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A systematic review of studies on freshwater lakes of Ethiopia

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ABSTRACT

Study Region: The study covers the freshwater lakes of Ethiopia, which constitute about 87 billion cubic meters of water volume. The lakes are facing continued ecosystem degradation threats.
Study Focus: The aim of this study was to make an inventory of existing literature regarding the freshwater lakes of Ethiopia and identify gaps and priorities for future research directions. This was done through a systematic review of published scientific literature related to the lakes and characterizing each study based on different criteria.
New Hydrological Insights for the Region: We found a total of 231 articles on freshwater lakes of Ethiopia published in peer-reviewed journals between 1930 and March 2021. Most studies were focused on hydrochemical and biological characteristics of lakes, with less attention to physical structure and processes (including siltation, lake morphometry and catchment biophysical characteristics). Furthermore, (a) less attention was given to the spatial and temporal dynamics of variables that affect the freshwater lakes, (b) there was limited linkage between landscape hydrological dynamics and freshwater lakes and (c) the smaller highland lakes were given limited attention. Future research should be oriented to the study of the relationship between catchment biophysical dynamics and lake hydrological characteristics.

1. Introduction

Different geological formations and climatic conditions have endowed Ethiopia with vast water resources and wetland ecosystems, including 12 river basins, eight major lakes and floodplains and several man-made reservoirs, with a total annual surface runoff of about 122 billion cubic meters (BCM) (Awulachew et al., 2007). There is a diversity of information published about the lake resources of Ethiopia, including their number. Hillman (1993) listed 77 lakes in the then geographical boundary of Ethiopia (including Eritrea). A study by Leykun (2003), based on secondary sources, estimated the number of lakes in the country to reach 70. But a report by Awulachew et al. (2007) estimated the number of lakes in the country to be only 20–30. Another study by Messager et al. (2016) identified about 240 sites as freshwater lakes in Ethiopia using a geostatistical and remote sensing approach. A compilation of results from bathymetry survey reports of the larger lakes (seven of the rift valley lakes, plus lakes Tana, Haike, Hardibo and Bishoftu) revealed that they contain about 87 BCM of water. In a more comprehensive study by Messager et al. (2016), the water in all the open water bodies of the country is estimated to be more than 335 BCM.

Many of these lakes are recognized for their outstanding biological diversity and societal significance (Belete et al., 2015). However, the lakes are facing substantial threats due to natural and anthropogenic factors such as increased water abstraction and

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intensified pollution sources. Population in the lake basins is high and continually growing due to the recent increase in large scale irrigation, which depends on water resources in the lakes and the rivers flowing to them (Seyoum et al., 2015). Such water use competition between irrigation, industrial and domestic uses contributes to complexity in the sustainable management of freshwater resources in Ethiopia. Moreover, climate change exacerbates the situation and induces water balance anomalies in many hydrological systems (Getnet et al., 2014). The threat is highly pronounced in the rift valley lakes, comprising a chain of nine lakes (from north to south: Ziway, Abiyata, Langano, Shala, Hawasa, Abaya, Beseka, Chamo and Chew Bahir) occupying the southern part of the Ethiopian rift valley basin. Lakes in the highland parts of the country also face water level reduction (Belete et al., 2015), water volume reduction (Aynew, 2002), surface area shrinkage (Ayenew, 2004), increasing levels of sediment deposition (Gadissa et al., 2018), reduced runoff inputs to the lakes and increased evaporation losses (Getnet et al., 2014).

Many studies have generated information on different aspects of freshwater resources in Ethiopia using various in situ observation, remote sensing, empirical and modeling approaches. Despite this and also the fact that both the highlands and the rift valley lakes of Ethiopia attract national and international scientific attention due to their ecological and ecosystem significance, systematically organized and synthesized information on the country's freshwater lakes is limited. Thus, a systematic review of existing scientific studies on Ethiopian freshwater lakes is an important endeavor in organizing a body of knowledge on the overall lake water resources of the country. Such a review can contribute to the building of a database and development of data-driven and knowledge-based lake-catchment management plans for the sustainable utilization of freshwater resources.

The aim of this study, therefore, was to make an inventory of existing literature regarding the freshwater lakes of Ethiopia, systematically synthesize the available knowledge and pinpoint gaps to be prioritized by future research. The specific objectives were to (1) examine the temporal pattern of scientific studies of freshwater lakes in Ethiopia; (2) analyze the major research themes covered by previous studies and thus the gaps in freshwater lake research; (3) analyze methods used by studies to extract hydrological information from freshwater lakes of Ethiopia and (4) synthesize the findings of previous studies about the hydrological status of the lakes. The outputs of this study provide a database about the freshwater lakes, identify research gaps and suggest future research directions.

2. Methods

2.1. *Study area*

Ethiopia is situated in the Horn of Africa between 3.4°N and 14.9°N, and 33.0°E and 48.0°E, with an area of 1,104,300 km^2. It is characterized by a wide variety of landscapes and landforms, which results from a complex geological process with alternating phases of orogenesis, peneplanation, crustal updoming, faulting, emplacement of huge amounts of lava and deep fluvial dissection (Abbate et al., 2015). This has created the Great Rift Valley of east Africa (of which Ethiopia contains a major part) and the huge land masses along its escarpments (Fig. 1).

This varied topography in turn produces a complex climate system, ranging from semi-arid in the lowlands to humid and warm (temperate) in the southwest highlands (Fazzini et al., 2015). Another result of the topography is the prevalence of complex hydrological systems with distinct basin characteristics between the lowlands and the highlands (Abbate et al., 2015). The highlands (found in the northwestern and the southeastern parts of the rift valley) are the source of eight large river basins, which radiate towards the surrounding lowlands. With the exception of the rift valley lake basins and the Afar depression, the drainage basins of the lowlands are to a great extent subject to the hydrology of the river basins descending from the highlands. A rough estimation of the surface water potentials of all these drainage basins is about 124.4 BCM, about 97 % of which flows towards neighboring countries (Billi et al., 2015).

Freshwater lakes make up the principal part of these hydrological resources and are large in number (exceeding 70) and vary considerably in their size and location. Some of them (e.g., lakes Hayk and Hashenge) form part of the large river basins; others – those in the rift valley – are marked by their own closed drainage basins and Lake Tana makes up a principal part of the Nile basin (Fig. 1). These lakes, together with their associated drainage basins, are fundamental parts of the structure and welfare of societies and natural ecosystems. In the study of Hughes (1992) the wetlands and lakes of Ethiopia were divided into ten major groups, with each group constituting the lakes and the nearby wetlands. These included Lake Tana, the Hashenge and Hayk lakes, lakes of the Bale mountains, lakes of Bishoftu, lakes of the southwest rift valley, lakes of the Awash River system, lakes of the Afar Depression and artificial impoundments and micro dams. In this study, we have covered all the relevant scientific articles associated with these lakes.

2.2. *Literature search and selection criteria*

The literature search process was conducted by targeting all scientific articles about the freshwater lakes of Ethiopia published in the English language in peer-reviewed journals and available in the following online databases: Google Scholar, Web of Science, Science Direct, ProQues Springer Link and Wiley Online. We developed our search strategy in two different ways, the first being to find articles based on their study area and the second based on thematic relevance. To address the first strategy, we initially listed the names and geographical locations of lakes from literature (Awulachew et al., 2007; Leykun, 2003; Messager et al., 2016; Schagerl, 2016). Some lakes were given different names in different studies and we tried to list all alternative names for each lake. We then searched scientific articles using the identified lake names as a key word. The second strategy was to find studies based on a search item relevant to lake hydrological characteristics. The combinations of words used were "Lakes" AND "Ethiopia" AND "water volume" OR "water quality" OR "hydrology" OR "water balance" OR "climate change" OR "limnology" OR "hydrogeology" OR "hydrobiology" OR "aquatic ecosystem" OR "ground water" OR "human impact" OR "siltation" OR "climate change" OR "hydrochemical" OR "physicochemical" OR "phytoplankton" OR "zooplankton" OR "evapotranspiration" OR "river inflow" OR "fauna" OR "flora" OR

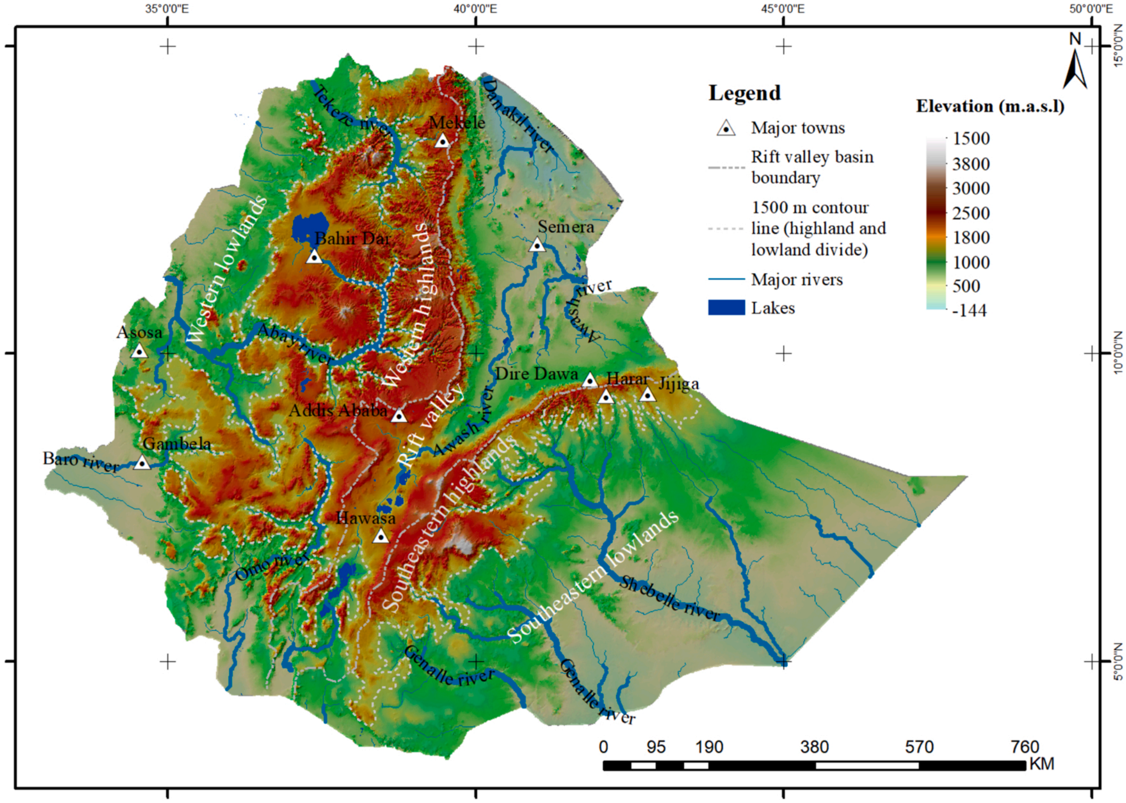

Fig. 1. A map of major terrain features of Ethiopia.

"watershed" OR "catchment" OR "basin" OR "water resource" OR "irrigation".

The last search was conducted on 21 March 2021. This produced a total of 696 papers. We then refined the search results based on inclusion criteria (Fig. 2) to only include studies that: (1) included self-produced data, at least in one variable, (2) were conducted in at least one of the lakes of Ethiopia or their catchments, (3) considered the effect of catchment behavior on at least one lake hydrological variable, (4) were based on empirical observation of samples of organic and inorganic elements from the lakes in relation to lake hydrological characteristics and (5) were published in peer-reviewed journals. In total, 231 articles met the inclusion criteria and were then further categorized and analyzed for the systematic review.

2.3. Data compilation and classification

A tabular template was prepared to record the metadata extracted from the respective publications. These metadata were reviewed and their characteristics assessed based on selected parameters such as the specific hydrological variables measured, the list of studied lakes, the spatial scale of the study, the observed analytical dimension (temporal, spatial, a combination of these or none), the study methods used and the research theme (topic).

The first step started with article registration and metadata organization. An article which passed the selection criteria was imported to Mendeley reference manager software. It was then registered with a unique identification number in the MS Excel-based metadata template. Relevant information (e.g., topic, author, year of publication) was then registered in consecutive columns.

Secondly, the variables of hydrological interest that were measured, estimated, quantified or analyzed quantitatively using first-hand data (i.e., measured data or secondary data that were compiled by the researcher during the research process) were extracted and labeled as either 'effect' or 'causal' variables based on how they were considered in the study. The effect variables were those subjected to the influence of one or more (independent) variables while the causal variables were those exerting some influence on another (dependent) variable. Studies which considered only one of the two variable types were considered as descriptive. Next, the co-occurrence frequencies of specific effect and causal variables were enumerated to examine the degree to which a pair of variables had been studied, or which variable pairs are missing in literature. Future research activity is recommended to focus on variables where low co-occurrence frequency is recorded, as little attention has so far been given to the causal associations of these variables.

