soil types on the western and southern plains around Lake Chamo are chromic verticals and eutric nitosol with textural classification ranging between clay to clay-loam. The soils along the western shore of Lake Abaya-Chamo are red, gray, and nitosols with a texture classification ranging from clay to clay loam (EPA, 2006).

The climate of the study site is semi-humid to sub-humid. The dependence of precipitation on altitude in the basin is characterized by higher precipitation in the mountains than in the rift valleys. Therefore, wetland Lake Abaya-Chamo is also characterized by a bimodal distribution of annual precipitation with ‘heavy’ rains in spring (March, April, and June) and light rains in September and October. The rainy seasons in the study area are from September to October and March to June, with average monthly minimum precipitation of in January and maximum in April. The weather is dry and hot mainly from December to February. The average minimum temperature of the coolest month and the regular daily maximum temperature of the warmest month are 15.8 °C and 33.4 °C, respectively.

Abaya-Chamo lake-wetland provides multiple ecological and economic benefits to people in the surrounding area. The lake supports different species of phytoplankton, freshwater invertebrates, bacteria-plankton, and different fish species of which are commercially important. The wetland flora, being a vibrant nesting site and feeding source for hundreds of birds and hippopotamus, supports wildlife and serves as a spawning-area for crocodiles (Unbushe, 2013). Rich bird fauna, sport fishing for Tilapia, Nile Perch and Tiger Fish, the ‘Asa-gebeya’/Crocodile Market (where crocodiles are not exchanged rather crowds of crocodiles are visited), the ‘Forty-Springs’ (from which name of ‘Arba-Minch’ Town was coined) provide special attraction to tourists. Crocodile Ranching/Farming is important income source via tourism and the export of skin of crocodiles (Legesse, 2007). The lakes also harbor large population of common hippopotamus (Hippopotamus amphibius), waterfowl, and several rare bird species including migratory ones. The conservation of these natural attractions approvals eco-tourism activities for conservation and sustainable use and generates revenue to the community (EPA, 2006).

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Lake Abaya-Chamo wetland shown rapid change in land use/land cover due to fast population growth-induced expansion of cultivated land and settlement at the cost forest and shrubland (Bekele, 2001). Crop farming and livestock rearing are important activities in the area surrounding the lakes. Widespread area to the West of Lake Abaya-Chamo was cleared in the 1960s and 1970s for expansion of large-scale farms for producing cotton, banana and other crops (Gelaw, 2019). State farms like Bilate, Arba-Minch and Sile (recently given for private investors) are examples of intensive farming in the plain area adjacent to the lakes.

Agroforestry is the most action within the alluvial plain of the western shores of the lakes, where it is practiced utilizing rain-fed and water system. Natural products (e.g. banana, mango, avocado, papaya, tomato), cereals (e.g. maize), vegetables (e.g. cabbage, pepper), tuber and root crops (casava, onion, carrot) and cotton are developed on the prolific soils adjoining to the wetland (Gelaw, 2007, 2019). Wetlands, woodland, forest and bush-lands have changed to settlement and cropland (Kebede, 2012). These wetlands present a rich biodiversity in western shores of the lake Abaya-Chamo wetland even if it has been extremely impacted by anthropogenic pressure.

3. Materials and methods

3.1. Research design

This study, being viewed via the pragmatic lens, was conducted based on the mixed-methods approach. That is, data acquisition and analyses were carried out using a mixture of methods from both the quantitative and qualitative approaches (Creswell, 2009). Cross-sectional survey design was used to acquire and analyze data using both the methods of quantitative and qualitative approaches simultaneously (in parallel).

3.2. Acquisition and processing of satellite imageries

Satellite data of Landsat TM of 1990, 2000, OLI of 2010 and 2019 of Lake Abaya-Chamo wetland, having spatial determination of 30m were downloaded from the site (https://earthexplorer.usgs.gov/) of the US Topographical Overview (USGS) (Table 1). Satellite data is the basic source of information which can be used for mapping and change detection in different land use/land cover categories of an area over the period of time. Landsat imageries captured from January and February were favored since these dates empower to secure adherent satellite free of the effect of cloud cover and to dodge the impact of regular variety on the classification of LULC classes. Subordinate information was moreover utilized amid investigation. All information was anticipated to the Universal Transverse Mercator (UTM) projection framework, zone 37N and datum of World Geodetic System-84 (WGS84) to guarantee consistency between datasets during analyses.

