



Review of characterization, factors, impacts, and solutions of Lake eutrophication: lesson for lake Tana, Ethiopia

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Abstract

Lake eutrophication and water quality deterioration have become a major environmental problem in urban areas and fertilized basins in developing countries across the world. This paper reviews the characterization, driving factors, and impacts of lake eutrophication as well as the mechanism of preventing and recovering lake eutrophication with case studies of eutrophic lakes across the world including Lake Tana, Ethiopia. In most waterbodies including lakes and reservoirs, total phosphorus concentration, chlorophyll a concentration, and Secchi disk visibility in association with species composition are the common criteria to classify lakes and reservoir as oligotrophic, mesotrophic, and eutrophic. Nutrient-rich runoff from cultivated land and industrialized and urbanized cities concentrated in phosphorus are the critical factors that drove eutrophication in water bodies. Among others, controlling external loading of nutrient, ecological, and mechanical methods were found to be common mechanisms to prevent and recover lake eutrophication. Avoiding the factors that are under human control, i.e., a reduction of external loading of nutrients especially targeted on phosphorus reduction into the water basins, relocates sewage, industrial and domestic waste discharges to be lined out of the catchment of the lake. Furthermore, motivating the community to use less phosphorus-containing fertilizers and promoting phosphorus-free detergents are suggested solutions to sustainably prevent and reduce eutrophication in the long run. These could be some possible measures to safeguard endangered Lake Tana of Ethiopia.

Keywords Eutrophication · Trophic status · Algal bloom · Nutrient enrichment · Plankton biomass · Self-purification

Introduction

Eutrophication of lakes causes pronounced impairments of water quality in lakes and hence poses significant environmental, economic, and social threats around the world (Kitsiou and Karydis 2011; Lewtas et al. 2015). The problem gets worse and results changes in the lake permanently into land in some parts of the world as industrialization,

urbanization, and agricultural intensification that increases to meet societal needs (Verdonschot et al. 2013). Lake eutrophication has gotten more attention in recent years from the ecosystem, biodiversity reserve, economic, and social perspectives (Yang et al. 2008). Characterization of lake eutrophication has no a clear delineation and distinct criteria. Nevertheless, mostly water bodies including lakes and reservoirs accruing large amounts of plant nutrients are considered as eutrophic. To specify, the amount of dissolved oxygen, species composition of the bottom fauna of the phytoplankton, concentration of nutrients, and various measures of biomass production are considered as criteria in one lake, but in other lakes, criteria like Secchi depth visibility, total phosphorus, and chlorophyll a concentration may be taken. Some lakes may be considered oligotrophic by one criterion and mesotrophic by others (Karydis 2018).

The factors that cause eutrophication may differ from one lake to the other contingent upon the environmental location in which the lake is located (Karydis 2018). However, nutrient-rich runoff from cultivated land use catchments and runoff water from industrialized, populated, and urbanized

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areas are critical factors. On the other hand, the natural process like volcanic eruption and dissolution of mineral rocks underneath which add nutrients is considered as the driver factors (Bertoni 2011). Examining the criteria to be considered to classify lakes' trophic status and identifying the possible factors that cause eutrophication from different lakes perspective are essential to propose an integrated and sustainable approach to prevent eutrophication.

Thus, the main purpose of this review is to provide brief literature survey which summarizes up to date justification on understanding characterization, the major causes, and effects of lake eutrophication to propose a better solution for Lake Tana in Ethiopia. Lake Tana has national and regional economic significance, and it is a UNESCO biodiversity-reserved highland lake (Wondie 2018).

Definition and characterization of lake eutrophication

Eutrophication of lake is a process in which a lake accumulated excessive amounts of plant nutrients. The word originally comes from the Greek word *eutrophos* meaning “well-nourished” (de Jonge and Elliot 2001). A eutrophic lake is relatively over rich in nutrient frequently due to runoff sourced from fertilized land, sewage effluent, and human residential and industrial settlements and results in promoting the growth of algae and other plant life in the lake, which depletes oxygen from the water body. Chemical engineers define eutrophication of a lake as the increase of vegetation in a particular portion of a lake, often caused by the runoff of nutrients (Pathak and Pathak 2012). Whereas ecologists define eutrophication as the upset of aquatic ecosystem with excessive nutrients result in rapid growth of algae and depilation of oxygen. They consider it as an obstinate condition for surface waters (Newman 2013). Limnologists also define as “an increase in the rate of supply of organic matter to an ecosystem.” According to them, in water bodies, the term “organic substance” denotes carbon-based compounds in living or previously living organisms and their leftover products. The environmentalist defines it as a common phenomenon of nutrient enrichment in enclosed lakes and estuaries due to a combination of agricultural runoff and human settlement (Radojevic and Bashkin 1999). Biologists see eutrophic lakes as a lake where one can find “abundant” food (nutrients) will favor “greedy” and quickly developing plants and algae over the body of water (Karydis 2018). As the definition slightly varies as the area of interest of scholars differs, the characterization of lake eutrophication criteria also varies slightly.