Thirdly, the lakes that were studied in each of the articles were listed, and the result was used to analyze the number of times each lake appeared in all the studies. The lake names were further cross-referenced with a list of variables in the articles, which was used to determine the number of times that a variable was studied for a specific lake. The assumption here was that lower frequency values would suggest increasing probabilities of research gaps and vice versa.

In the fourth step the spatial units studied in each article were identified as terrestrial, aquatic or aquatic-terrestrial, based on the data collection site and the characteristics of the variables measured. Aquatic studies are those conducted on data from the lake ecosystem's aquatic part only, with no variables representing the terrestrial parts. Terrestrial studies are those which were conducted with data from the drainage areas that contribute water to the lake with no variables measured from the aquatic part. Aquatic-terrestrial studies are those conducted using data from both the lake and its drainage area (or those which consider both components as aggregated units). The result was used to evaluate if the relationship between terrestrial and aquatic parts of a lake ecosystem has been well addressed.

Fifthly, the studies were categorized into four major groups based on whether the studies considered temporal, spatial, spatio-temporal analytical dimensions, or did not consider any analytical dimensions at all. The latter studies are those that did not present any spatial and temporal variation in variables of interest; instead, they presented information in spatially aggregated form (or at a specific location) and at an instant time.

Lastly, the methods employed to extract information about the characteristics of each variable were listed and used to quantify the frequency of each method per variable for all the reviewed articles, which helped in evaluating the pattern of hydrological research methods used in the studies.

Once registration of the major characteristics was completed, the studies were grouped into six exclusive categories, with each category characterized by a similar research thematic area, namely catchment biophysical analysis, hydrobiology, hydrogeology, lake water storage analysis, paleohydrology and water quality analysis. The criteria for categorization were the topic, abstract, list of variables, spatial unit studied and temporal scope of the study. The process started with a preliminary evaluation of the articles to

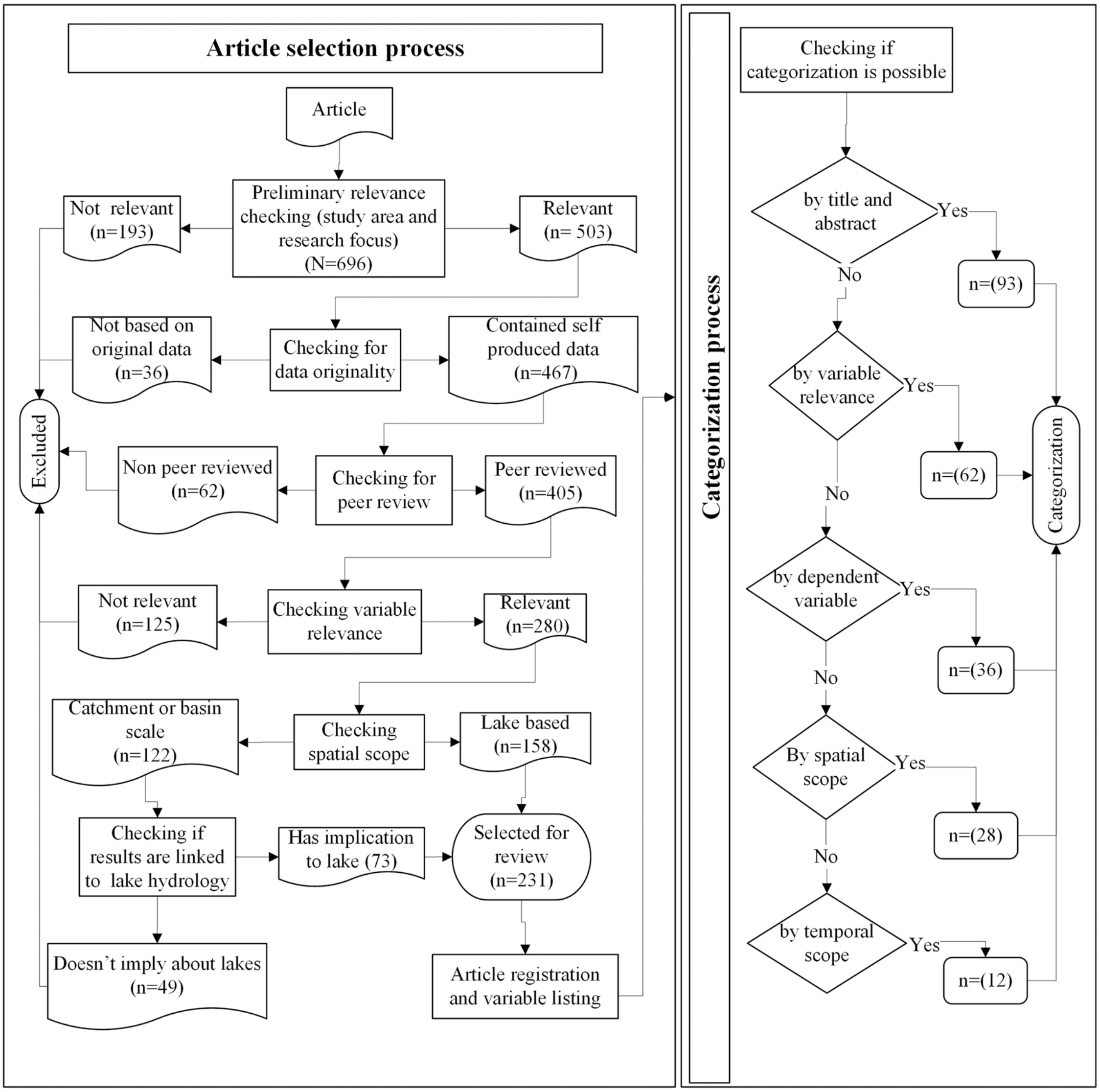

Fig. 2. Article selection and categorization framework used in the study.

derive a possible list of research themes by which the articles could be grouped. The resulting list of more than ten research themes was then refined to six categories based on similarities between the themes. Each article was then assigned to one of the six categories based on the characterization criteria. The categorization process was conducted based on a sequence of steps illustrated in Fig. 2. It starts with assigning an article to one of the research themes based on its topic and abstract relevance. However, if the topic and abstract information implied multiple themes, the article continued to be evaluated through four consecutive evaluation steps until it was possible to assign it to one of the appropriate research themes. A detailed description of each criterion can be found in Appendix I.

2.4. Synthesis of findings on the hydrological status of major lakes

To present synthesized hydrological information on the lakes, the papers were further screened for information on the hydrological status of some major lakes, based on the following selection criteria: (1) studies conducted on one of the Ethiopian rift valley lakes or Lake Tana; (2) studies presenting original research (not review) of the temporal dynamics of one or more lake water storage variables such as water balance, water volume storage, water level dynamics, lake surface area size and lake siltation rate and (3) studies addressing the causes of the changes in a specific variable. Based on the water balance closure and water volume conditions, the lakes are characterized into static (stable water balance closure and water volume and relatively small anthropogenic intervention in their catchments), resilient (positive and stable water balance closure and water volume even with intensive anthropogenic intervention in their catchments) and declining (reduction of water volume and a negative water balance closure term).

3. Results

3.1. Historical trend of scientific publications on the freshwater lakes of Ethiopia

The earliest publication on Ethiopian freshwater lakes was in 1930 (Fig. 3), while the number of studies per year tended to increase through time at different rates. The publication pattern until the 1990s was very intermittent for most of the research themes, with the gap between consecutive publications exceeding two decades, specifically between 1940 and 1960. Even though the gap was narrowed in the following decades (in the 1970s and 1980s), the total number of publications per year remained lower than five until 2000, rose to more than six between 2001 and 2003 and then reached 23 between 2018 and 2020 (Fig. 3).

3.2. Major research themes in freshwater lake studies in Ethiopia

A comparison of studies among different research themes shows that lake water storage analysis, with 65 articles, was the most frequently studied (Fig. 3). In terms of historical trends, the earliest publication found on this theme was the bathymetry study of Lake Bishoftu by Prosser et al. (1968), followed by a bathymetry survey report on lakes Chamo and Abaya by Awulachew (1999). The most frequently investigated effect variable in this theme was water balance (49; hereafter the number in parentheses refers to the number of studies), as influenced by climate (22), anthropogenic factors (8) and land cover change (5) (Fig. 4). Lake water volume was the second most frequently studied variable (39), of which 17 were investigated as a function of climate, and eight as affected by anthropogenic variables. Lake morphometric variables were covered by 15 studies, of which four were investigated in relation to climate and three to land cover change. Siltation was the other effect variable studied under this theme, particularly in relation to catchment soil characteristics (7). In the co-occurrence analysis we found a considerable number of purely descriptive studies that did not report any causal variables, particularly for water balance (13) and water volume (11) studies.

In terms of analytical dimensions, the majority of the studies of lake water storage (62 %) considered the spatiotemporal dynamics

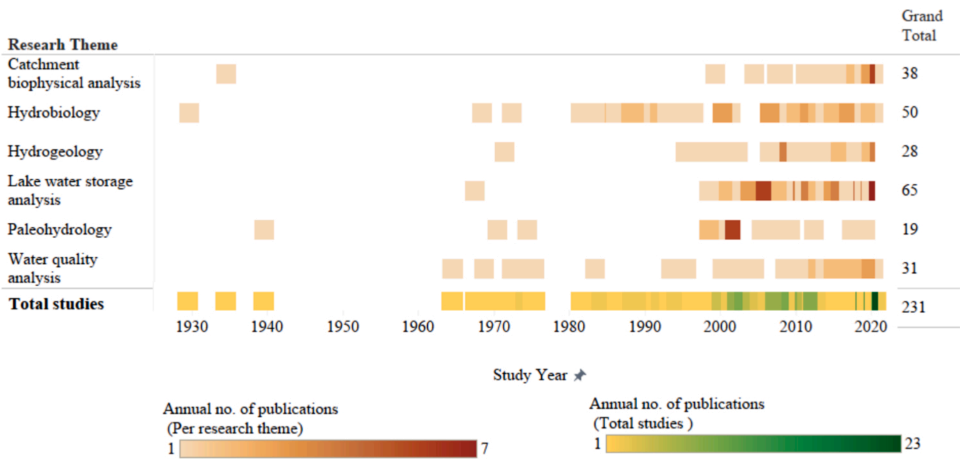

Fig. 3. Historical trend of scientific publications on freshwater lakes of Ethiopia by research theme.

Research Theme	Effect variables	Causal variables: Anthropogenic activity	Climate	Hydro-geomorphology	Hydrochemical	Land cover	Morphometry	Soil characteristics	Tectonic activity	Descriptive studies
Catchment biophysical analysis	Land cover	6	1							1
	Soil characteristics	1				3				2
	Water balance	2	7			1				
	Descriptive studies	10	5							
Hydrobiology	Aquatic organisms	2	1		34		1			14
Hydrogeology	Groundwater flux		5	18						2
	Hydrochemical		2	10						2
Lake water storage analysis	Water balance	8	22			5		1		13
	Lake water volume	8	17			2		1		11
	Morphometry	1	4			3				7
	Siltation	2	2			1		7		5
Paleohydrology	Water balance		8							
	Hydro-geomorphology		4						4	
	Hydrochemical		5							1
	Lake water volume		12						1	
Water quality	Hydrochemical	13		3			1			15

Number of studies: 1 – 34

Fig. 4. Co-occurrence frequency in the reviewed articles of cause-and-effect variables by major research themes. Empty cells in the table represent research gaps.

of water storage characteristics (Fig. 5a). The remaining 25 % and 12 % considered the temporal and spatial dimensions respectively. Most of the studies (62 %) took the aquatic and terrestrial parts of the lake system as the spatial unit of study while the remaining studies focused only on the aquatic parts (Fig. 5b).