Table 1. Sensor Type, Resolution, Acquisition Date and Source of Satellite Images used for the Study.

| Sensor Type | Resolution | Path/Row | Acquisition Date | Source |
|-------------|------------|----------|------------------|--------|
| Landsat-5 TM | 30 m | 169/56, 169/55 | Jan 12, 1990 | http://earthexplorer.usgs.gov |
| Landsat-7 ETM+ | 30 m | 169/56, 169/55 | Jan 27, 2000 | http://earthexplorer.usgs.gov |
| Landsat-8 OLI | 30 m | 169/56, 169/55 | Mar 05, 2010 | http://earthexplorer.usgs.gov |
| Landsat-8 OLI | 30 m | 169/56, 169/55 | Mar 10, 2019 | http://earthexplorer.usgs.gov |
The imageries were checked against any defects such as striping. All image scenes were subjected to image processing using ENVI software (version 5.3), and each was clipped using the base-map of lake Abaya-Chamo wetland. Geometric and radiometric corrections were made for the images of the four periods (Table 1). The two scenes (i.e. the one that fall within path 169 and row 56/55, and the other that fall in path 169 and row 56/55) of each data set were mosaicked using linear contrast stretching and histogram equalization technique to create a single image covering the whole study area for each period.

3.3. Image classification

Landsat TM of 1990, ETM+ of 2000, and OLI of 2010 and 2019 were also classified using supervised classification (maximum likelihood technique) separately to identify LULC classes of the study area. This method assumes the normal distribution of DN values, allowing the function to determine the probability of a pixel belonging to a specific feature class and assign each pixel to the highest probability class (Lillesand et al., 2004). The classifications were repeated numerous times by adding more training sites so as to come up with satisfactory results. Supervised classification was chosen to compare the outputs with results of the classification; this was particularly vital for this study because it identifies and locates LULC types, which are known priori through a combination of interpretation of aerial photography, survey analysis and fieldwork.

3.4. Accuracy assessment

In the accuracy assessment, confusion matrices and Kappa coefficient of agreement were calculated for each classification map. Estimation of Kappa coefficients yields statistics, which are measures of agreement or accuracy between the remote sensing-derived classification map and reference data (as shown by the major diagonal) and the chance agreement, which is indicated by the row and column totals (referred to as marginal) (Jensen, 2005). The classification results were compared with the ground truth (data) to confirm accuracy of the classification process. It is a way to ensure the number of correctly classified faithful pixels and the number of errors propagated during data collection, analysis and transformation (Edwards et al., 1998). The accuracy of LULC maps produced was evaluated using overall accuracy (OA), producer’s accuracy (PA), user’s accuracy (UA) and Kappa statistics. PA quantifies the error of omission, while UA quantifies error of commission. Kappa is another method of expressing classification accuracy as it measures the chance agreement. Accuracy assessment was run in order to measure (statistically) the level of accuracy and degree of acceptance of analysis results of the GIS and remote sensing-based LULC classification and change detection of lake Abaya-Chamo wetland (Table 3). In this paper, reference data were collected during field work using Global Positioning System (GPS) and the reference points were independent of the ground truths that are used in the classification scheme. About 396 GCPs were collected from the field for accuracy assessment. Besides, Google Earth was also used to aid the validation process. Accordingly, the overall accuracy, Kappa coefficient, producer’s accuracy and user’s accuracy were computed from the confusion matrix. Kappa is expressing classification accuracy as it measures the chance agreement. It has been found to be stronger than the overall accuracy of images (Jensen 2005; Lillesand et al., 2014). The \( \text{KHAT} \) statistic is a measure of the difference between the actual agreement between reference data and an automated classifier and the chance agreement between the reference data and a random classifier (Jensen, 1996). Conceptually, K can be defined as:

\[
K = \frac{\text{observed accuracy} - \text{chance agreement}}{1 - \text{Chance agreement}}
\]  
(Eq. 1)

where K is Kappa coefficient, \( r \) is the number of rows in the matrix, \( x_{ii} \) is the number of observations in row \( i \) and column \( i \) (the diagonal elements), \( x_{i+} \) are the marginal totals of row \( i \), \( x_{+i} \) are the marginal totals column \( i \), and \( N \) is the total number of observations (Bishop and Fienberg 2007). In reality, the value of \( K \) usually ranges between 0 and 1. Kappa coefficient of is calculated as follows (Eq. 2):

\[
K = \frac{N \sum_{i=1}^{r} \sum_{j=1}^{c} (x_{i,j} - \frac{x_{i+} * x_{+j}}{N^2})}{N^2 - \sum_{i=1}^{r} x_{i+} * \sum_{j=1}^{c} x_{+j}}
\]  
(Eq. 2)

where: \( N \) is the total number of observations in the entire error matrix, \( k \) is the total number of classes or categories, \( x_{ij} \) refers to the number of observations correctly classified for a particular category, and \( x_{i+} \) and \( x_{+i} \) refer to the marginal totals for row \( i \) and column \( i \) associated with the category. Assessing the overall levels of accuracy of the supervised classification for the years 1990, 2000, 2010, and 2019 was found as 88.9, 90.21, 91.20 and 97.92% respectively by adopting confusion matrix technique and 0.887, 089, 0.884 and 0.968 of kappa index value (Table 3).