Therefore, there is a bias and doubt in its clear delineation and distinct criteria for characterization of lake eutrophication as it is interpreted and understood differently by different experts. However, the overall criteria seem more or less similar except the emphasis given with specific criteria depending on a particular location and geographical setup in which the lake

is found. According to European Union Environmental Directives, nutrient enrichment, increment in primary productivity, hasty algal growth, change in species composition of algae and higher plants, impacts on water turbidity, considerable changes in the dissolved oxygen curve (concentration), and change in fauna biodiversity are considered as a common criteria to characterize eutrophication in all aquatic environments including lake (Andersen et al. 2004; Voulvoulis et al. 2017). According to these criteria, the classification of lakes trophic status is entirely expressed from biotic elements view perspective into five categories that are high, good, sufficient, poor, and bad ecological status. In this classification, the high ecological status lake has an almost undisturbed biological condition whereas a lake which has bad ecological status has a serious alternation of biological quality elements.

In other ways, Horlacher et al. (2012) identified three main criteria for the degree of eutrophication levels. According to their study, total phosphorus concentration, mean chlorophyll concentration, and mean Secchi disk visibility were criteria to classify lake and reservoir as ultra-oligotrophic, oligotrophic, mesotrophic, or hypereutrophic. They indicated that strict boundaries for these classes were often difficult to define. However, based on their criteria, oligotrophic lakes were characterized by poor nutrient enrichment and primary productivity, high clarity of water body, and varied biota. Eutrophic lakes have high nutrient enrichment and primary productivity, low transparency, and high biomass of fewer species with a relatively larger proportion of cyanobacteria. Thus, both of the above characterizations' strategies have no delimited scale for each trophic status levels since both are qualitative and interpreted in a relative way to classified lakes in different trophic level. This is the reason why some lakes considered oligotrophic by one criterion and meso-eutrophic by the other (Carlson and Mar 2007). Even with the same criteria, one lake may be considered as oligotrophic with one scholar and eutrophic by another. A need for advancement on characterization criteria became important that minimizes the overlaps and doubts which relies on numeric bases. Related to this, indexes and guidelines based on numeric value have been developed for classification of lake eutrophication. But, it lacks accuracy (Yang et al. 2008). As Cheng and Li (2006), among the available water parameters, total nitrogen, total phosphorus, and chlorophyll “a” (TN, TP, and chl a “a”) are selected for calculating TNI to classify the eutrophication status of lakes into four categories (Table 1).

$$\text{Here TNI} = \sum w_j \text{TNI}_j, \quad w_j = r_{ij}^2 / \sum r_{ij}^2$$

where TNI is the sum of indexes of all nutrient parameters, TNI_j is the TNI of j parameter, W_j is the proportion of j parameter in the TNI, and r_{ij} is the relation of chlorophyll with the other parameter.

Whereas Tchobanoglous et al. (2003) used simple ranges of concentration of total nitrogen (TN), total phosphorus (TP), dissolved oxygen in hypolimnion (DO % saturation),

Table 1 The burden values of N and P in various eutrophic water

Eutrophic status	TP (µg/L)	TN (µg/L)	Primary productivity	TNI	References
Oligotrophic water	5~10	250~600	5–300 mg C/m ²	0~30	(Yang et al. 2008)
Moderately eutrophic	10~30	500~1100	1000 mg (m ² .d)	31–60	(Cheng and Li 2006)
Eutrophic	30~100	1000~2000	–	61–100	(Richardson et al. 2007)
Hyper-eutrophic	> 100	> 2000	–	> 100	

chlorophyll a and phytoplankton production without indexes to classify lakes and estuaries as oligotrophic, mesotrophic and eutrophic. Their classification is presented in Table 2.

Comparing the two classification criteria, the former classification used four categories of trophic status whereas the second one used three. In addition, the second one employed DO in hypolimnion (% saturation) as criteria for classification, but the first one did not. Moreover, a slight concentration variation, especially in the second classification, may level the lake from one trophic state to the next trophic state. For instance, if you consider total N, a concentration change of 1 µg/L may level the lake which has originally 199 µg/L (oligotrophic) to concentration 200 µg/L (mesotrophic) level with respect to this parameter. The other limitation of this classification is that the lake may be oligotrophic with respect to one of the parameters but may be mesotrophic with respect to the other. In such cases, it is difficult to level the trophic status of the lake compulsively.

Such limitations in classification criteria of the trophic status of lakes led researcher to develop a comprehensive criteria that has resistance for minor concentration change and reported as single numerical value TSI (Barki & Singa 2014). Carlson (1977) cited in Barki and Singa (2014) who developed a numerical trophic state index for lakes that incorporates most lakes in a scale of 0 to 100. Each major division (10, 20, 30, etc.) represents a doubling in algal biomass. The index amount can be summed and considered as a single numerical figure from the three parameters which closely associated to lake eutrophication that are Secchi disk transparency, chlorophyll a, and total phosphorus (Eq. 1). The Carlson (1977) criteria which was used to ranking lakes into three major categories, i.e., oligo, meso, and eutrophic, still have been frequently used by many researchers in the area of aquatic

science. Therefore, in comparison, this classification preferred mostly over the others due to its interrelated parameters and has relatively sharp values and provide information as a single number which needs simple arithmetic (mathematics) to rank lakes based on their trophic status.