The second highest number of studies was found in the hydrobiology research theme (50), with a focus on the study of aquatic organisms in relation to the environmental factors affecting them. The earliest publication located was the study of Omer-Cooper (1930), which is the expedition report by a British scientist in which he introduced the freshwater fauna of Ethiopia to the international

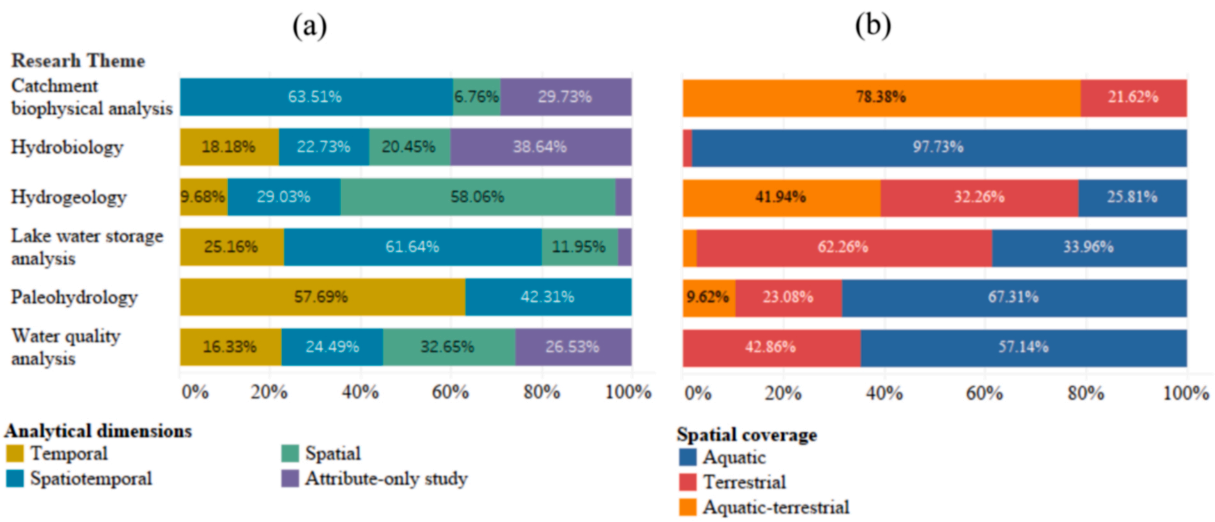

Fig. 5. Classification of publications by research theme and by focus in terms of (a) type of measured analytical dimensions and (b) spatial coverage.

scientific community. Subsequent publications were in 1969 (Urban, 1969) and 1973 (Talling et al., 1973), with a gap until 1982 (Goll, 1982), since when publication has continued with only a short time interval between studies (Fig. 3). The variable co-occurrence is restricted largely to that between aquatic organisms and hydrochemical characteristics (34), with a very limited appearance of the other causal variables which have been shown to have a significant effect on aquatic organisms in other international studies (Yang et al., 2013). An example is the relationship between aquatic organisms and many catchment biophysical variables, such as land cover, climate change, anthropogenic activity and soil characteristics (Joniak et al., 2017; Szpakowska et al., 2022; Tahiru et al., 2020). Similarly, the influence of lake morphometric characteristics on the behavior of aquatic ecosystems is also poorly addressed (Haas et al., 2010; Stefanidis and Papastergiadou, 2012). The majority of the studies (38 %) were only spatially aggregated and related to a specific point in time rather than examining spatial and temporal dynamics. The spatial coverage of almost all studies was limited to the aquatic parts of the lake ecosystem, with little or no attention to the terrestrial parts (Fig. 5b).

Catchment biophysical analysis ranked third in terms of study frequency. The focus of studies in this theme was on catchment biophysical variables such as land cover, topography, soil, anthropogenic factors, and their impact on hydrological characteristics. The number of studies found was 38, with the earliest publication in 1935 (Cheesman, 1935) giving a historical record of Lake Tana and its environment. This study might be significant as a historical document of basin environments but is less relevant in terms of the actual hydrological behavior of the basin. A substantial increase in publications on biophysical characterization of lakes and basins was observed since 2005. In terms of variable frequency, most studies were conducted to assess land and water resource utilization patterns, with the majority of them being descriptive studies (15) conducted without any use of explanatory variables. The causality studies are focused on climate change impacts on water balance (7) and anthropogenic effects on land cover change (6) (Fig. 4). The majority of studies (64 %) considered the spatiotemporal dimension, with most of the rest being simply attribute studies (Fig. 5b). The spatial scope of most studies (78 %) was limited to the terrestrial parts of the lake ecosystems.

Lake water quality was the fourth most-frequently studied research theme (31). The main concern of these studies was the measurement and analysis of the hydrochemical characteristics of the surface and underground waters found within the lake basins. The earliest publication date was 1965, with two publications, both of which were about a chemical study of African lakes, including the rift valley lakes of Ethiopia (Baxter et al., 1965; Talling and Talling, 1965). In following years, publication was neither sustained continuously nor interrupted totally, but continued to appear on a five-year average interval (Baumann et al., 1975; Baxter et al., 1973). A sustained trend of publication started only in 2004, from when there is a minimum of one publication every other year (Fig. 3). In terms of the variables examined, they are characterized by the predominant use of hydrochemical characteristics as the effect variable, with only anthropogenic factors as causal variables to explain the water quality dynamics. Many studies (15) in this research theme are also descriptive, focused only on presenting water quality characteristics without reference to the causal factors affecting water quality (Fig. 4). Some 33 % and 24 % of these studies considered the spatial and the spatiotemporal dimensions respectively, while most of the remaining studies (exceeding 26 %) did not consider any aspects of variability. In terms of spatial coverage, the majority of the studies (57 %) looked at the aquatic parts of the lake ecosystems, with 43 % considering both the aquatic and terrestrial parts. (Fig. 5b).

The hydrogeology studies focused on groundwater characterization and geological evolution analysis of the lake basins. We found 28 studies, with the first publication in 1972 (Searle and Gouin, 1972), although this was not directly relevant to the hydrological features of the lakes, but gave some accounts of the geological characteristics of the basins related to their gravity profile. However, more regular publication did not start until the study of Darling et al. (1996), which gives the earliest account of groundwater interactions between the lakes and their catchments. In terms of variable frequency, studies in this category tended to focus on the groundwater flux (flow direction and volume estimation) and its hydrochemical characteristics, with the frequent use of hydro-geomorphological factors as explanatory variables. The focus was only limited to these three variables, with a limited co-occurrence frequency of other important variables which might have an influence on groundwater characteristics (Fig. 4). Some 58 % of studies considered the spatial dimensions of the hydrogeological variables (Fig. 5a). In terms of spatial scope , 42% of studies were conducted on the terrestrial parts, 32 % on the aquatic-terrestrial parts and 26 % on the aquatic parts (Fig. 5b).

Paleohydrology studies were the least frequently addressed research theme (19). These focused on tracing the evolution of water and material movement in the lake basins on a geological time scale. The earliest publication was in 1940 (Nilsson, 1940), which can be considered as a pioneering study of the lake basin evolution process of the rift valley lakes and Lake Tana and was a paleolimnological account of past climate change at a regional scale. Subsequent publications were in 1971 (Grove and Goudie, 1971) and 1975 (Grove et al., 1975), with a trend of more frequent publication starting only in 1990 (Fig. 3). The commonly used effect variables have included lake water volume (12), water balance (8) and hydrochemical variables (5), all of which were assessed as a function of climate variables. In addition to climate variables, tectonic factors were employed as causal variables, mainly to assess the hydro-geomorphological process (Fig. 4). Most of the paleohydrological research was conducted by considering only the temporal dimension (58 %), the remainder covering both the spatial and temporal dimensions (Fig. 5a). The target of most studies was the aquatic parts of the lake system (67 %), with only 23 % of studies considering both the aquatic and terrestrial parts in their spatial coverage (Fig. 5b).

3.3. Number and type of study lake

From the total of 70 lakes included in the literature search process (using their names as a keyword), we found scientific studies on only 27 of them (Fig. 6). The most studied lakes were lakes Ziway and Hawasa, with 77 and 50 studies respectively. The next most referenced was Lake Tana with 47 studies, followed by lakes Abiyata (41), Shalla (36), Langano (34), Abaya (28) and Chamo (22). There were also several studies on the smaller lakes, including five of the Bishoftu crater lakes (22), Hayk (10) and Ardibo (2). The number of studies for these and many other lakes are not displayed in Fig. 6; instead, they were merged and reported as "other smaller lakes'' (OSL; Fig. 7), since they are too numerous to mention individually. There were also many regional studies which provide essential hydrological information for entire basins, typically for the central rift valley lakes basin region (CRLB), without explicitly attributing their results to a specific lake (Grove et al., 1975; Wagesho et al., 2012).

Analysis of the articles by lake and variable revealed two different patterns, for Lake Tana and for the rift valley lakes. For Lake Tana, most studies were associated with climate and water balance aspects, with the fewest investigating hydro-geomorphology and lake morphometry variables. In the rift valley lakes, on the other hand, most studies looked at hydrochemical, water balance, anthropogenic activity and climate variables, followed by aquatic organisms and lake water volume variables. The least frequently addressed topics included siltation, catchment soil characteristics, lake morphometry and groundwater flux (Fig. 7). There was also a substantial variation in study numbers per variable between the different rift valley lakes, with most records relating to three of them – Ziway, Abiyata and Hawasa - and with decreasing numbers towards the southern rift valley lakes such as Abaya and Chamo (Fig. 7).

3.4. Hydrological information estimation methods used in freshwater lake studies

The hydrological information estimation methods differed depending on the variable types (Fig. 8). Physical modeling, numerical modeling, analytical water sampling analysis and confirmatory statistical analysis constituted the most common hydrological information estimation methods.

Modeling constituted the most frequently used method, predominantly physical modeling, followed by numerical modeling. One of the most frequent application areas of modeling was to estimate information about water balance components. Numerical modeling was typically based on the use of time series hydroclimate records of nearby meteorological stations, while the physical modeling technique derived the required parameters after representing the variables of interest in a geospatial database (Alemu et al., 2020).

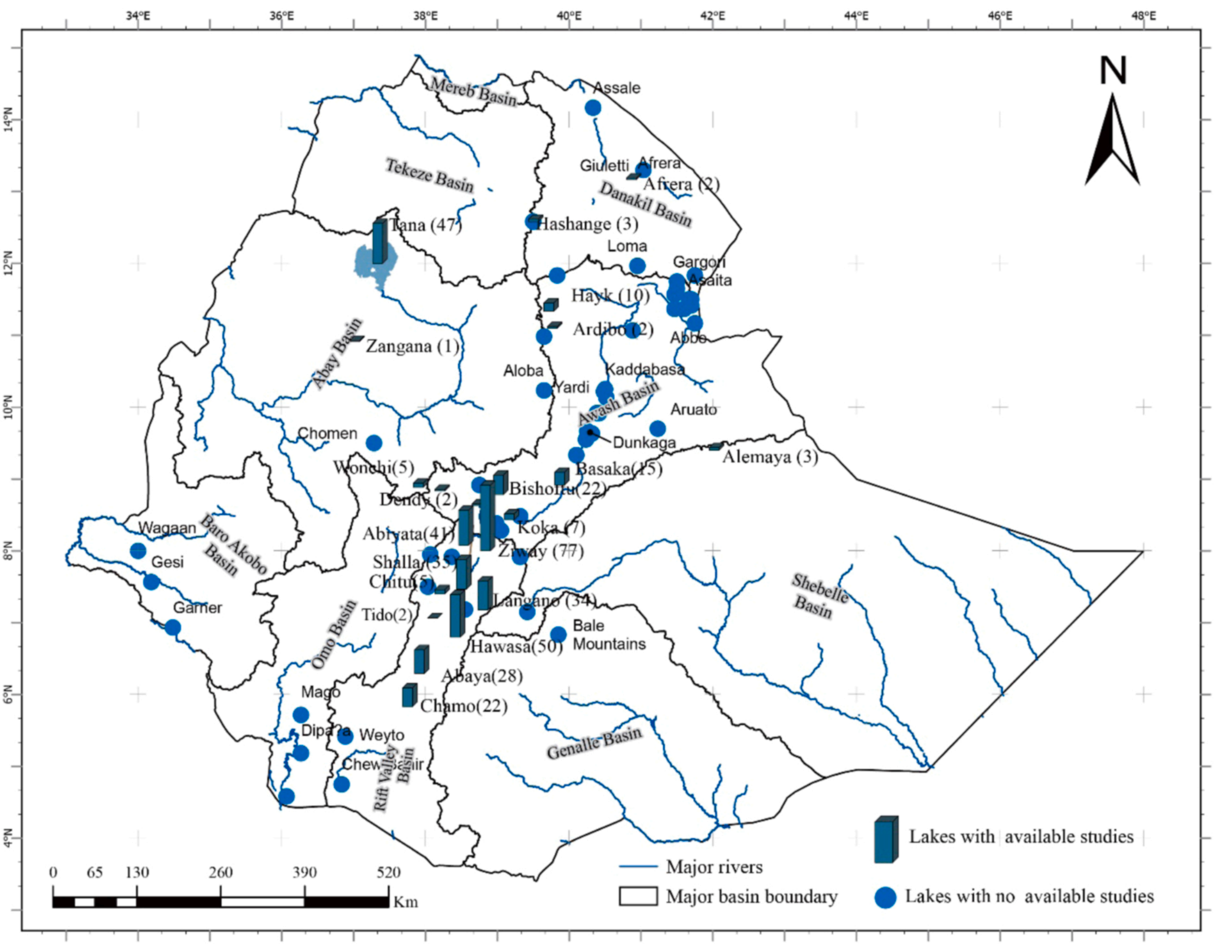

Fig. 6. Location map of major freshwater lakes of Ethiopia with number of scientific studies conducted on each lake. The length of the bar is proportional to the number of scientific studies found, while the number in parentheses is the exact number of studies referring to each lake. NB: The labels for Lake Bishoftu represent the aggregate results of five of the permanent crater lakes found around the town of Bishoftu; such as lakes Hora, Babogaya, Bishoftu, Kilole and Arenguade.