3.5. Collection of field data

Reference data were collected for training and validation of each LULC type of Abaya-Chamo lake wetland for each satellite image in each period. Geographic locations of ground truth LULC classes, used to calibrate the classification procedure, were identified using high spatial resolution imagery made freely available through Google Earth Pro. About 396 reference samples were derived from the LULC of the lake-wetland in 2019 and via the support of Spot map of 2019. Reference data for 2019 were collected directly from the field between September 2018 to February 2019 using handheld GPS. About 100, 100, 96 and 100 GCP samples were collected for 1990, 2000, 2010 and 2019, respectively, which were used for accuracy assessment. Verification of the mapped lake-wetland was done through field visits, comparison with features on Google Earth and the DEM, and the use of prior knowledge of features present in the study area. The ground-truth points were randomly chosen. Ground-truthiness of the mapped features was necessary for the verification and accuracy assessment of the features.

3.6. Change detection

To analyze the schemes of LULC change, post classification comparison approach was performed. This technique gives the provides “from-to” data and minimizes the conceivable impacts of atmospheric varieties and sensor contrasts (Lu et al., 2004). In this manner, Landsat imageries of the three references a long time were to begin with freely classified. Presently, the classified imageries were compared and alter insights were computed by comparing picture values of one information set with the comparing values of the moment information set. The comparison values were summarized and presented in terms of range changes in hectares, rates and rate of modification. The degree of zone alter (add up to alter) for each LULC lesson was gotten by subtracting the range of starting year (most seasoned date) from the esteem of later date (last year) of the consider period.

Arc Map GIS 10.5 raster calculator was used to perform the change detection analysis. Change detection analysis was applied on results of the supervised classification about the six LULC classes of Abaya-Chamo lake-wetland for periods 1990–2000, 2000–2010, 2010–2019 and 1990–2019. The magnitude of area change of each LULC class in each period we employed the following equation (Eq.3):

\[
M = (A_{2}-A_{1})/A_{1} * 100
\]  
(Eq. 3)

where: \( M \) is magnitude of area change of a LULC class in a period, \( A_{1} \) is area (ha) of the LULC class in the initial or earlier year, and \( A_{2} \) is area (ha) of the same LULC class in the recent year. We have also calculated the
rate of change of LULC changes between years to estimate the spatial changes in land uses with the equation (Eq. 4).

\[ R = \frac{(A_2 - A_1)}{t} \times 100 \]  

(Eq. 4)

where: \( R \) is annual ‘Rate’ of area change (in ha and %), \( A_1 \) is area (ha) of a LULC class in the initial year, \( A_2 \) is area (ha) of the LULC class in the recent year, and \( t \) is the time-interval between the initial and recent years. Change matrix model (the raster calculator) was used to compute the area change from one LULC class to another type between the periods accounted in the study. The degree of change in each period was statistically tested by the Wilcoxon Signed ranks test. The Wilcoxon Signed ranks test is a non-parametric statistical test used to assess the difference between two conditions where the samples, in this case the variation of the LULC class, are correlated. Data sets can be compared multiple times over consistent time periods (between early and late years).

3.7. Data analysis

LULC changes of Lake Abaya-Chamo wetland were analyzed using GIS and remote sensing techniques. Different spectral signatures of similar pixel samples were selected from satellite imageries using the maximum likelihood method, which served as a separability measure for different land use/land cover classes which were later on grouped with maximum likelihood method, which served as a separability measure for similar pixel samples were selected from satellite imageries using the GIS and remote sensing techniques. Different spectral signatures of

3.7. Data analysis

LULC changes of Lake Abaya-Chamo wetland were analyzed using GIS and remote sensing techniques. Different spectral signatures of similar pixel samples were selected from satellite imageries using the maximum likelihood method, which served as a separability measure for different land use/land cover classes which were later on grouped with spectrally identical signatures. Determination of appropriate classes was done based on level ‘I’ of the LULC classification and six classes were identified (Table 2). Computer aided interpretation of images was conducted using environmental resources data analysis system (ERDAS) Imagine 2014, ArcGIS 10.5, GPS (Garmin 5.1)-based data and environment for visualizing images (ENVI) 5.0 software, which were used for satellite image processing, classification of LULC, accuracy assessment and analysis of the wetland dynamics. Microsoft excel was also used for analysis.