$$TSI = \frac{TSI(TP) + TSI(CHL) + TSI(SD)}{3} \tag{1}$$

As Carlson (1977), chlorophyll a is a specific form of chlorophyll in the algae, due to its green pigment the algae used to absorb most energy from wavelengths of violet-blue and orange-red light for photosynthesis. It indirectly indicates how much algae are in the lake. Lakes with a TSI value in the range of 40 and 50 fall in the category of mesotrophic with moderate productivity. Due to its intermediate productivity, there is less algal growth in comparison to eutrophic and comparatively more algal growth to oligotrophic lakes. Lakes with a TSI value that falls greater than 50 fall in the category of eutrophic in which high productivity of algae biomass that results decline of the clearness of the water and gives the water a greenish or brown color, and values less than 40 fall in the oligotrophic state (lower productivity) of the water body and result in the clearest water body.

The United States Environmental Protection Agency (US-EPA) has developed a nutrient criteria approach for lakes and reservoirs to classify them into different trophic status levels and characterize the water quality status of the lakes (USEPA 2000). Several trophic state variables have been proposed by the agency to predict the trophic state of the lakes and to establish criteria to address eutrophication concerns. These include selected primary nutrient concentrations (such as total phosphorus, soluble reactive phosphorus, total nitrogen, total Kjeldahl nitrogen), plant biomass load (Secchi depth, organic

Table 2 Eutrophication criteria for lakes and reservoirs

Parameter	Oligotrophic	Mesotrophic	Eutrophic
Total N (µg/L)	< 200	200–500	> 500
Total P (µg/L)	< 10	10–20	> 20
DO in hypolimnion(% saturation)	> 80	10–80	> 10
Chlorophyll a (µg/L)	< 4	4–10	> 10
Phytoplankton production (gCm ⁻² d ⁻¹)	7–25	75–250	350–700

carbon, chlorophyll a), and regional land use pattern. All these parameters could be used to design specific criteria to formulate water quality and eutrophication concerns. However, chlorophyll a, TP, TN, and Secchi depth were most frequently recommended to characterize the trophic state of the natural and man-made lakes in the USA (USEPA 2009). Hence, four trophic state grades (oligotrophic, mesotrophic, eutrophic, and hypereutrophic) states have been recognized by the agency based on the aforementioned indicator parameters (USEPA 2009).

In 2007 and 2012, the US Environmental Protection Agency (EPA) conducted a national lake assessment (NLA) survey on 50,000 and 1038 lakes respectively so as to identify the current water quality status, biological and habitat conditions, and recreational suitability based on specific indicator parameters. For some of the indicators, results were analyzed against the least disturbed lake, which was acted as a reference lake. Whereas, the trophic state of these water bodies was evaluated by considering four alternative trophic status indicators, namely: Chlorophyll-a, Secchi transparency, Total Nitrogen, and Total Phosphorus. Accordingly, the lakes were classified into four trophic levels (oligotrophic, mesotrophic, eutrophic, and hypereutrophic). Table 3 shows the percentage of lakes that fall into the particular trophic status when individual indicator parameters were used. As it can be seen from Table 3, the four indicator parameters differently classified the status of the lake but the report concluded that chlorophyll a concentration could be the better indicator parameter to evaluate the trophic status of the lakes due to the fact that this indicator relies on the direct measurement of live organisms in the lake than others (USEPA 2009; USEPA 2016).

In addition, for each condition (biological, chemical recreational suitability, and physical), selected indicator parameters were proposed by the NLA crew, and the measured values were compared against a reference lake in which its biological or water quality is closer to its natural state or having list disturbed lake condition or environment. This reference lake could be used as a benchmark for proposing thresholds for the least disturbed, moderately disturbed, and most disturbed or good, fair, and poor condition with respect to the threshold value. A good or least disturbed condition refers to when more than 75% of an

indicator scores value is closely matching with the reference value. Poor condition or most disturbing condition implies when more than 95% of an indicator score values deviate from the reference or threshold values of the reference lake. On the other hand, moderately disturbed or fair condition denotes for those lakes whose indicator values are in-between the two states. Accordingly, the following indicator parameters were proposed for the four conditions. Biological conditions (indicators: sediment diatoms, phytoplankton (algae), zooplankton, benthic macroinvertebrates, algal density, chlorophyll a), chemical conditions (TP, TN, DO, temperature, pH, turbidity, acid neutralizing capacity, salinity, sediment mercury, pesticides), recreational conditions (indicators: pathogens (*enterococci*), algal toxin (microcystins), algal cell counts (Cyanobacteria), algal density (chlorophyll a)), and physical conditions (pathogens (*enterococci*), algal toxin (microcystins), algal cell counts (Cyanobacteria), algal density (chlorophyll a) (USEPA 2000; USEPA 2009; USEPA 2012).