Variables	Ziway	Hawasa	Tana	Abiyata	Shalla	Langano	CRLB	OSL	Abaya	Chamo
	Lakes									
Hydrochemical	31	28	7	17	17	16	7	29	12	11
Climate	22	8	20	15	11	14	4	8	6	2
Water balance	17	8	17	10	6	8	3	11	9	5
Aquatic organism	18	18	8	8	9	6		19	8	9
Lake water volume	12	10	11	15	9	11	1	12	7	5
Anthropogenic activity	16	9	6	5	2	4	11	7	5	4
Hydro-geomorphology	11	4	3	8	9	8	10	3	2	1
Groundwater flux	7	1	3	5	4	4	6	1	2	1
Land cover	4		4	4		1	6	3	1	
Morphometry	2	1	1	2				8	2	2
Siltation	5	1	6	2	1	1			1	1
Soil characteristics	3	1	5	1			2			1
Tectonic activity	3	1		2	3	3				

No of studies
1 31

Fig. 7. Numbers of studied variables by major freshwater lakes of Ethiopia. (Numbers in the matrix cells are counts of studied variables. An article containing more than one variable and lake may be counted multiple times and the counts in the table may represent multiple frequency values. CRLB: central rift valley lake basin; OSL: other smaller lakes.).

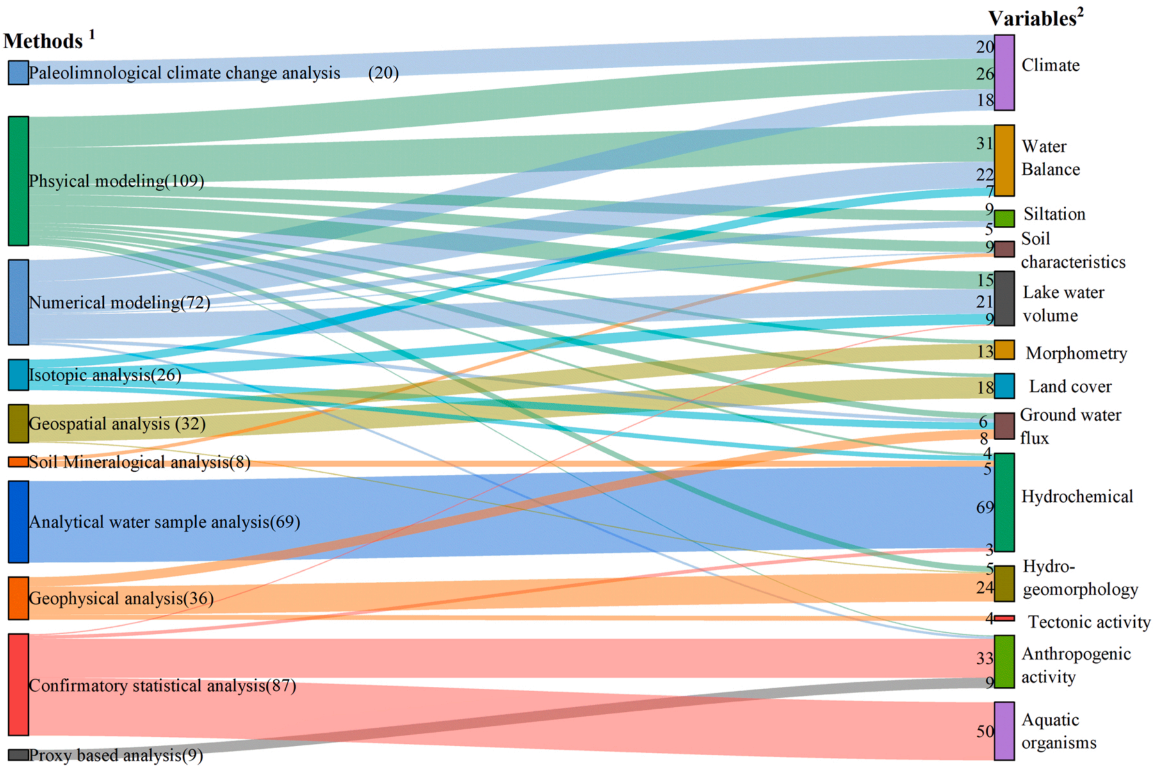

Fig. 8. Frequency of hydrological information estimation methods used per variable type. Link size is proportional to the number of times a method was applied to study a variable. ([1] The values in parentheses represent the total number of studies that used a specific method. [2] The values represent the number of times a method was used to study a variable in the link; unlabeled links denote a value of less than three).

Both modeling methods were also common in the study of lake water volume dynamics through estimating lake water volume from time series lake level records, lumped water budget equations (for numerical models) and lake bathymetry datasets (for physical models). The other common application areas of modeling were related to siltation and catchment soil erosion volume estimation. More specifically, physical modeling approaches were used to quantify the average sediment load of studied lakes and to estimate lake bottom sediment volumes through bathymetry differentiation methods. The most frequent use of physical models (109 studies) might indicate increasing attempts to consider spatial and temporal dimensions while measuring hydrological dynamics. Many of the physical and numerical models used by the reviewed studies were, however, universal in nature and employed without prior understanding of their compatibility with the context of the study area. The use of infrequent (both spatially and temporally) observation data for calibration of model simulation was another critical problem observed in water balance studies.

The approach used to study climate variability differed depending on the temporal scale of the studies. Most studies concerned with the last few hundred years of climate change were conducted through time series analysis of climate data and physical modeling approaches. The former is used to trace climate change through confirmatory statistical analysis of meteorological data, while the latter identifies past and future changes based on different downscaled regional and global climate models. The other method used in the climate change studies was paleolimnological climate analysis, which was mainly employed to trace climate change on a geological time scale (e.g., Legesse et al., 2002; Telford et al., 1999); it determined the chronology (e.g., Lamb et al., 2007), accumulation rate (e.g., Sagri et al., 2008) and lithological characteristics of sediments on a millennium-scale time frame and associated the result with climate change observations (Lamb, 2002).

Many studies about the surface and subsurface water physicochemical characteristics were conducted using analytical water sampling techniques (Teklu et al., 2018). There were also some water quality studies conducted through mineralogical analysis of sediments, in which the physicochemical characteristics of sample sediments from the lake were used as the main indicators of pollution from the catchments (Moges et al., 2017). A few others, concerned with tracing geological time scale change in the physicochemical characteristics of lake waters, used an isotope-based water age determination system (Wagner et al., 2018).

Aquatic life studies of the lakes have mostly used a confirmatory data analysis system, through making empirical observations of the interaction between the aquatic organisms' characteristics and water characteristics. The observations were then analyzed using inferential statistics (hypothesis testing, producing estimates, regression analysis) to verify the effect of lake water hydrological characteristics on the behavior of aquatic organisms (Fetahi et al., 2011; Lemma, 2009; Wood and Talling, 1988). Confirmatory data analysis was also applied to study anthropogenic impacts on lake ecosystems to verify whether different anthropogenic interventions (both in the catchment and the lakes) and socio-economic changes have had any significant impacts on lake hydrology. Typical examples are estimation of water abstraction impacts on lake water volume (by lake water storage studies) and tracing anthropogenic

Table 1
Synthesis of prevailing hydrological conditions of different lakes and their causal factors as reported in previous studies.

Lake	Variables	Prevailing conditions	Causal factors
Abaya	Lake water volume	Stable[1]	
	Water balance	Negative closure term[2; 3]	
	Siltation	Increasing[2]	Land use change[2]
Abiyata	Lake water volume	Decreasing[1; 4; 5; 6; 7; 8]	Industrial water use[1; 5; 8]; inflow reduction[1; 5; 6; 7]
	Water balance	Inflow reduction[6]	Increase in evaporation loss[6]; land use change[6]; upstream irrigation[6]
		Negative closure term[1; 7; 9]	Industrial water use[1; 7]; inflow reduction[1; 7]
Chamo	Lake water volume	Stable[1; 2; 4]	
	Siltation	Increasing[2]	Land use change[2]
	Water balance	Positive closure term[2; 3]	
Hawasa	Lake water volume	Decrease in water storage capacity[10]	Siltation[10]
		Increasing[11; 12]	Increase in precipitation[11; 12]; land use change[11]
	Siltation	Increasing[10]	Land use change[10]
	Water balance	Positive closure term[1; 11; 12; 13]	
Langano	Lake water volume	Stable[1; 4; 5; 6; 14]	
	Water balance	Positive closure term[9]	
Shalla	Lake water volume	Stable[1]	
	Water balance	Balanced closure term[9]	
Tana	Lake water volume	Stable[15; 16; 17]	
	Siltation	Decreasing[18]	Catchment conservation[18]; decrease in runoff discharge[18]
	Water balance	Balanced closure term[19]	
		Positive closure term[16; 17; 20; 21; 22]	
Ziway	Lake water volume	Decreasing[1; 14; 23]	Prolonged dry period[14; 23]; upstream irrigation[1; 14]
		Stable[6]	
	Siltation	Increasing[24; 25]	Increasing soil erosion[26]; land use change[24]
	Water balance	Inflow reduction[6; 27]	Increase in evaporation loss[6; 27]; land use change[6; 24]; upstream irrigation[6; 27]
		Negative closure term[24]	Land use change[24]; upstream irrigation[24]
		Positive closure term[28]	

Sources: [1]Ayenew 2004; [2]Awulachew 2006a; [3]Tibebu Kassawmar et al., 2011; [4]Belete et al., 2015; [5]Alemayehu et al., 2006; [6]Getnet et al., 2014; [7]Legesse et al., 2004; [8]Aynew, 2002; [9]Ayenew and Becht, 2008; [10]Abebe et al., 2018; [11]Ayenew and Gebreegziabher, 2006; [12]Belete et al., 2017; [13]Ayenew et al., 2007; [14]Seyoum et al., 2015; [15]Chebud and Melesse, 2009; [16]Dessie et al., 2015; [17]Kebede et al., 2006; [18]Lemma et al., 2020; [19]Setegn et al., 2008; [20]Duan et al., 2018; [21]Rientjes et al., 2011; [22]Wale et al., 2009; [23]Asfaw et al. (2020); [24]Desta et al. (2017); [25]Aga et al., 2019; [26]Aga et al. (2018); [27]Desta and Lemma, 2017; [28]Goshime et al., 2020.

sources of water pollution from nearby catchments. With very few exceptions (e.g., Yohannes et al., 2013), many studies indicated potential impacts of certain anthropogenic interventions on lake ecosystems without explicitly stating the magnitude of such influences. This is partly a reflection that most studies aimed to infer the impact of terrestrial/basin areas on the aquatic system without considering both the aquatic and terrestrial components in their spatial scope. This was typically exhibited in water quality and hydrobiology research where the spatial scope of most studies was restricted only to the aquatic parts of the lakes. The problem was also apparent in catchment biophysical studies, in which the likelihood of land cover change and land management impacts on lake hydrology were inferred from literature, with no empirically observed data (Elias et al., 2019; Lemma, 2003; Meshesha et al., 2012).

The study of groundwater dynamics was mainly based on isotopic analysis, geophysical analysis and ground water modeling approaches. The isotope analysis approach compared the isotope composition of different water sources that contribute to the groundwater system of the basins (Legesse et al., 2002), revealing any subsurface hydraulic links and the contribution of different water balance components to recharging or depleting the groundwater of the basin. The geophysical analysis approach, on the other hand, was used to identify subsurface hydraulic links and groundwater flow volumes through direct measurement of groundwater flux (Ayenew et al., 2009; Molin and Corti, 2015). Many of these studies were subjected to the problem of limited hydrologic data from poor observation networks and repetitive use of similar hydrologic parameters while estimating many variables.