4. Results

4.1. Accuracy assessment

Accuracy levels of all the six LULC classes upon values of both the Producer’s Accuracy (PA) and User’s Accuracy (UA) were approximately 80 % and above except the PA of ‘forest’ for the period 1990 (79.03 %), 2010 (79.02 %) and 2019 (78.79 %) (Table 3). The low accuracy level of forest in the three periods under study could be perhaps due to proximity in the spectral/reflectance value of ‘forest’ to that of ‘agroforestry’ (agriculture) of mango trees, which creates ambiguity during image classification. Anyway, results of the PA and UA indicate that all the classified LULC classes of 1990, 2000, 2010 and 2019 satisfy the recommended accuracy level (above 80 %); that is, there are strong agreements between the classified LULC classes and the GCP data.

In 1990, 2010 and 2019 periods Kappa’s were 88.9%, 90.2%, 91.2% and 97.9%, and the Kappa coefficient of each period were 0.887, 0.890, 0.884 and 0.968 (Table 3). The Kappa coefficient is a measure of the contract/precision between the reference data of the classified image and the value of the LULC class. The factor is -1 to 1. The Kappa coefficient represents 0.0 to 0.20, 0.21–0.40, 0.41–0.60, 0.61 to 0.60, 0.60–0.80 and 0.81–1.0, and represents a slight, moderate, substantial fair and strong and perfect convention & if < 0 replicate no agreement (Manonmani and Suganya, 2010). The high Kappa coefficients were accurate because the GIS based classification of the LULC in 2010, 2010 and 2019 and 2019 showed strong consent with GCP data. This level of precision can be used for the classification, detection and forecasting of Changes LULC.

4.2. LULC classification and wetland change in Lake Abaya-Chamo

Abaya-Chamo lake-wetland experienced dynamics among the different LULC classes within 1990–2019. The land use/cover status of Lake Abaya-Chamo wetlands was mapped for the year 1990, 2000, 2010 and 2019 to analyze the patterns of change that occurred in the area (Figure 2 and Tables 4 and 5). Therefore, based on the GIS-based image analysis six land use/land cover types were identified. The detail land use/land cover status of the area is presented as follows; Forest, waterbody, settlement, shrub-land, agricultural land and wetland are the main LULC classes of the lake-wetland.

4.2.1. Forest

A continuous decline of forest cover was observed over the study period. Of the total area of the area in 1990, forest constituted about 4.005%. In 2000 it accounted for 2.597% and 2010and 2019 showed increase 5.156% and 4.36% respectively, of the total area of the study site (Table 4). During the study period, forest showed reduction in coverage by 35.2% at an average rate of 3418 ha/decade. The depletion of forest cover occurred due to the destruction of natural forests for farm plots, settlement expansion and construction materials. In the second period of the study 2010–2019 the forest cover was increased by 8.9%, as one moves from the period 1990–2000 to 2000–2010 and then to 2010–2019, forest cover and agricultural land of Abaya-Chamo lake-wetland revealed no clear trends in their patterns of change across the three decades. In fact, both ‘forest’ cover and ‘agricultural’ land experienced similar (declining) trend in the initial period (1990–2000) studied, where the magnitude of change (decline) of the respective LULC classes was 35.2 % (3,418 ha) and 1.4 % (416 ha). However, forest area of the lake-wetland revealed an increase by 98.6 % (6,210 ha).

4.2.2. Water body

This land cover comprises the lakes, ponds and reservoirs found in the study area. Water body with magnitude of expansion of 0.4 % (599 ha), 0.7 % (967 ha) and 1.1 % (1,443 ha) in the periods 1990–2000, 2000–2010 and 2010–2019, respectively, exhibited a consistently increasing trend in the three decades studied. However, the increasing trend of ‘water body’ was different from that of ‘settlement’ in that ‘water body’ of the lake-wetland had been increasing with consistently increasing magnitude of change as one moves from the earliest period (1990–2000) through the next (2000–2010) to the latest period (2010–2019) accounted in by the study (Table 4).

4.2.3. Agriculture

This land cover includes areas, which are continuously and seasonally cultivated with rain fed and using irrigation schemes. Agricultural land continued to decline by 0.8 % (242 ha) in the next/second period (2000–2010) under study (Table 4). In the last period (2010–2019) accounted in by the study, the trend of forest cover of Lake Abaya-Chamo

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Table 2: Contextual description of the LULC classes of Abaya-Chamo lake wetland.