Factors driving lake eutrophication

The factors that drive eutrophication differ from one lake to the other depending on the environmental settings in which the lake is located (Liu et al. 2010). However, nutrient-rich runoff from cultivated land use catchments and runoff of water from industrialized, populated, and urbanized cities including the non-point sources are the major cause of eutrophication across the world (Yang et al. 2008). On the other hand, the natural process like volcanic eruption and dissolution of mineral rocks underneath add nutrients like phosphorus which increase the productivity of the lake are considered as a driving factor in some lakes (Freedman 2014; Liu et al. 2010).

Though nutrient enrichment either anthropogenic or with natural process is taken as the main cause of lake eutrophication, the proportion between total nitrogen with phosphorus and other conditions shall be taken into consideration (Freedman 2014). That means an excessive amount of nitrogen and phosphorus does not lead necessarily to eutrophication unless the optimum condition that leads to eutrophication is fulfilled. The TN to TP ratio is high in oligotrophic lakes

Table 3 The percentage of lakes in the USA by trophic state, when individual trophic state indicators were used

Indicator	Percent of the lakes (in 2007 and 2012) by trophic state				
	Oligotrophic	Mesotrophic	Eutrophic	Hypereutrophic	Reference
Chlorophyll a *	12.8	36.6	30.1	20	(USEPA 2009)
	10%	35%	34%	21%	(USEPA 2016)
Secchi transparency	10.5	22.5	39.8	18.4	
Total nitrogen	22.1	37.5	22	18.4	
Total phosphorus	25	28.8	24.7	21.4	

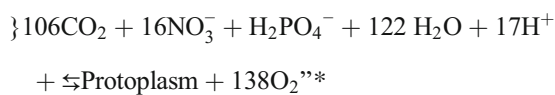
* Oligotrophic (≤ 2 $\mu\text{g/L}$), mesotrophic ($> 2\text{--}7$ $\mu\text{g/L}$), eutrophic ($> 7\text{--}30$ $\mu\text{g/L}$), hypereutrophic (> 30 $\mu\text{g/L}$)

and very low in eutrophic lakes constantly, but this ratio is accompanied by conditions like temperature and light transparency (Downing 1997; Mccauley and Downing 1992). For example, algae bloom in eutrophic lakes is highly related to vertical light structure (Williamson et al. 2011). So, the major factor that causes eutrophication of lake includes (a) nutrient enrichment of phosphate and nitrate; (b) light transmittance, adequate temperature, and water residence time or flushing rate; (c) microbial and biodiversity; and (d) climate change and exploitation of natural resources. The fulfillment of all of these causes directly or indirectly intensifies eutrophication in water bodies including lakes.

Excessive nutrient loads

Studies show that large input of plant nutrients chiefly phosphorus and nitrogen typically from anthropogenic pressure to a water body enhanced lake eutrophication (Bowes et al. 2016; Pathak and Pathak 2012; Yang et al. 2008). The main consequence of enriched of nutrients to the body of water is an imbalance in the food web that result in high levels of algal bloom and phytoplankton biomass in water bodies. This, in turn, results in depletion of oxygen in the lake ecosystem which is toxic for the aquatic community. However, different analogies are there regarding nutrient loads into bodies of water relative to nitrogen and phosphorus in connection with their contribution to be the causes of eutrophication.

- A. Phosphorus is usually the limiting agent in algal growth, and much of it is released from point sources such as sewage works and runoff from fertilized catchments is considered as the main factor for the cause of eutrophication in comparison to nitrogen. See the reaction equation of algal bloom.



- B. The low lake TN: TP ratio considered as a cause of the eutrophication process and responsible for most of the lake trophic state change. That means the TN to TP ratio varies with lake trophic state. The TN to TP ratio is high in oligotrophic lakes and very low in eutrophic lakes.
- C. The positive relationship of N (TN) to total P (TP) exists in the pelagic zone of variety of the world’s lakes.

The excessive enrichment of N and P are a crucial factor for the process of eutrophication in lakes. However, the critical and significant is the phosphorus input into the body of water that aggravates eutrophication in bodies of water including lakes. As it is indicated in chemical equation (*), phosphorus is limiting element in the production of protoplasm. Studies

which have focused on the assessment of the trophic status of lakes showed that in the vast majority of lakes, the limiting element is phosphorus for growth of algal biomass (Le et al. 2010; Morabito et al. 2018; Yang et al. 2008). According to these studies, phosphorus is taken the limiting element for the growth of algal biomass and phytoplankton, and the concentration of total phosphorus is taken into account to estimate a trophic state index of lakes. It was also indicated in China in more than 40 Yangtze lakes that the phosphorus is the critical factor controlling primary productivity including phytoplankton growth regardless of nitrogen concentration. In this report, primary productivity and total phytoplankton biomass are estimated based on total phosphorus, not by total nitrogen concentration (Wang and Wang 2009).

On the other side, primary productivity and the growth of phytoplankton biomass are influenced by the ratio of TN:TP (Ryther and Dunstan 1971). The N:P ratio 16:1, that is present in elemental atomic ratios in plankton O:C:N:P (276:106:16:1; $106\text{CO}_2 + 16\text{NO}_3^- + \text{H}_2\text{PO}_4^- + 122 \text{H}_2\text{O} + 17\text{H}^+ + \text{Protoplasm} + 138\text{O}_2$), is maintained under maximal growth rates in nutrient-poor waters and is considered as reference value (Karydis 2018). The variation from the reference N to P ratio can be associated with eutrophication problems.