A geospatial data analysis approach was typically employed to derive lake morphometric and catchment land cover variables. It was based on the representation of lake bathymetry data in a geospatial database and then deriving the required parameters with the 3D analytical capacities of spatial analysis software. In the case of catchment land cover studies, geospatial approaches were used to derive multi-temporal land cover information from remote sensing observations.

3.5. Synthesis of findings on the hydrological status of major freshwater lakes of Ethiopia

In Table 1 we present synthesized findings related to selected lake water volume variables with a specific focus on the major rift valley lakes and Lake Tana.

The static lakes are Shalla (Ayenew, 2004) and Langano (Alemayehu et al., 2006; Ayenew, 2004; Belete et al., 2015; Getnet et al., 2014; Seyoum et al., 2015), which are characterized by positive water balance closure terms and a stable water volume condition with a relatively small anthropogenic intervention in their catchments. The resilient lakes are Abiyata, Chamo, Hawasa and Tana, which maintain a positive water balance closure term and a relatively stable water volume, even though they are subject to intensive anthropogenic intervention and climate change factors. Some examples of these interventions are massive sediment load from upland watersheds (Abebe et al., 2018; Awulachew, 2006a; Lemma, 2009), new settlement and conversion of forest to agricultural land (Abebe et al., 2018; Awulachew, 2006a; Ayenew and Gebreegziabher, 2006; Wondie, 2018) and water diversions that decrease water flows into the lakes (Awulachew, 2006a; Dile et al., 2016). The reason the lakes can maintain a positive water balance closure term with the presence of such intensive anthropogenic intervention is, however, poorly documented in many studies. An exception to this is Lake Hawasa, where neo-tectonism (Ayenew and Becht, 2008; Ayenew and Gebreegziabher, 2006) and climate factors (Ayenew and Gebreegziabher, 2006; Belete et al., 2017) explain why its water volume remained unchanged over time.

The declining lakes are Abiyata and Ziway, which were characterized by a reduction of water volume and a negative water balance closure term in many of the studies. The causes of the change are associated with high water abstraction and climate factors (Table 1). The underlying threat emanates from diversion of Lake Ziway's inflowing rivers for irrigation in the upper catchment, which consequently reduces the volume of water flowing into the lake and, eventually, the water volume of the lake itself (Aynew, 2002; Meshesha et al., 2012; Seyoum et al., 2015). The lowered water volume in Lake Ziway in turn brought about a reduction in the outflowing river volume that inflows towards Lake Abiyata (Belete et al., 2015; Seyoum et al., 2015), which is thus one of the main causes of Abiyata's water volume reduction. Water abstraction from Lake Abiyata for soda ash production is an added factor (Aynew, 2002; Legesse et al., 2004), although it is not clearly defined which of the two factors has the greater impact. On the other hand, increasing evaporation due to prolonged dry periods has been reported as a common factor aggravating the reduction of water volumes of both lakes (Asfaw et al., 2020; Desta and Lemma, 2017; Seyoum et al., 2015).

4. Discussion

4.1. Historical trend of publication records

Scientific inquiry and acquisition of information regarding the freshwater lakes of Ethiopia date back to the beginning of the 20th century, with a notable contribution from colonial expeditions and personal accounts of travelers. The earliest available scientific records were from Hugh Scott's expedition to the then Abyssinia (Omer-Cooper, 1930), which presented quantitative information about selected hydrochemical characteristics of lakes of the rift valley region. The detailed results of his investigation, published as a series of papers in consecutive study years, presented the earliest known scientific records of the freshwater fauna of Ethiopia. The other study of significant historical importance is that of Nilsson (1940), which presented a comprehensive scientific account of the geological evolution of the lakes of the central rift valley region and Lake Tana, with a qualitative description of their basin environments. We then found hardly any published articles in the following years until 1965 (Talling and Talling, 1965).

The year 1965 could be considered the beginning of a new era in the study of freshwater lakes of Ethiopia in terms of sustained publication, the institutionalization of research activities and the widening of research themes. This period marked the introduction of higher education and the establishment of research institutions in the country, making possible the development of longer-lasting research activities than the colonial expedition and travel account-based research traditions. The average number of research publications per year was still less than two, but it continued without interruption with a gradually increasing volume. With the exception of lake water storage studies, publications started to emerge in all the other research themes. The initial themes of this period (the post 1965 era) were water quality (Talling and Talling, 1965) and hydrobiology (Urban, 1969) followed by paleohydrology (Grove and Goudie, 1971) and hydrogeological studies (Searle and Gouin, 1972). The number of lakes studied and the diversity of research approaches used also increased, ranging from descriptive study to confirmatory analysis of water quality impacts on aquatic organisms (Baxter et al., 1973; Talling et al., 1973; Talling and Talling, 1965) However, there exists an interruption in the publication record between 1974 and 1984, a period that coincided with a time of political transition from the imperial regime to a socialist military power. This was known for its political instability and economic stagnation, where state attention was diverted towards security and political issues (Mengistie, 2021), which might account for the reduced number of publications during this time. Most significantly, the country's political alignment was directed towards the then Soviet bloc and its relations with the West were severely strained (Markakis, 1981). This might have halted the involvement in the scientific endeavors of western scholars, who contributed the most during the previous decades.

In the last 25 years, the study of freshwater lakes of Ethiopia has advanced in more ways than ever before, in terms of thematic area, the number of lakes studied, and the number of research studies published per year. In this period, the number of state-owned universities grew, which resulted in an increase in research involvement by domestic scholars. It was also a time where strong institutional linkages were created between domestic and international research institutions. The progress is also attributed to significant advances in hydrological research methods, easier accessibility of hydrological data, software and hardware advancements, the explosion of geospatial technology and greater international linkage through internet and web-based data sharing mechanisms. This might also be the reason for the abrupt increase in the frequency of lake water storage studies after the 1990s (Awulachew, 1999). In the lake water storage research theme, the different morphometric characteristics of the lakes were determined (Abebe et al., 2018) including lake areas, depths, volumes and overall bathymetry measurements. The water balance state of most of the lakes was also estimated to a reasonable level of accuracy through a variety of numerical and physical water balance modeling approaches (Belete et al., 2017). Lake water quality levels and their usability for different human consumption purposes were also determined (Zinabu et al., 2002). Cause and effect relational analysis between catchment biophysical dynamics and lake hydrological dynamics has also started to be considered (Billi and Caparrini, 2006). Understanding the long-term hydrological dynamics of the lakes (both qualitative and quantitative dynamics) and their response to the changing trends of hydrological causal factors became the main research agenda of studies in recent decades (Awulachew, 2006a; Legesse et al., 2004).

The historical record of publication on the freshwater lakes of Ethiopia is evidence for the ongoing advancement of scientific research endeavors in the field of hydrology and lake ecosystem studies. One of the observed trends is an increase in the number of variables addressed by the studies over time. Studies in the early period (pre-1960) were limited to aquatic organism characterization and lake water physiochemical characteristics. This was followed, after the 1970s, by lake water volume studies and water balance measurement with the causal factors affecting it. Variables dealing with catchment biophysical characteristics (specifically land cover and climate change) newly emerged after the 1990s. Methodological complexity also advanced with the increasing number of variables addressed by the studies. In this regard, articles in the early days were narrative, qualitative studies based on personal observation. This was followed by quantitative measurement of variables based on empirical observation of hydrological phenomena. Empirical observation-based analysis then transformed to modeling hydrological phenomena using a variety of conceptual and hydrological models. The current frontier is now causality analysis of multiple hydrological variables and simulation and prediction of hydrological phenomena.

4.2. Implications of variable co-occurrence frequency and research methods

Our analysis shows that variable co-occurrence frequency differs between the research categories. In the lake water storage theme, water balance and lake water volume analysis were largely examined in relation to land use change, climate change and morphology, with the majority of studies focused on climate change effects on water balance and lake water volume. A potential research gap in the study of lake water volume is the impact of land cover and anthropogenic activity on lake water volume. Another potential research gap is in lake morphometric and siltation studies, where there is a less frequent appearance of these variables, with the majority of studies conducted without considering any causal factors affecting lake hydrology.

On the other hand, in the hydrogeology research category, much effort has been directed to the study of groundwater flux and mobilization of hydrochemical variables as a function of basin geomorphological characteristics. Other important factors that could have affected groundwater characteristics, such as anthropogenic intervention, climate change and land cover change were given less attention. In paleoenvironmental research, the focus was oriented to reconstruction of millennia-scale hydrological histories of the basins. But among the many environmental variables involved in the basin evolution process, climate change was the only driving factor considered by the studies.

With very few exceptions, the tradition of hydrobiology research was characterized by a single variable combination, limited only to lake water hydrochemical variables and aquatic organism characteristics. This was also an issue in the water quality studies, where anthropogenic intervention was considered as the only source of water pollution. In contrast, the attention given to examining the effects of many hydrological variables such as lake morphometric characteristics, lake water volume dynamics, catchment biophysical changes (including land cover and soil characteristics) and climate change on water quality and aquatic organisms was very limited.

In catchment biophysical studies, a research gap is indicated both in terms of the very low number of variables investigated (compared to current studies in hydrological science) and in the limited study of causality analysis. Most attention was given to situational analyses of prevailing land and water utilization patterns, rather than causality analyses between different biophysical variables. More specifically, the impact of ongoing land cover, vegetation, socio-economic and demographic changes on water balance and catchment erosion processes received little attention.

Our observations about the frequency of studied variables and the way the variables were treated (whether they are effect or causal variables) might have implications for the state of current hydrological research beyond the specific case of hydrological research in Ethiopia. One of these implications relates to the repetitive use of specific cause-and-effect variables while conducting casualty analysis. The most-focused-on cause-and-effect studies are legacy-driven variables, which were proved to have a well-known causality relationship by the scientific literature, and little attention has been given to new insights, relationships, and associations of variables. An example is the tendency to focus only on water physico-chemical characteristics while studying the factors affecting aquatic organism characteristics (Olkeba et al., 2020; Wood and Talling, 1988). There has been also a tendency to focus on the linear relationship of hydrological variables without considering the counter effect of a change in one variable on the other, or validating if the association between variables could work in reverse order. For instance, there is a consideration of anthropogenic factors only as a causal variable, with little attention given to the impact of hydrological factors on the anthropogenic ones (Desta et al., 2017; Getnet et al., 2014). Furthermore, the meta-analysis shows that most hydrological studies, while conducting causality analysis on different hydrological variables, have made limited efforts to establish new empirical relationships. For example, demographic changes have been put forward as evidence of anthropogenic impacts on lake ecosystems without providing measured evidence (Elias et al., 2019; Pascual-Ferrer et al., 2014; Teffera et al., 2017).

4.3. Spatial and temporal variability measurement approaches

Hydrological phenomena and their causal factors change through time and space. Consideration of these dynamics in the research process is of fundamental importance to the reliability of a study (Zhang et al., 2016). In this regard, the reviewed papers vary considerably in terms of research strategies to consider spatial and temporal dynamics, although hydrobiology and water quality studies took approximately the same approach in considering these dimensions. The typical method for consideration of spatial variation was to take water and plankton samples at different locations in the lakes and determine the presence of statistically significant variation in the characteristics of the samples (Kibret and Harrison, 1989; Tamire and Mengistou, 2013; Teklu et al., 2018). The results were, however, less informative on the spatial variation of the variables at different parts of the lake, since the geographical location was rarely considered in the data analysis process. This approach is also not purely experimental and the results might be subject to methodological biases, since they were drawn from observations where the researcher had no mechanism to control all the dependent and independent variables. For temporal change, the research tradition has been to take samples at the same location at different times, typically to reveal seasonal dynamics rather than tracing long-term changes (Gebre Mariam, 2002; Kebede and Belay, 1994), which remains a critical research gap both in the study of hydrobiology and water quality. The absence of routine water quality and aquatic organism monitoring mechanisms in and around the lakes makes it a challenge to conduct space-time analyses.

The typical spatial dimension considered by the hydrogeological studies consisted of taking groundwater samples at different parts of the basin and analyzing them to look for corresponding similarities in their hydrochemical characteristics. The results have been used to define a hypothetical boundary for groundwater flow direction in a basin. There has also been a strong tendency to represent the spatial variation of geomorphological characteristics using geospatial data sources and spatially explicit data analysis approaches (Le Turdu et al., 1999). Studies which considered the temporal dimension have attempted to reveal groundwater flow dynamics by comparing radiocarbon and isotope characteristics of groundwater samples taken from recharge and destination areas of a basin (e.g., Bretzler et al., 2011). In hydrogeological studies, the greatest attention has been directed only to tracing the direction of groundwater flow, with little focus on the estimation of groundwater volume (and flow dynamics) in specific geographical areas (Ayenew et al., 2009).