| LULC type     | Description                                                                 |
|---------------|-----------------------------------------------------------------------------|
| Agriculture   | Farmland used for growing cereals, tuber and root crops, agroforestry practice and horticulture including currently uncultivated (arable) land and fallowed plots. |
| Shrubland     | Area covered with more of short, hard woody stem trees (brushes), limited herbaceous plants (shrubs) and isolated trees which often are mixed with undergrowth of grasses. |
| Forest        | Area of dense, tall trees having interlocked canopies, including woodland and riverine forests. |
| Swamp/Wetland | Is spongy, soft, wet/marshy land saturated with water, adjacent to Abaya-Chamo lakes, and on the banks of tributary-rivers of the lakes having permanent and seasonal grasses. |
| Water body    | Area with temporary and permanent water cover which includes lakes, intermittent ponds and other areas with shallow water cover. |
| Settlement    | Consists of homesteads of rural villages and buildings of urban areas (with commercial and residential purposes), camps, warehouses, roads and other infrastructures. |
wetland was reversed to decline by 15.4 % (1,926 ha); whereas, the agricultural land of the study site increased by 12.2 % (3,723 ha) (Table 4). This LULC showed drastic expansion as compared to other cover classes during the study period. There was few cultivated land prior to 1970s and more frequently after the 1991 government change, which resulted in a fast increase of settlement and agricultural areas in the lake shores. This also further share with migration played a significant role in the reduction of shrub-land and forest areas surrounding Lake Abaya-Chamo wetlands, whereas the resettlement programs played a significant role in the reduction of forest and shrub-land in other area. The expansion of commercial farms and cash crops such as banana, cotton, fruit and vegetable, and the redistribution of land (mostly shrub-land forest and wetland) to landless farmers and military veterans. The western shores of the two lakes are extensively used for big state farm (Arba-Minch, Wajifo State Farm and Sille State farm) and recently leased for privet investors. The reduction in depth of lakes occurs as a consequence of buffer zone cultivation and as a result of human intervention such as establishment of irrigation schemes through abstraction of water from the lakes and consuming rivers flowing into lakes. The use of rivers that feed the lakes for irrigation decreased the lakes depth and consequently resulted in drastic effects on the wetlands and aquatic communities.

4.2.4. Settlement

As is illustrated in Table 4, settlement area in the Western coast of Abaya-Chamo lake-wetland revealed a continuously increasing trend in the three periods accounted in by the study, that is, where it has expanded by 47.1 % (5,147 ha), 27.2 % (4,373 ha) and 55.3 % (11,298 ha) in the periods 1990–2000, 2000–2010 and 2010–2019, respectively. The high annual rate of expansion of settlement (by 6.4 % or 693.9 ha) in 1990–1990 was a consequence of various factors such as rural to rural migration (in-migration) to the plain Western coasts of the wetland, natural increase-induced expansion of rural villages, and development and expansion of infrastructures (Arba-Minch University, Arba-Minch Airport Terminal, modern irrigation structures, concrete and asphalted roads, and the Arba-Minch Crocodile Ranch) surrounding the lake-wetland. Expansion of urban centers like Birbir (Mirab-Abaya) town and Arba-Minch city was also a vital cause for the high rate of settlement increase of Agroforestry practice is also assumed to have been among the reasons for the low magnitude of increase (by 10 % or 3,065 ha only) of agricultural land in the three decades studied; this is so because, smallholder farmers in the Western coast of the lake-wetland were indicated to have been replacing the maize-dominated cereal croplands with banana and mango-dominated agroforestry (Gelaw, 2007); that is why (despite the increasing human population in Abaya-Chamo depression/basin) agricultural land of the study site had exhibited decreasing trend by 1.4 % (416 ha) in 1990–2000 and by 0.8 % (242 ha) in 2000–2010 (Table 4). In fact, Ethiopia has experienced a nearly loss of Harromaya lake and its swamp area due to LULC dynamics and the use of the lake's tributaries for irrigation farming (Giweta and Worku, 2018).

4.2.5. Shrub land

This land cover contains short; grazing lands, tress, grass and bushes, which have an opened cover. Shrub-land area revealed consistently declining trends in the three periods within 1990–2019. The result indicated that shrubland covered 20.8% of the total area in the year 1990. However, its cover was 2.4 % (1,212 ha), 21.1 % (10,441 ha) and 33.6 % (13,114 ha) in the period 1990–2000, 2000–2010 and 2010–2019, respectively, that is, where its magnitude of decline was small (2.4 % or 1,212 ha) in 1990–2000, medium (21.1 % or 10,441 ha) in 2000–2010 and the largest (33.6 % or 13,114 ha) in the latest period (2010–2019) studied (Table 4). This land cover was reduced by 48.5% at an average rate of 2063.9 ha/decade during the study period. In the district, shrubland is a potential area for agricultural activities, settlement and charcoal production of the people and the reduction of its cover could be attributed to the expansion of settlement and cultivated lands at the cost of this cover class. This happened largely due to increasing conversion of ‘shrubland’ to cropland (since the turn of the 21st C) by local farmers and small-scale investors who began extensive use of the salty-water of Abaya-Chamo lakes for irrigation-based cash crop production (e.g. banana, mango, papaya, tomato, cabbage, onion) in the Western coast and adjacent areas of the lake-wetland.