In most lakes of the world, it is found that there is a positive correlation between N (TN) and total P (TP). That means, lakes enriched with phosphorus also they are enriched with nitrogen (Elser et al. 2007). If the slop of this relationship is constant, the N to P ratio is not taken as a factor to rank the lake trophic status. However, oligotrophic or eutrophic lakes have divergent N to P ratios. For instance, consider city Park Lake in USA ratio (2:1) and Chivero Lake in Zimbabwe ratio (6.5:1) (Elser et al. 2007).

In general, nitrogen and phosphorus deposition in lakes play a great role to accelerate eutrophication, but significant eutrophication took place due to phosphorus input. For this, we can consider as an example the eutrophication prevalent in many Great Lakes of North America in 1950 (Yang et al. 2008). According to this finding, phosphorus is often the limiting factor responsible for eutrophication and phytoplankton growth in the Great Lakes of North America, since nitrogen fluxes in these lakes were found relatively large. Therefore, the crucial point as a factor for lake eutrophication is nutrient accumulation in the body of water; basically, phosphorus takes the lion share. Thus, this gives a clue to identify the critical factor for proposing a mechanism to protect lake eutrophication.

Physical factors

One important feature to consider in a lake or reservoir eutrophication is the flushing rate of the lake which is explained by

exchange rate of water that enters into the lake and that discharges from the lake. The average residence time of the water in the lake can be determined using the volume of water present divided by the flow rate into the lake or discharged from the lake. Under peak flow circumstances especially in the open lake, the average residence time of water will be smaller which could hinder the growth of slow-growing phytoplankton such as cyanobacteria, yet more nutrients and pollutants could be carried into the water body (Hudnell 2008; Paerl and Huisman 2008). Here evapotranspiration will also facilitate or inhibit the residence time of water both in open as well as in closed lake system. It is noticeable that the duration in which the water spent in closed lakes is much longer than in open lakes. That is why many closed lakes are frequently exposed to eutrophication than the open ones. Research reports by Cook et al. (2005) and Krzyk (2015) indicated that some lakes are exposed for tidal effects and prone to containment, because of their outlet; they are regularly renewed and very unlikely to become eutrophic. In such lakes, self-purification of the lake regularly takes place due to the short residence time of the polluted water.

On the other hand, thermal stratification in standing water bodies (such as reservoirs, lakes, and lagoons), temperature, light transmittance or clarity of water body, and depth of water influences the development of aquatic algae and phytoplankton. The optimum temperature is associated with adequate sunlight energy penetration through depth of the water profile to undergo photosynthesis that results in an algal bloom. Particularly, the temperature is an important variable because the rate of chemical and biological processes differs as temperature differs. Mostly, high temperature can lead to longer growth periods and favor cyanobacterial growth (Paerl and Huisman 2008). That is being the case, increased catalytic light and temperature conditions during spring and summer explains why eutrophication is a phenomenon that happens mainly during these seasons. Once eutrophication happened, eutrophication itself affects the penetration of light through the water body because of the shadow effect coming from the development of algae and other living organisms, and this reduces photosynthesis in deep water layers and aquatic grass and weeds bottom development. In general, closed lakes are more often prone to eutrophication than open lakes across the world. For instance, in South Africa, a study by the Council for Scientific and Industrial Research (CSIR) using remote sensing has shown that more than 60% of the dams surveyed were eutrophic since the water from the dams were limited to freely discharged and refresh itself (Mark and Stewart 2015).

Biodiversity and microbial dynamics

Conservation of biodiversity for the functioning of a “healthy” ecosystem is important since a healthy ecosystem enables to resist and recover from disturbance. On the contrary, loss of

biodiversity leads to a disturbed ecosystem which is described as an invasion of alien species, loss of ecological networks, and improper functioning of natural stimuli response in the ecosystems like prey and predator relations. Such unnatural relations, especially in the aquatic environment, result in unbalancing microbial activity that results in algae bloom which is a sign of eutrophication (Karydis 2018). For example, Lake Chad which is located in the border of Nigeria, Cameroon, and Chad is exposed to unnatural relations in the aquatic environments. This lake comprises of unique mix of terrestrial and aquatic biodiversity even though most of its large mammal species have been hunted virtually to extinction. According to Ebenki (2015), crocodiles and hippos were particularly important agents for maintaining a healthy wetlands ecosystem. Today, however, the replacement of these mammals with cattle has severely degraded the wetlands ecosystem. That is why Lake Chad’s level has varied greatly over time and shrunk from 22000km² to 300km² in the last four decades (Ebenki 2015).