Paleohydrological studies generally used the same strategy (both in data collection and geospatial data analysis) as the hydrogeological studies when considering the spatial dimension. The only difference was the sample type, with the former using paleoenvironmental samples instead of groundwater, the result being used to analyze the spatial and temporal variation of sediment deposition rates in different parts of the studied basin (Benvenuti et al., 2002; Sagri et al., 2008) The temporal dimension was addressed through estimation of sediment and water ages using carbon radiogenic, stable isotope geochemistry and diatom stratigraphy techniques (Benvenuti et al., 2013; Telford et al., 1999). On the other hand, there were many studies which focused only on the temporal dimension, relying on environmental samples from a single location, or using non-spatially explicit methods of data analysis in representing their result (Legesse et al., 2002).

Among the research themes, lake water storage studies consider the spatiotemporal dimension more frequentely than other themes. The studies in this category used long-term hydroclimate records for estimation of important hydrological variables (Ayenew, 2004; Vallet-Coulomb et al., 2001), which made the majority of them consider the temporal dimension. The spatial dimension was addressed through estimation of areal average climate variables, deriving catchment biophysical variables (Ayenew, 2003; Getnet et al., 2014) and estimation of lake morphometric variables (Awulachew, 2006b; Aynew, 2002), typically using a geospatial data analysis approach. Despite the increasing attempts to consider spatial and temporal variabilities, long term lake water volume estimations still rely on point-based water level records. This, however, could affect the accurate estimation of water volume because of water level variations that result from lake morphometric changes due to sediment erosion and deposition (Håkanson, 1982). The use of 3D-based lake bathymetry datasets and spatially distributed hydrological models would overcome this problem, but these methods are rarely used for water volume dynamics estimation, most likely due to their large data requirements (Duan and Bastiaanssen, 2013).

Studies in the catchment biophysical analysis category used a similar approach to lake water storage studies in measuring spatial and temporal variations (Temesgen et al., 2013). Despite this, most studies failed to present empirical evidence about the magnitude of change of many catchments' biophysical variables (specifically hydroclimate variables). This may be because the data interpretation phase of many studies ended at a descriptive analysis stage (mainly presenting long-term average results) without proving if statistically significant change had happened throughout their study period. In addition, many of the climate change studies, irrespective of their use of different approaches, failed to trace fine-detail temporal and spatial changes, as they relied on climate data from sparse weather observation networks. Despite this challenge, recent advances in geospatial technologies and remote sensing-based weather variable estimation methods are creating an opportunity for increased use of physical-based climate change models. However, the spatial and temporal details are still very coarse when compared to the heterogeneity of many factors affecting climate variables.

4.4. Studies on the different lake ecosystem components

The lake ecosystem is one that is intimately coupled with the land surrounding it in its drainage area. Thus, considering the drainage basin as a unit and as a basic component in the functioning of lakes is an important research approach to address these complex relationships (Wetzel, 2001). With the exception of the lake water storage research theme (where the majority of studies included basin area as a spatial unit of study), most studies failed to adopt this integration, as they were conducted on only one of the two components of a lake ecosystem (either the aquatic or terrestrial parts) or considered them as separate entities in their data analysis. This is one of the notable research gaps of the previous studies, as it limits understanding of the functional relationship between aquatic and terrestrial parts of lake ecosystems, as well as not identifying the root causes of lake water dynamics. The issue is evident in water quality and hydrological studies, where insufficient attention was given to studying the effects of catchment biophysical dynamics on water quality and aquatic ecosystems.

4.5. Frequency of studies in different lakes

The analysis of the number of studies per lake indicates that the greatest focus was given to the rift valley lakes and Lake Tana, with the total number of lakes studied being 27. The total number of lakes in the country has, however, been estimated to be more than 70, which indicates that many of them have been left unexplored by the scientific community. Some examples of lakes missed in the assembled studies include a series of lakes in the Afar triangle region (such as lakes Beda, Liddo-Debado, Yardi and Afambo) and lakes in the southwest of Ethiopia such as lakes Mago, Gesi, Wagaan, Chomen and Granger. The most frequently investigated lakes (Ziway and Hawasa) are those with relatively higher levels of economic significance in terms of lake water usability, as they are less alkaline than the others. The least studied variable for most of the lakes was related to catchment biophysical conditions, indicating lack of emphasis on basin-based studies as well as a pattern of overlooking causal variables.

4.6. Synthesis of results and implication to research gaps

A synthesis of previous studies' findings suggests that much of the existing literature is focused on the understanding of prevailing hydrological conditions and ongoing temporal trends, with less emphasis on quantifying the effect of different causal factors on the hydrological system. There was clearly a consensus that the primary threats came more from anthropogenic than from natural factors. In all the studies, however, quantitative evidence about the contribution of each factor to observed hydrological changes was lacking. Most of the causal claims were based on inference from previous literature and qualitative analysis of perceived causal factors (Ayenew, 2004; Ayenew and Becht, 2008). This makes it difficult to prioritize the different factors of change based on their effect on lake hydrology.

On the other hand, it was found that the results of the studies (specifically those which claimed the prevalence of a stable hydrological state for some lakes) were not in line with the most widely-held views of current lake hydrological conditions. The public perception is that ecosystem degradation has reached its worst-ever levels. However, many studies did not show how bad these impacts are, and some others even claimed that the lakes are resilient rather than being degraded. One of the reasons could be that the severe ecosystem degradation is a relatively recent phenomenon, whereas the studies were done over the last 30 years or more. The other reason could be the coarseness in the temporal and spatial scale of measurements commonly employed to detect ongoing hydrological changes, which might have left undetected micro-scale changes and their accumulated impacts. A case in point is the use of medium and coarse resolution remote sensing products to detect catchment biophysical changes and lake morphometric dynamics, yet little is known about whether changes are really occurring at these resolutions. Likewise, there is doubt as to whether methods used to detect siltation and runoff impacts are sensitive enough to detect micro-level changes. Some of the approaches are not spatially explicit at all, while in others, where the spatial dimension is considered, the data models were developed at a catchment level whereas actual changes happen at a farm plot level, which may be less than a hectare in size (Aga et al., 2018; Gadissa et al., 2018; Legesse et al., 2010). Thus, current change detection methods may only be able to detect changes once the magnitude of the change has become large in size and reached an irreversible stage. We therefore believe that an important scientific endeavor in the discipline of hydrology might be the development of research methods that can detect micro-scale environmental and hydrological changes.

5. Conclusion

In this study, making use of a systematic literature review, we have examined research trends, listed major achievements and identified evidence-based research gaps. We found 231 scientific articles about the freshwater lakes of Ethiopia published in peer-reviewed journals between 1930 and March 2021. Scientific achievements and research gaps vary considerably depending on the research theme. The highest number of studies was found in lake water storage and hydrobiology research themes and the least in paleohydrology. In the water quality and hydrobiology themes the research was almost entirely limited to studying only two variables, namely lake hydrochemistry and aquatic organisms. Other important variables (such as lake morphometry dynamics, climate change) were barely considered. In the lake water storage analysis research theme, the sharpest focus was on estimation of water balance, with less attention to morphometric characteristics of the lakes. Our assessment of spatial and temporal variability indicated that many studies considered only one of the two dimensions, or focused on the attributes of the phenomenon rather than its variability. In terms of study area coverage, the number of studies of smaller highland lakes was very limited, which makes them the least known aquatic ecosystems in the country. Methodologically, the method of information acquisition for some variables was less diverse, as well as far behind contemporary hydrological research methods (e.g., for aquatic organism and lake water hydrochemical characteristics). Based on these and other results we have identified major research gaps which should be prioritized in future endeavors. The results reported here provide useful preliminary information that can guide the formulation of future research activities on the freshwater lakes of Ethiopia.

Further recommended review work includes a critical assessment of the findings of previous studies based on the major research themes. This would add detail to the findings of the current study and reveal more explicit information about the study of freshwater lakes of Ethiopia. A further recommendation is to make a comparison of the results of previous studies to trace historical trends in lake ecosystems based on the chronology of studies. A detailed review of the hydrological models used in these studies, and their compatibility with the context of the freshwater lakes of Ethiopia, is another research topic we identified.

CRediT authorship contribution statement

Yonas Getaneh: Methodology, Investigation, Writing – original draft preparation, **Wuletawu Abera**.: Formal analysis, Validation, Visualization. **Asefa Abegaz**: Supervision., Writing – review & editing: **Lulseged Tamene**: Resources, Conceptualization, Supervision, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix I. Criteria used to categorize articles into different research thematic categories

Main issues highlighted in the topic and abstract	Variables addressed	variable considered as effect/dependent in the research objective	Spatial coverage	Temporal scope	Appropriate research theme
Lake water volume dynamics and the factors affecting them	Lake water storage and volumetric-related variables and the factors affecting them	Lake water volume	Lake based or basin scale	20th century	Lake water storage analysis
The state of one or more biophysical variables in the catchments and their implication for the lakes	Any biophysical variable about catchment landscape characteristics and their causal factor	Catchment landscape characteristics	Catchment only or basin scale	20th century	Catchment biophysical analysis
The study of hydrochemical properties of lake water	One or more lake water hydrochemical variables and their causal factors	Lake water quality	Any	20th century	Lake water quality studies
The state of aquatic ecosystems as affected by lake hydrological characteristics	Characteristics of aquatic organisms in the lakes and the factors affecting them	Aquatic organisms	Any	20th century	Hydrobiology
Groundwater flow characteristics in and around the lakes	Groundwater flow, its volume estimates and hydrochemical characteristics and the causal factors affecting it	Groundwater volume	Any	Any scope	Hydrogeology

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(*continued*)

Main issues highlighted in the topic and abstract	Variables addressed	variable considered as effect/dependent in the research objective	Spatial coverage	Temporal scope	Appropriate research theme
Geological time scale environmental change and basin evolution processes in and around the lakes	Any hydrological variables other than groundwater flow		Any	Geological time scale	Paleohydrology

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101250.

References

Abbate, E., Bruni, P., Sagri, M., 2015. Geology of Ethiopia: a review and geomorphological perspectives. In: Billi (Ed.), Landscapes and Landforms of Ethiopia. Springer, pp. 33–64. https://doi.org/10.1007/978-94-017-8026-1_2.

Abebe, Y., Bitew, M., Ayenew, T., Alo, C., Cherinet, A., Dadi, M., 2018. Morphometric change detection of Lake Hawassa in the Ethiopian rift valley. Water 10, 1–15. https://doi.org/10.3390/w10050625.

Aga, A., Chane, B., Melesse, A., 2018. Soil erosion modelling and risk assessment in data scarce rift valley lake regions, Ethiopia. Water 10, 1684. https://doi.org/10.3390/w10111684.

Aga, A.O., Melesse, A.M., Chane, B., 2019. Estimating the sediment flux and budget for a data limited rift valley lake in Ethiopia. Hydrology 6, 1–23. https://doi.org/10.3390/hydrology6010001.

Alemayehu, T., Ayenew, T., Kebede, S., 2006. Hydrogeochemical and lake level changes in the Ethiopian rift. J. Hydrol. 316, 290–300. https://doi.org/10.1016/j.jhydrol.2005.04.024.

Alemu, M.L., Worqlul, A.W., Zimale, F.A., Tilahun, S.A., Steenhuis, T.S., 2020. Water balance for a tropical lake in the volcanic highlands: Lake Tana, Ethiopia. Water 12, 2737. https://doi.org/10.3390/w12102737.

Asfaw, W., Haile, A.T., Rientjes, T., 2020. Combining multisource satellite data to estimate storage variation of a lake in the Rift Valley Basin, Ethiopia. Int. J. Appl. Earth Obs. Geoinf. 89, 102095 https://doi.org/10.1016/j.jag.2020.102095.

Awulachew, S.B., 1999. Physical morphometric characteristics and capacity curves of Abaya and Chamo Lakes. Zede J. 16, 26–37.

Awulachew, S.B., 2006a. Modelling natural conditions and impacts of consumptive water use and sedimentation of Lake Abaya and Lake Chamo, Ethiopia. Lakes Reserv. Res. Manag. 11, 73–82. https://doi.org/10.1111/j.1440-1770.2006.00293.x.

Awulachew, S.B., 2006b. Investigation of physical and bathymetric characteristics of Lakes Abaya and Chamo, Ethiopia, and their management implications. Lakes Reserv. Res. Manag. 11, 133–140. https://doi.org/10.1111/j.1440-1770.2006.00300.x.

Awulachew, S.B., Yilma, A.D., Loulseged, M., Loiskandl, W., Ayana, M., Tena, A., 2007. Water Resources and Irrigation Development in Ethiopia. IWMI, Iwmi.