4.2.6. Wetlands

This land cover includes areas seasonally or permanently wet or flooded and also have swampy vegetation cover (often short and tall grass, and hydrophytes vegetation at the buffer of the lakes). In the last two columns of Table 4, the overall magnitudes of change of the six LULC classes of Lake Abaya-Chamo wetland have been computed and displayed. Wetland/swamp area has continuously declined throughout 1990–2000, 2000–2010 and 2010–2019 where its magnitude of shrinkage in the respective periods was 11.4 % (700 ha), 16 % (867 ha) and 31.3 % (1,424 ha) (Table 4). Conversion to water body and cropland (cash crop farming) contributed to the continuous decline of ‘swamp’ area (Zekarias et al., 2021). In fact, Ethiopia has experienced a nearly loss of Harromaya lake and its swamp area due to LULC dynamics and the use of the lake's tributaries for irrigation farming (Giweta and Worku, 2018).

4.3. Driving forces of wetland LULC changes in Lake Abaya-Chamo

The net increase in forest cover of lake Abaya-Chamo wetland (by 8.9 % or 866 ha) in the period 1990–2019, most likely, was a result of the expansion of agroforestry (e.g. banana, mango, avocado and papaya) practice at the expense of shrubland in the Western cost of the lake-wetland. In other words, the categorization of, especially, mango-forest during image classification, to a little extent, is thought to have contributed to the increase in forest cover in 1990–2019; that is why the accuracy level of forest cover (upon the producer's index) was the lowest for 1990 (79%), 2010 (79%) and 2019 (78.8%) (Table 4). The expansion of agroforestry practice is also assumed to have been among the reasons for the low magnitude of increase (by 10 % or 3,065 ha only) of agricultural land in the three decades studied; this is so because, smallholder farmers in the Western coast of the lake-wetland were indicated to have been replacing the maize-dominated cereal croplands with banana and mango-dominated agroforestry (Gelaw, 2007); that is why (despite the increasing human population in Abaya-Chamo depression/basin) agro-cultural land of the study site had exhibited decreasing trend by 1.4 % (416 ha) in 1990–2000 and by 0.8 % (242 ha) in 2000–2010 (Table 4). In fact, the lateral expansion of Abaya and Chamo lakes' water was also the other driving force for the decline of agricultural land; the siltation-led expansion of the lake water, according to a Key Informant having

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**Table 3. Producer's accuracy (PA) and User's accuracy (UA) of LULC maps of 1990, 2000, 2010 and 2019.**

| LULC            | 1990   |  | 2000   |  | 2010   |  | 2019   |  |
|-----------------|--------|  |--------|  |--------|  |--------|  |
|                 | PA (%) |  | UA (%) |  | PA (%) |  | UA (%) |  |
| Forest          | 79.03  |  | 82.22  |  | 88.64  |  | 92.12  |  |
| Water           | 90.00  |  | 82.93  |  | 91.60  |  | 88.00  |  |
| Settlement      | 91.06  |  | 80.00  |  | 92.80  |  | 86.01  |  |
| Shrub-land      | 79.60  |  | 81.90  |  | 81.02  |  | 87.07  |  |
| Agriculture     | 84.05  |  | 91.07  |  | 89.07  |  | 79.80  |  |
| Wetland/Swamp   | 86.03  |  | 87.50  |  | 87.40  |  | 88.05  |  |

Kappa statistics 88.90 90.21 91.20 97.92

Producer's accuracy (PA) and User's accuracy (UA) of LULC maps of 1990, 2000, 2010 and 2019.
farmland in Omo Lante (administrative unit) (Western cost of lake Abaya), has invaded significant share of his farmland and the landholdings of other smallholder farmers who have farm-plots proximate to the lake.

In the 1970s and 1980s the then government launched a villigization program in the area. People in the highlands were drove into settling in the basin. Upon coming, the farmers grew maize, cotton, and sweet potatoes; only later were different plants introduced and grown, such as

Figure 2. LULC of lake Abaya-Chamo wetland in 1990, 2000, 2010 and 2019.
mango and bananas. Population growth-induced expansion of settlement (by 190 % or 20,818 ha) in the study area (in 1990–2019) has also contributed for the significant decline in shrubland cover (Tables 4 and 5). An informant also added that migrants played significant role in the reduction of shrubland area. Population increase-led expansion of settlement (infrastructures), agroforestry practice and drought might have been the other driving forces of the decline of ‘swamp’ area, especially, in 1990–2000 since the magnitude of decline of ‘swamp’ area had exceeded the magnitude of expansion of ‘water’ body by 101 ha in the same period (Table 4). Overgrazing and intensive livestock grazing induced compaction of the spongy soil/land might also have a slight contribution to the shrinkage of the ‘swamp’ area of Lake Abaya-Chamo wetland. Studies indicate that farm expansion, sedimentation, eutrophication, pollution by chemical farm-inputs, open access and overuse of resources, diverting water for irrigation, poor catchment management, were among the major drivers of LULC dynamics and wetland degradation in different parts of Ethiopia (Tenalem, 2009; Simane et al., 2013; Teklu and Kasahun, 2017; Giweta and Worku, 2018).