Overexploitation of natural resources and climate change

The natural cycle in aquatic environment upsets due to human intervention; this may lead to the dominance of one species over the others that disturb the natural process of oxygen exchanges and other nutrients cycles. Especially, the overexploitation of natural resources related to upset of the ecological balance of the aquatic system leads to eutrophication (Ansari and Gill 2014). Overexploitation of natural resources especially those related to ecological imbalance is considered as one factor that accelerates eutrophication in lakes by reduction of self-purification capacity of lakes (Ansari and Gill 2014). It is identified that lakes accumulate large quantities of solid material (sediments or sands) transported by the inflow rivers. The deposition of sediments or sands is used naturally to absorb and filtrate large amounts of nutrients and pollutants. However, exploitation of these sediments usually sands for construction purpose upsets the self-purification capacity of lakes (Koehnken et al. 2020). In other words, the assimilation capacity of pollutants (usual nutrients) by the lake declines, this in turn, aggravate eutrophication. On the contrary, excess accumulation of sediments also has a negative effect. Once the sediments start to fill the basin and increasing the interaction between water and sediment, the resuspension of nutrients present at the bottom of the basin is facilitated. This phenomenon could, in fact, lead to further deterioration of water quality accentuating the processes connected with eutrophication (Koehnken et al. 2020).

Some studies pointed out that occurrences of climate changes could affect lake eutrophication due to the fact that surface water quality is expected to deteriorate in response to global warming (Mitchell 2013; Moss 2014). Due to complicated and non-linear processes in lake water, it difficult to

understand the exact mechanism of the consequence of climate change and global warming on water eutrophication. However, few studies have anticipated that climate change and global warming effects had led to arise in toxin-producing cyanobacteria algal blooms in freshwater ecosystems (Paerl 2014; Paerl et al. 2004). In the same studies, it is indicated that the increasing temperatures and more intense rainfalls expected with climate variation will also aggravate mineralization of nutrients from catchment soils and increase soil erosion (Adrian et al. 2009; Moss 2014).

Though nutrient load is a primary factor that drives eutrophication once it is reaching a constant level in water bodies, increase in some phenomenon such as temperature, precipitation, wind velocity, and radiation from sunlight are believed to raise the risk of water eutrophication (Rolighed et al. 2016; Rui et al. 2012; Schabhüttl et al. 2013). Therefore, climate change which is explained in terms of changes in precipitation, temperature, wind speed, and incoming solar radiation will directly impact water quality by effecting changes in stream flow and water temperatures. That means nutrient input in lakes and estuaries is directly proportional to runoff water caused due to heavy precipitation in the catchment (Rui et al. 2012). If the runoff water around the catchment area increases, the probability of transporting nutrient into the water bodies also increases. The high temperature often aggravates the growth of cyanobacteria than other phytoplankton species (Alves-de-Souza et al. 2015; Schabhüttl et al. 2013). In general, nowadays, the number of lakes liable to eutrophication is much more than before due to climate change (Adrian et al. 2009; Alves-de-Souza et al. 2015; Freedman 2014; Paerl et al. 2004; Rolighed et al. 2016; Rui et al. 2012). Figure 1 shows the schematic representation of factors driving lake eutrophication.

Impacts of lake eutrophication

Lake eutrophication is followed by several consequences ranging from economic loss to biodiversity losses (Freedman 2014). Economic losses can arise from the loss of tourism revenue, navigation and boating opportunities, loss of property value due to esthetic issues, costs to maintain a disturbed ecosystem that is impacted by eutrophication, costs related to taste-and-odor problems with drinking water, and costs related to fishing. In addition, social issues can be linked back to the environmental and economic issues like loss of recreation, and loss of the esthetic values of lakes and other water bodies can negatively affect many people. However, many studies describe the impact of lake eutrophication commonly with a change in physical and chemical water quality and ecological parameters (Ansari and Gill 2014; Tibebe et al. 2019; Worku and Sahile 2017).