Ayenew, T., 2003. Environmental isotope-based integrated hydrogeological study of some Ethiopian rift lakes. J. Radioanal. Nucl. Chem. 11–16. https://doi.org/10.1023/A:1024772621428.

Ayenew, T., 2004. Environmental implications of changes in the levels of lakes in the Ethiopian Rift since 1970. Reg. Environ. Chang. 4, 192–204. https://doi.org/10.1007/s10113-004-0083-x.

Ayenew, T., Becht, R., 2008. Comparative assessment of the water balance and hydrology of selected Ethiopian and Kenyan Rift Lakes. Lakes Reserv. Res. Manag. 13, 181–196. https://doi.org/10.1111/j.1440-1770.2008.00368.x.

Ayenew, T., Gebreegziabher, Y., 2006. Application of a spreadsheet hydrological model for computing the long-term water balance of Lake Awassa, Ethiopia. Hydrol. Sci. J. 51, 418–431. https://doi.org/10.1623/hysj.51.3.418.

Ayenew, T., Becht, R., van Lieshour, A., Gebreegziabher, Y., Legesse, D., Onyando, J., 2007. Hydrodynamics of topographically closed lakes in the Ethio-Kenyan Rift: the case of lakes Awassa and Naivasha. J. Spat. Hydrol. 7, 81–100.

Ayenew, T., Fikre, S., Wisotzky, F., Demlie, M., Wohnlich, S., 2009. Hierarchical cluster analysis of hydrochemical data as a tool for assessing the evolution and dynamics of groundwater across the Ethiopian rift. Int. J. Phys. Sci. 4, 076–090.

Aynew, T., 2002. Recent changes in the level of Lake Abiyata, central main Ethiopian Rift. Hydrol. Sci. J. 47, 493–503. https://doi.org/10.1080/02626660209492949.

Baumann, A., Förstner, U., Rohde, R., 1975. Lake Shala: Water chemistry, mineralogy and geochemistry of sediments in an Ethiopian Rift lake. Geol. Rundsch. 64, 593–609. https://doi.org/10.1007/BF01820685.

Baxter, R.M., Prosser, M.V., Talling, J.F., Wood, R.B., 1965. Stratification in tropical African lakes at moderate altitudes (1,500 TO 2,000 m. Limnol. Oceanogr. 10, 510–520. https://doi.org/10.4319/lo.1965.10.4.0510.

Baxter, R.M., Wood, R.B., Prosser, M.V., 1973. The probable occurrence of hydroxylarnine in the water of an Ethiopian lake. Limnol. Oceanogr. 18, 470–472. https://doi.org/10.4319/lo.1973.18.3.0470.

Belete, M., Diekkrüger, B., Roehrig, J., 2015. Characterization of water level variability of the main Ethiopian Rift Valley Lakes. Hydrology 3, 1. https://doi.org/10.3390/hydrology3010001.

Belete, M., Diekkrüger, B., Roehrig, J., 2017. Linkage between water level dynamics and climate variability: the case of Lake Hawassa hydrology and ENSO phenomena. Climate 5, 21. https://doi.org/10.3390/cli5010021.

Benvenuti, M., Carnicelli, S., Belluomini, G., Dainelli, N., Di Grazia, S., Ferrari, G.A., Iasio, C., Sagri, M., Ventra, D., Atnafu, B., Kebede, S., 2002. The Ziway-Shala lake basin (main Ethiopian rift, Ethiopia): a revision of basin evolution with special reference to the Late Quaternary. J. Afr. Earth Sci. 35, 247–269. https://doi.org/10.1016/S0899-5362(02)00036-2.

Benvenuti, M., Bonini, M., Tassi, F., Corti, G., Sani, F., Agostini, A., Manetti, P., Vaselli, O., 2013. Holocene lacustrine fluctuations and deep CO_2 degassing in the northeastern Lake Langano basin (Main Ethiopian rift). J. Afr. Earth Sci. 77, 1–10. https://doi.org/10.1016/j.jafrearsci.2012.09.001.

Billi, P., Caparrini, F., 2006. Estimating land cover effects on evapotranspiration with remote sensing: a case study in Ethiopian Rift Valley. Hydrol. Sci. J. 51, 655–670. https://doi.org/10.1623/hysj.51.4.655.

Billi, P., Golla, S., Tefferra, D., 2015. In: Billi, P. (Ed.), Ethiopian Rivers. Springer, Netherlands, Dordrecht, pp. 89–116. https://doi.org/10.1007/978-94-017-8026-1_4.

Bretzler, A., Osenbrück, K., Gloaguen, R., Ruprecht, J.S., Kebede, S., Stadler, S., 2011. Groundwater origin and flow dynamics in active rift systems – a multi-isotope approach in the Main Ethiopian Rift. J. Hydrol. 402, 274–289. https://doi.org/10.1016/j.jhydrol.2011.03.022.

Chebud, Y.A., Melesse, A.M., 2009. Modelling lake stage and water balance of Lake Tana, Ethiopia. Hydrol. Process. 23, 3534–3544. https://doi.org/10.1002/hyp.7416.

Cheesman, R.E., 1935. Lake Tana and Its Islands. Geogr. J. 85, 489–502. https://doi.org/10.2307/1785868.
Darling, W.G., Gizaw, B., Arusei, M.K., 1996. Lake-groundwater relationships and fluid-rock interaction in the East African Rift Valley: isotopic evidence. J. Afr. Earth Sci. 22, 423–431. https://doi.org/10.1016/0899-5362(96)00026-7.
Dessie, M., Verhoest, N.E.C., Pauwels, V.R.N., Adgo, E., Deckers, J., Poesen, J., Nyssen, J., 2015. Water balance of a lake with floodplain buffering: Lake Tana, Blue Nile Basin, Ethiopia. J. Hydrol. 522, 174–186. https://doi.org/10.1016/j.jhydrol.2014.12.049.
Desta, H., Lemma, B., 2017. SWAT based hydrological assessment and characterization of Lake Ziway sub-watersheds, Ethiopia. J. Hydrol. Reg. Stud. 13, 122–137. https://doi.org/10.1016/j.ejrh.2017.08.002.
Desta, H., Lemma, B., Gebremariam, E., 2017. Identifying sustainability challenges on land and water uses: the case of Lake Ziway watershed, Ethiopia. Appl. Geogr. 88, 130–143. https://doi.org/10.1016/j.apgeog.2017.09.005.
Dile, Y.T., Karlberg, L., Daggupati, P., Srinivasan, R., Wiberg, D., Rockström, J., 2016. Assessing the implications of water harvesting intensification on upstream-downstream ecosystem services: a case study in the Lake Tana basin. Sci. Total Environ. 542, 22–35. https://doi.org/10.1016/j.scitotenv.2015.10.065.
Duan, Z., Bastiaanssen, W.G.M., 2013. Estimating water volume variations in lakes and reservoirs from four operational satellite altimetry databases and satellite imagery data. Remote Sens. Environ. 134, 403–416. https://doi.org/10.1016/j.rse.2013.03.010.
Duan, Z., Gao, H., Ke, C., 2018. Estimation of lake outflow from the poorly Gauged Lake Tana (Ethiopia) using satellite remote sensing data. Remote Sens. 10, 1060. https://doi.org/10.3390/rs10071060.
Elias, E., Seifu, W., Tesfaye, B., Girmay, W., 2019. Impact of land use/cover changes on lake ecosystem of Ethiopia central rift valley. Cogent Food Agric. 5 https://doi.org/10.1080/23311932.2019.1595876.
Fazzini, M., Bisci, C., Billi, P., 2015. The climate of Ethiopia. In: Billi, P. (Ed.), Landscapes and Landforms of Ethiopia. Springer, pp. 65–87. https://doi.org/10.1007/978-94-017-8026-1_3.
Fetahi, T., Mengistou, S., Schagerl, M., 2011. Zooplankton community structure and ecology of the tropical-highland Lake Hayq, Ethiopia. Limnologica 41, 389–397. https://doi.org/10.1016/j.limno.2011.06.002.
Gadissa, T., Nyadawa, M., Behulu, F., Mutua, B., 2018. The effect of climate change on loss of lake volume: case of sedimentation in central rift valley basin, Ethiopia. Hydrology 5, 67. https://doi.org/10.3390/hydrology5040067.
Gebre Mariam, Z., 2002. The effects of wet and dry seasons on concentrations of solutes and phytoplankton biomass in seven Ethiopian rift-valleylakes. Limnologica 32, 169–179. https://doi.org/10.1016/S0075-9511(02)80006-8.
Getnet, M., Hengsdijk, H., van Ittersum, M., 2014. Disentangling the impacts of climate change, land use change and irrigation on the Central Rift Valley water system of Ethiopia. Agric. Water Manag. 137, 104–115. https://doi.org/10.1016/j.agwat.2014.02.014.
Goll, P.H., 1982. Seasonal changes in the distribution of biomphalaria sudanica sudanica (martens) in lake zwai, ethiopia. Ann. Trop. Med. Parasitol. 76, 159–164. https://doi.org/10.1080/00034983.1982.11687522.
Goshime, D.W., Absi, R., Haile, A.T., Ledésert, B., Rientjes, T., 2020. Bias-corrected CHIRP satellite rainfall for water level simulation, Lake Ziway, Ethiopia. J. Hydrol. Eng. 25, 05020024. https://doi.org/10.1061/(asce)he.1943-5584.0001965.
Grove, A.T., Goudie, A.S., 1971. Late quaternary lake levels in the rift valley of Southern Ethiopia and elsewhere in tropical Africa. Nature 234, 403–405. https://doi.org/10.1038/234403a0.
Grove, A.T., Street, F.A., Goudie, A.S., 1975. Former lake levels and climatic change in the rift valley of southern Ethiopia. Geogr. J. 141, 177–194. https://doi.org/10.2307/1797205.
Haas, T.C., Blum, M.J., Heins, D.C., 2010. Morphological responses of a stream fish to water impoundment. Biol. Lett. 6, 803–806. https://doi.org/10.1098/rsbl.2010.0401.
Håkanson, L., 1982. Lake bottom dynamics and morphometry: the dynamic ratio. Water Resour. Res. 18, 1444–1450. https://doi.org/10.1029/WR018i005p01444.
Hillman, J.C., 1993. Ethiopia: Compendium of Wildlife Conservation Information, Ethiopian Wildlife Conservation Organization and the Wildlife Conservation Society-international New York Zoological Park. Ethiopian Wildlife Conservation Organisation,, Addis Ababa.
Hughes, R.H., 1992. A Directory of African Wetlands. IUCN,.
Joniak, T., Kuczyńska-Kippen, N., Gąbka, M., 2017. Effect of agricultural landscape characteristics on the hydrobiota structure in small water bodies. Hydrobiologia 793, 121–133. https://doi.org/10.1007/s10750-016-2913-5.
Kebede, E., Belay, A., 1994. Species composition and phytoplankton biomass in a tropical African lake (Lake Awassa, Ethiopia. Hydrobiologia 288, 13–32. https://doi.org/10.1007/BF00006802.
Kebede, S., Travi, Y., Alemayehu, T., Marc, V., 2006. Water balance of Lake Tana and its sensitivity to fluctuations in rainfall, Blue Nile basin, Ethiopia. J. Hydrol. 316, 233–247. https://doi.org/10.1016/j.jhydrol.2005.05.011.
Kibret, T., Harrison, A.D., 1989. The benthic and weed-bed faunas of Lake Awasa (Rift Valley, Ethiopia). Hydrobiologia 174, 1–15. https://doi.org/10.1007/BF00006053.
Lamb, H.F., 2002. Multi-proxy records of Holocene climate and vegetation change from Ethiopian crater lakes. Biol. Environ. 35–46.
Lamb, H.F., Leng, M.J., Telford, R.J., Ayenew, T., Umer, M., 2007. Oxygen and carbon isotope composition of authigenic carbonate from an Ethiopian lake: a climate record of the last 2000 years. Holocene 17, 517–526. https://doi.org/10.1177/0959683607076452.
Le Turdu, C., Tiercelin, J.J., Gibert, E., Travi, Y., Lezzar, K.E., Richert, J.P., Massault, M., Gasse, F., Bonnefille, R., Decobert, M., Gensous, B., Jeudy, V., Tamrat, E., Mohammed, M.U., Martens, K., Atnafu, B., Chernet, T., Williamson, D., Taieb, M., 1999. The Ziway-Shala lake basin system, Main Ethiopian Rift: influence of volcanism, tectonics, and climatic forcing on basin formation and sedimentation. Palaeogeogr. Palaeoclimatol. Palaeoecol. 150, 135–177. https://doi.org/10.1016/S0031-0182(98)00220-X.
Legesse, D., Gasse, F., Radakovitch, O., Vallet-Coulomb, C., Bonnefille, R., Verschuren, D., Gibert, E., Barker, P., 2002. Environmental changes in a tropical lake (Lake Abiyata, Ethiopia) during recent centuries. Palaeogeogr. Palaeoclimatol. Palaeoecol. 187, 233–258. https://doi.org/10.1016/S0031-0182(02)00479-0.
Legesse, D., Vallet-Coulomb, C., Gasse, F., 2004. Analysis of the hydrological response of a tropical terminal lake, Lake Abiyata(Main Ethiopian Rift Valley) to changes in climate and human activities. Hydrol. Process. 18, 487–504. https://doi.org/10.1002/hyp.1334.
Legesse, D., Abiye, T.A., Vallet-Coulomb, C., Abate, H., 2010. Streamflow sensitivity to climate and land cover changes: Meki River, Ethiopia. Hydrol. Earth Syst. Sci. 14, 2277–2287. https://doi.org/10.5194/hess-14-2277-2010.
Lemma, B., 2003. Ecological changes in two Ethiopian lakes caused by contrasting human intervention. Limnologica 33, 44–53. https://doi.org/10.1016/S0075-9511(03)80006-3.
Lemma, B., 2009. Observations on the relations of some physico-chemical features and DVM of Paradiaptomus africanus in Lakes Bishoftu-Guda and Hora-Arsedi, Bishoftu, Ethiopia. Limnologica 39, 230–243. https://doi.org/10.1016/j.limno.2008.06.007.
Lemma, H., Frankl, A., Dessie, M., Poesen, J., Adgo, E., Nyssen, J., 2020. Consolidated sediment budget of Lake Tana, Ethiopia (2012–2016). Geomorphology 371, 107434. https://doi.org/10.1016/j.geomorph.2020.107434.
Leykun, A., 2003. The distribution and status of Ethiopian Wetlands: An overview, proceeding of a seminar on the resources and status o f Ethiopia's wetlands.
Markakis, J., 1981. The military state and Ethiopia's path to "socialism". Rev. Afr. Polit. Econ. 7–25.
Mengistie, S., 2021. Historical upheavals of the educational policy formulation and implementation in Ethiopia. pp. 35–57. https://doi.org/10.1007/978-3-030-44217-0_2.
Meshesha, D.T., Tsunekawa, A., Tsubo, M., 2012. Continuing land degradation: cause-effect in Ethiopia's central rift valley. L. Degrad. Dev. 23, 130–143. https://doi.org/10.1002/ldr.1061.
Messager, M.L., Lehner, B., Grill, G., Nedeva, I., Schmitt, O., 2016. Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nat. Commun. 7, 1–11. https://doi.org/10.1038/ncomms13603.
Moges, M.A., Schmitter, P., Tilahun, S.A., Steenhuis, T.S., 2017. Watershed modeling for reducing future non-point source sediment and phosphorus load in the Lake Tana Basin, Ethiopia. 〈https://doi.org/10.1007/s11368–017-1824-z〉.