4.4. Consequences of LULC changes in Lake Abaya-Chamo wetland

The lateral expansion of Lake Abaya and Chamo affects the highly populated area, indicating a serious concern for inundation of the adjacent fertile and flat-lying farmland (Figure 3), which is the basic means of subsistence for local populations. During the second half of the 1970s, the water level in the Lake Abaya had a decreasing trend, but since 1987 the water level is seen to have constantly increased and the lake is expanding toward the western alluvial plain, threatening the farmlands and infra-structure. The lake level rise could be attributed to either tectonic or hydrologic effects. Tectonic processes and consequently the vertical movements strongly influence the topography of an area as well as the lake water level. Also, the extreme soil erosion caused by deforestation and expansion of farmland, could contribute to an increase in sediment deposition, leading to the progressive siltation of lakes. Large-scale deforestation in the study area was associated with start of permanent settlement that took place in the area from the 1960s. The well-developed alluvial fans of the study area as well as shifting of the

### Table 4. Area Change (ha) between LULC classes of Lake Abaya-Chamo wetland 1990–2019.

| LULC        | 1990 (ha) | %  | 2000 (ha) | %  | 2010 (ha) | %  | 2019 (ha) | %  |
|-------------|-----------|----|-----------|----|-----------|----|-----------|----|
| Forest      | 9719      | 4.005 | 6301      | 2.597 | 12511     | 5.156 | 10585     | 4.362 |
| Water body  | 134708    | 55.523 | 135307    | 55.770 | 136274    | 56.168 | 137717    | 56.763 |
| Settle.     | 10921     | 4.5013 | 16068     | 6.622 | 20441     | 8.425 | 31739     | 13.082 |
| Shrubland   | 50636     | 20.870 | 49424     | 20.371 | 38983     | 16.067 | 25869     | 10.662 |
| Agri.       | 30515     | 12.577 | 30099     | 12.406 | 29857     | 12.306 | 33580     | 13.840 |
| wetland     | 6116      | 2.5208 | 5416      | 2.232 | 4549      | 1.874 | 3125      | 1.288 |
| Total       | 242615    | 100  | 242615    | 100  | 242615    | 100  | 242615    | 100  |

Source: Own Analysis (Note: Settle = Settlement. Agri = Agriculture land)

### Table 5. Percentage Change (ha) between LULC classes of Lake Abaya-Chamo wetland 1990–2019.

| LULC Class | 1990–2000 | % | 2000–2010 | % | 2010–2019 | % | 1990–2019 | % |
|------------|-----------|---|-----------|---|-----------|---|-----------|---|
| Forest     | -3418     | -35.2 | 6210      | 98.6 | -1926     | -15.4 | 866       | 8.9 |
| Water body | 599       | 0.4  | 967       | 0.7  | 1443      | 1.1  | 3009      | 2.2 |
| Settle.    | 5147      | 47.1  | 4373      | 27.2  | 11298     | 55.3  | 20818     | 190.6 |
| Shrubland  | -1212     | -2.4  | -10441    | -21.1 | -13114    | -33.6 | -24767    | -48.9 |
| Agri.      | -416      | -1.4  | -242      | -0.8  | 3723      | 12.5  | 3065      | 10.0 |
| wetland    | -700      | -11.4 | -867      | -16.0 | -1424     | -31.3 | -2991     | -48.9 |

Source: Own Analysis (Note: Settle = Settlement. Agri = Agriculture land)
Bilate River delta into the lake indicate a high sediment yield in tributaries of the Lake Abaya. According to Schütt et al. (2002), the depth of Lake Abaya is 26 m at maximum, which makes the lake level very sensitive to a high sediment input.

5. Discussion

Settlement, agriculture, water body and forest cover of lake Abaya-Chamo wetland with magnitudes of changes of 190 % (20,818 ha), 10 % (3,065 ha), 2.2 % (3,009 ha) and 8.9 % (866 ha), respectively, revealed net increases in three decades (1990–2019). Settlement and agricultural areas of the study site have been expanding at 6.4 % (693.9 ha) and 0.3 % (102.2 ha) per annum, respectively, in the last three decades (1990–2019). Similarly, the annual rates of increase of forest cover and water surface of lake Abaya-Chamo wetland in the 30-years’ period were 0.3 % (28.9 ha) and 0.07 % (100.3 ha), respectively. On the contrary, shrubland cover of the study area experienced significant net decline by 48.9 % (24,767 ha) in the same period; this implies that shrubland cover of the lake-wetland has been declining at a rate of 1.6 % (825.6 ha) per/ year in the three decades studied. The area extent of wetland/’swamp’ cover also showed a net decline by 48.9 % (2,991 ha) in 1990–2019, where the wetland/swamp area of the study site has been shrinking at 1.6 % (99.7 ha) each year in the three decades’ period (Table 4).