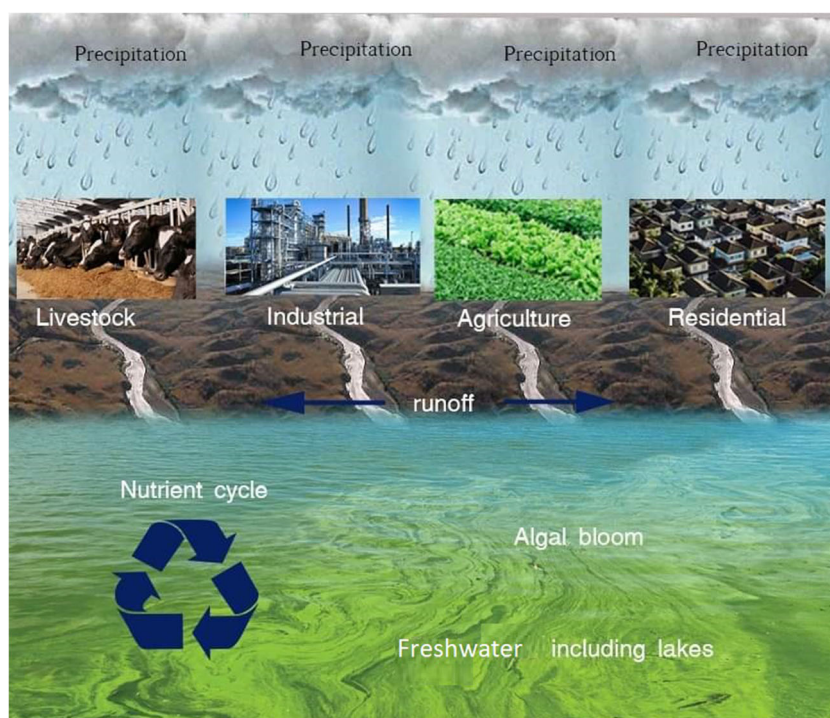
Deterioration of water quality

Deterioration in water quality is described by changes in physicochemical water quality parameters (Alobaidy et al. 2010; Tibebe et al. 2019). It has been noted that the physicochemical water quality parameters change considerably as the trophic status of waterbody changes. In most eutrophic lakes, the physicochemical water quality parameters deviate from the normal surface water quality standards set by EPA. For example, Alobaidy et al. (2010) assessed and examined the historical changes in water quality of Dokan Lake in Kurdistan region, Iraq, for 10 selected water quality parameters. In their assessment and examination turbidity, pH, total solids, conductivity, hardness, alkalinity, dissolved oxygen, biochemical oxygen demand, and nitrite and nitrate were taken and examined in the collected water samples across time in three sample locations in the lake. After performing their computation on the experimental value of the test results for water quality index values, the computed annual WQI values ranged from 53.18 in the year 2000 to 101.26 in the year 2009 and, therefore, can be classified and labeled into “Good water” in the year 1978, 1979, 1980, 1999, 2000, and 2008 to “Poor water” in the year 2009. But it was generally observed that 14, 80.50, and 5.50% of all monthly computed WQI values from 1978 to 2009 have labeled under “Excellent,” “Good,” and “Poor” water quality, respectively. The WQI values were calculated by considering values of each of ten water quality indicators against the national and international standards as well as collective expert opinions from previous studies. Based on these, lake water quality is labeled as Excellent, good, poor, very poor and unsuitable if WQI <50; 50–100; 100–200; 200–300 and >300 respectively (Alobaidy et al. 2010). However, the authors did not link the WQI values with eutrophication status of the lake.

Ecological impacts

Chemical and physical water quality parameters in most case considered as a criterion to show the impact of eutrophication on the lake ecosystem (Alobaidy et al. 2010; Tibebe et al. 2019). Though these parameters are not quite complex to level each trophic status of lakes, they interact each other, and their concentration show inconsistency fluctuation ranges as a variation in space and seasons. Therefore, the ecological impacts of lake eutrophication are considered as relatively consistency and with minimal range of fluctuation. Among these common ecological impacts observed during eutrophication in lakes and that facilitating primary production, decreased biodiversity, changes in species composition and dominance, and toxicity are the primary ones (Ansari and Gill 2014; Cronberg 1982; Hering et al. 2013; Karydis 2018; Vandekerckhove and Cardoso 2010).

Fig. 1 Schematic representation of factors driving lake eutrophication



Degradation of biodiversity

During the initial stage of eutrophication, some species such as algae experience a population increase (called an algal bloom) and aggravate the eutrophication process. The increment of algae bloom limits the sunlight available to bottom-dwelling organisms and causes wide swings in the amount of dissolved oxygen in the water. Thus, in lakes and estuaries which are affected seriously by eutrophication, the algae and the plant community finally dies off, settles to the bottom of the lake, and decomposes (Ansari and Gill 2014; Estep and Reavie 2015). When the aquatic plant community dies, the oxygen is taken up from the body of water and is then used up for facilitating the decaying process of the dead plant communities (Williamson et al. 2011). In the decomposition process, the organisms that crack down the phytoplankton biomass use up all of the remaining oxygen left at the bottom of the lake or estuaries. “When dissolved oxygen levels fall to hypoxic levels, fish and other aquatic animals choke (Reynolds 2006; Williamson et al. 2011). As a result, creatures such as fish, shrimp, and especially immobile bottom dwellers die off.” Some species of fish are disappeared (die off) due to the oxygen dropout, and this seriously affects biodiversity in the lake ecosystem. Whereas most of the remaining fish species often move far to other large bodies of water due to the upset of their original habitat. This can influence the new and older bodies of water because these latest species of fish have become invasive species. If some of these insidious species were strong and predatory, the new

body of water would suffer because many of the fish community would die to be sources of food for the new fish community. This would bring a consequence of new fish community emergent in the new lake ecosystem and would also reduce some of the species of fish that had previously made that body of water their territory (Meena and Jha 2018).

Changes in species composition and dominance of alien species

Changes in species composition and dominance are an extension of the impact of eutrophication on the decline in biodiversity because a decline in biodiversity is accompanied by changes in species composition and dominance of another species usually alien species due to natural process (Meena and Jha 2018). As it is indicated in European Water Framework Directives (WFD), alien species constitute a major pressure in aquatic environments, both ecologically and economically (Vandekerhove and Cardoso 2010).