Molin, P., Corti, G., 2015. Topography, river network and recent fault activity at the margins of the Central Main Ethiopian Rift (East Africa). Tectonophysics 664, 67–82. https://doi.org/10.1016/j.tecto.2015.08.045.

Nilsson, E., 1940. Ancient Changes of Climate in British East Africa and Abyssinia. Geogr. Ann. 22, 1–79. https://doi.org/10.1080/20014422.1940.11880682.

Olkeba, B.K., Boets, P., Mereta, S.T., Yeshigeta, M., Akessa, G.M., Ambelu, A., Goethals, P.L.M., 2020. Environmental and biotic factors affecting freshwater snail intermediate hosts in the ethiopian rift valley region. Parasites Vectors 13, 1–13. https://doi.org/10.1186/s13071-020-04163-6.

Omer-Cooper, J., 1930. 13. Dr. Hugh Scott's expedition to Abyssinia. – a preliminary investigation of the freshwater fauna of Abyssinia. Proc. Zool. Soc. Lond. 100, 195–207. https://doi.org/10.1111/j.1096-3642.1930.tb00973.x.

Pascual-Ferrer, J., Pérez-Foguet, A., Codony, J., Raventós, E., Candela, L., 2014. Assessment of water resources management in the Ethiopian central rift valley: environmental conservation and poverty reduction. Int. J. Water Resour. Dev. 30, 572–587. https://doi.org/10.1080/07900627.2013.843410.

Prosser, M.V., Wood, R.B., Baxter, R.M., 1968. Bishoftu Crater Lakes – a bathymetric and chemical study. Arch. fur Hydrobiol. 65, 309.

Rientjes, T.H.M., Perera, B.U.J., Haile, A.T., Reggiani, P., Muthuwatta, L.P., 2011. Regionalisation for lake level simulation – the case of Lake Tana in the Upper Blue Nile, Ethiopia. Hydrol. Earth Syst. Sci. 15, 1167–1183. https://doi.org/10.5194/hess-15-1167-2011.

Sagri, M., Bartolini, C., Billi, P., Ferrari, G., Benvenuti, M., Carnicelli, S., Barbano, F., 2008. Latest pleistocene and Holocene river network evolution in the Ethiopian lakes region. Geomorphology 94, 79–97. https://doi.org/10.1016/j.geomorph.2007.05.010.

Schagerl, M., 2016. Soda Lakes of East Africa, Soda Lakes of East Africa. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-28622-8.

Searle, R., Gouin, P., 1972. A gravity survey of the central part of the Ethiopian Rift valley. Tectonophysics 15, 41–52. https://doi.org/10.1016/0040-1951(72)90048-0.

Setegn, S.G., Srinivasan, R., Dargahi, B., 2008. Hydrological modelling in the lake Tana Basin, Ethiopia using SWAT model. Open Hydrol. J. 2, 49–62. https://doi.org/10.2174/1874378100802010049.

Seyoum, W.M., Milewski, A.M., Durham, M.C., 2015. Understanding the relative impacts of natural processes and human activities on the hydrology of the Central Rift Valley lakes, East Africa. Hydrol. Process. 29, 4312–4324. https://doi.org/10.1002/hyp.10490.

Stefanidis, K., Papastergiadou, E., 2012. Relationships between lake morphometry, water quality, and aquatic macrophytes, in greek lakes. Fresenius Environ. Bull. 21, 3018–3026.

Szpakowska, B., Świerk, D., Dudzińska, A., Pajchrowska, M., Gołdyn, R., 2022. The influence of land use in the catchment area of small waterbodies on the quality of water and plant species composition. Sci. Rep. 12, 7265. https://doi.org/10.1038/s41598-022-11115-w.

Tahiru, A.A., Doke, D.A., Baatuuwie, B.N., 2020. Effect of land use and land cover changes on water quality in the Nawuni Catchment of the White Volta Basin, Northern Region, Ghana. Appl. Water Sci. 10, 198. https://doi.org/10.1007/s13201-020-01272-6.

Talling, J.F., Talling, I.B., 1965. The chemical composition of African lake waters. Int. Rev. der Gesamt Hydrobiol. und Hydrogr. 50, 421–463. https://doi.org/10.1002/iroh.19650500307.

Talling, J.F., Wood, R.B., Prosser, M.V., Baxter, R.M., 1973. The upper limit of photosynthetic productivity by phytoplankton: evidence from Ethiopian soda lakes. Freshw. Biol. 3, 53–76. https://doi.org/10.1111/j.1365-2427.1973.tb00062.x.

Tamire, G., Mengistou, S., 2013. Macrophyte species composition, distribution and diversity in relation to some physicochemical factors in the littoral zone of Lake Ziway, Ethiopia. Afr. J. Ecol. 51, 66–77. https://doi.org/10.1111/aje.12007.

Teffera, F.E., Lemmens, P., Deriemaecker, A., Brendonck, L., Dondeyne, S., Deckers, J., Bauer, H., Gamo, F.W., De Meester, L., 2017. A call to action: strong long-term limnological changes in the two largest Ethiopian Rift Valley lakes, Abaya and Chamo. Inl. Waters 7, 129–137. https://doi.org/10.1080/20442041.2017.1301309.

Teklu, B.M., Hailu, A., Wiegant, D.A., Scholten, B.S., Van den Brink, P.J., 2018. Impacts of nutrients and pesticides from small- and large-scale agriculture on the water quality of Lake Ziway, Ethiopia. Environ. Sci. Pollut. Res. 25, 13207–13216. https://doi.org/10.1007/s11356-016-6714-1.

Telford, R.J., Lamb, H.F., Mohammed, M.U., 1999. Diatom-derived palaeoconductivity estimates for Lake Awassa, Ethiopia: evidence for pulsed inflows of saline groundwater? J. Paleolimnol. 21, 409–421. https://doi.org/10.1023/A:1008092823410.

Temesgen, H., Nyssen, J., Zenebe, A., Haregeweyn, N., Kindu, M., Lemenih, M., Haile, M., 2013. Ecological succession and land use changes in a lake retreat area (Main Ethiopian Rift Valley). J. Arid Environ. 91, 53–60. https://doi.org/10.1016/j.jaridenv.2012.12.001.

Tibebu Kassawmar, N., Ram Mohan Rao, K., Lemlem Abraha, G., 2011. An integrated approach for spatio-temporal variability analysis of wetlands: a case study of Abaya and Chamo lakes, Ethiopia. Environ. Monit. Assess. 180, 313–324. https://doi.org/10.1007/s10661-010-1790-z.

Urban, E.K., 1969. Ecology of water birds of four rift valley lakes in Ethiopia. Ostrich 40, 315–322. https://doi.org/10.1080/00306525.1969.9639131.

Vallet-Coulomb, C., Legesse, D., Gasse, F., Travi, Y., Chernet, T., 2001. Lake evaporation estimates in tropical Africa (Lake Ziway, Ethiopia). J. Hydrol. 245, 1–18. https://doi.org/10.1016/S0022-1694(01)00341-9.

Wagesho, N., Goel, N.K., Jain, M.K., 2012. Investigation of non-stationarity in hydro-climatic variables at Rift Valley lakes basin of Ethiopia. J. Hydrol. 444–445, 113–133. https://doi.org/10.1016/j.jhydrol.2012.04.011.

Wagner, B., Wennrich, V., Viehberg, F., Junginger, A., Kolvenbach, A., Rethemeyer, J., Schaebitz, F., Schmiedl, G., 2018. Holocene rainfall runoff in the central Ethiopian highlands and evolution of the River Nile drainage system as revealed from a sediment record from Lake Dendi. Glob. Planet. Change 163, 29–43. https://doi.org/10.1016/j.gloplacha.2018.02.003.

Wale, A., Rientjes, T.H.M., Gieske, A.S.M., Getachew, H.A., 2009. Ungauged catchment contributions to Lake Tana's water balance. Hydrol. Process 23, 3682–3693. https://doi.org/10.1002/hyp.7284.

Wetzel, R.G., 2001. Limnology: Lake and River Ecosystems. Gulf professional publishing.

Wondie, A., 2018. Ecological conditions and ecosystem services of wetlands in the Lake Tana Area, Ethiopia. Ecohydrol. Hydrobiol. 18, 231–244. https://doi.org/10.1016/j.ecohyd.2018.02.002.

Wood, R.B., Talling, J.F., 1988. Chemical and algal relationships in a salinity series of Ethiopian inland waters. Hydrobiologia 158, 29–67. https://doi.org/10.1007/BF00026266.

Yang, L., Mei, K., Liu, X., Wu, L., Zhang, M., Xu, J., Wang, F., 2013. Spatial distribution and source apportionment of water pollution in different administrative zones of Wen-Rui-Tang (WRT) river watershed, China. Environ. Sci. Pollut. Res. 20, 5341–5352. https://doi.org/10.1007/s11356-013-1536-x.

Yohannes, Y.B., Ikenaka, Y., Saengtienchai, A., Watanabe, K.P., Nakayama, S.M.M., Ishizuka, M., 2013. Occurrence, distribution, and ecological risk assessment of DDTs and heavy metals in surface sediments from Lake Awassa-Ethiopian Rift Valley Lake. Environ. Sci. Pollut. Res. 20, 8663–8671. https://doi.org/10.1007/s11356-013-1821-8.

Zhang, S., Liu, Y., Li, M., Liang, B., 2016. Distributed hydrological models for addressing effects of spatial variability of roughness on overland flow. Water Sci. Eng. 9, 249–255. https://doi.org/10.1016/j.wse.2016.07.001.

Zinabu, G.M., Kebede-Westhead, E., Desta, Z., 2002. Long-term changes in chemical features of waters of seven Ethiopian rift-valley lakes. Hydrobiologia 477, 81–91. https://doi.org/10.1023/A:1021061015788.