Studies also revealed that the degradation of forest, woodland and shrubland covers in the Western coast of the Abaya-Chamo depression was caused by fast population growth-led expansion of settlement and agriculture, which was rooted by high magnitude of in-migration from Gamo-highlands and Wolaita areas since the 1960s (Gelaw, 2019; Zekarias et al., 2021). Abaya-Chamo wetland ecosystem is under considerable stress due to unsustainable resource exploitation, inadequate and inappropriate management, degradation of the lakes’ catchment and the rising demand for water, fish and farm products.

‘Swamp’ area of the lake-wetland, like shrubland cover, has been decreasing at progressively increasing magnitudes of changes in the four decades’ period (1990–2019); that is, where the magnitude of decline of the swamp cover was smaller (11.4 % or 700 ha) in the initial period (1990–2000), moderate (16 % or 867 ha) in 2000–2010 and the largest (31.3 % or 1,424 ha) in the latest period (2010–2019) accounted in by the study (Table 4). This is mainly a result of the progressively increasing sediment load into Abaya and Chamo lakes (Schütt et al., 2002). Meaning, land degradation in the Western Escarpment of the Southern Rift-Valley of Ethiopia [due to exploitation of fuel-wood and construction materials, overgrazing, over-browsing, and conversion of forest and woodland to cropland and settlement (Kebede, 2012; Assefa and Bork, 2016; Gelaw, 2019)] has resulted in increasing siltation in the floors of Abaya and Chamo lakes; the increasing siltation, in turn, led to the decline depth of the lakes (Schütt et al., 2002), and the displacement and lateral expansion of the lakes’ water, and the subsequent shrinkage of the ‘swamp’ area (Zekarias et al., 2021) of the lake-wetland by 48.9 % (2,991 ha) within 1990–2019 (Table 4). That is, the progressively increasing siltation-led expansion of ‘water’ body was the main cause of decline of the ‘swamp’ area of Abaya-Chamo lake-wetland; this is so because, the progressively increasing magnitude of increasing trend of ‘water’ body had been accompanied by progressively increasing magnitude of decline trend of ‘swamp’ area in the three decades’ period as these LULC classes are configured inherently adjacent to each other (Table 4 and Figure 2). Siltation problem of Abaya-Chamo lakes is the main cause of swamp area loss, a consequence of LULC dynamics and a vital degradation indicator of the lake-wetland.

6. Conclusion

Lake Abaya-Chamo wetland is getting threatened overtime due to largely anthropogenic factors-induced LULC dynamics in the period 1990–2019. Settlement, agriculture, water body and forest cover of the lake-wetland showed net increases in three decades. Whereas, shrubland and ‘swamp’ area experienced significant net decline (by almost half of each) in 30 years. While settlement and water body increased at progressively increasing magnitudes of changes in three decades, shrubland and swamp cover declined at progressively increasing magnitudes of loss in the same periods. Increasing agroforestry practice by smallholder farmers and small-scale investors overtime contributed to the net increase in forest cover, and for the huge magnitude of shrinkage of shrubland (by 48.9 %) in lake Abaya-Chamo wetland. Decline of shrubland and natural forest was also driven by settlement and farm expansion. Generally, the LULC dynamics led to depletion of natural forest and shrubland in the coasts and uplands of the lake-basin, increasing runoff erosion and sediment load into plus pollution of the lake-wetland, invasion of the lakes by a strange plant water hyacinth (‘emboch’), siltation-led displacement of the lakes’ water, area shrinkage and loss of biodiversity of the swamp, and to the overall degradation of lake Abaya-Chamo-wetland and its ecological services in the Southern Rift-Valley of Ethiopia.

Ultimately the result of the research has been concluded by pointing out the major threats of the wetlands siltation: namely deforestation of the upland (i.e. Deprived land use practice), cultivation of wetlands (on the lakeshore and buffer zones) and Sedimentation due to very inadequate soil and irrigation mechanism put in place on the courses of the rivers flowing into the wetlands.

To curb the impact of LULC dynamics on wetlands, the administration should: (i) articulate clear policy, established and legal framework on the management of wetlands; (ii) revise the investment policy and enforcement of impact assessment; (iii) enforce ‘user tax’ (on users of land, water) and/or ‘pollution charge’ (on polluters of land, water) on investors in agriculture and other sectors in risky areas, adjacent to wetlands; (iv) reforest and afforest the uplands surrounding wetlands; and (v) revise the policy on the allocation of land uses.

Declarations

Author contribution statement

Tariku Zekarias, Vanum Govindu, Yechale Kebede, Abren Gelaw: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

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