The alien species are introduced in the lake ecosystem in most case after the serious effect of eutrophication in the lake or estuaries. As a consequence, the eutrophication may cause aggressive effects by making abundant a normally limiting nutrient. To make brief this section, we can take an example from the history of Lake Ontario for two periods or two trophic status conditions as reported by Estep and Reavie (2015). In the first period, i.e., “Pre-European Settlement (1650s to 1750): Species are identified to be tolerant to eutrophic conditions (e.g., *C. atomus*, *A. granulata*) and common

in nutrient-enriched water bodies such as oligotrophic to mesotrophic lakes and reservoirs (e.g., *A. distans*, *C. ocellata*, *C. bodanica*, *A. italica*) were fairly abundant, inferring that the lake was naturally oligotrophic to mesotrophic, and seasonally productive” were observed, and in the second period, i.e., “In the period 1830–1900: Phytoplankton production increased by the end of the period along with diatoms favoring enrichment (e.g., *A. granulata*, *C. stelligera*, *A. islandica*), summer blooming (e.g., *C. comensis*), and eutrophics conditions (e.g., *F. crotonensis*). Oligotrophic diatoms declined” were observed (Estep and Reavie 2015).

Measures to prevent lake eutrophication

The theories of ecological resilience and recovery indicated that once lake eutrophication occurred, it took more time, higher costs, and intensive energy to restore it to its original trophic status (Andersen et al. 2004; Gunderson 2000). These studies advise to focus on prevention mechanism rather than restore a eutrophic lake. The common and most suggested prevention mechanism on this area are generalized in three parts. The first one is controlling nutrient loads more targeting on phosphorus reduction which includes catchment management, restructuring of industrial layout, and inhabiting of human intervention. The second one is mechanical methods which include in lake remediation including physical, biological, and chemical application. The third one is employing an ecological mechanism which includes ecosystem restoration, oxygenation, shellfish introduction in estuaries, and seaweed farming.

Controlling nutrient loads targeted on phosphorus reduction

Controlling nutrient load focuses on phosphorus reduction which is the best mechanism to prevent lake eutrophication compared to the others and often suggested by many researchers on this area (Paerl et al. 2004, 2018; Wang and Wang 2009; Yang et al. 2008). However, this measure employed in different ways which include nutrient reduction focused on either phosphorus reduction only or reduction both phosphorus and nitrogen, catchment management to control diffused sources of nutrients, and restructuring industrial layout to control point sources including sewage treatment facility and inhabiting human intervention. In fact, all techniques that are catchment management, industrial layout restructuring, and inhabiting human intervention are under the category that aimed at the reduction of external loading of nutrients into the lake.

As Cook et al. (2005), eutrophication is typically prevented by controlling nutrient inputs. For instance, to restore Lake Washington in North America, Seattle (USA) from this problem, the diversion of municipal wastewater results in a

reduction of TP and algal biomass followed by increases in transparency and deep water oxygen (Edmondson 1994; Edmondson and Lehman 1981). During 1930s sewage inflow into the lake enhances the in-lake phosphorus concentration and aggravates the lake eutrophication. Consequently, for the period 1955 to 1976, bloom of cyanobacteria covered the portions of the lake. The diversion of sewage focusing on phosphorus reduction has been put in practice and ended all sewage input before 1968. After this sewage diversion, total phosphorus concentration decreased significantly from 0.07 mg/L in 1968 to 0.02 mg/L in 1979.

This is also again proved in China, lake restoration experiment practice that focuses only on phosphorus control mitigate eutrophication (Wang and Wang 2009). The diversion experimental project of Lake Xihu has been put in to practice since 2003. In this experiment, River Qiantangjiang is diverted into various regions for treatment before joining the Lake Xihu. Before the preliminary treatment, there were high TN and TP of 3.08 mg/L and 0.13 mg/L, respectively, in 2005. After the treatment, TN and TP became 2.07 mg/L and 0.04 mg/L which revealed that in the treatment process phosphorus was markedly reduced compared to nitrogen. But phytoplankton and algal biomass in the lake was low. Therefore, the experimental project of Lake Xihu proved that reduction targeting in phosphorus can effectively mitigate eutrophication.

There are more examples of lakes across the world recovered from eutrophication by phosphorus reduction only (Ahlgren et al. 1988; Schindler et al. 2008; Wang et al. 2006). To mention Vollenweider (1976), cited in Paerl et al. (2004), developed a model with many years of research on the effect of nutrient additions on lake productivity. In his model, the data from most of the lakes and reservoirs that had been studied in the world accurately predicted trophic status based only on input rates of one nutrient (P). This was very critical and considered as positive support for mitigation of eutrophication by reduction of phosphorus only. According to Schindler et al. (2008), to mitigate eutrophication, reducing nitrogen loading cannot inhabit the phytoplankton biomass rather only phosphorus reduction can recover the lake from eutrophication and inhabit cyanobacterial growth. Actually, this is linked to the chemical reaction expression of algal bloom in eutrophic water body, i.e. $\{106\text{CO}_2 + 16\text{NO}_3^- + \text{H}_2\text{PO}_4^- + 122\text{H}_2\text{O} + 17\text{H}^+ + \text{Protoplasm} + 138\text{O}_2\}$ in this chemical equation the limiting reagent is phosphorus, so controlling phosphorus enables to control the growth of protoplasm in algae. That is why phosphorus reduction is critical when we talk about external loading of nutrients into water bodies.

On the other hand, reduction in external loading of both nitrogen and phosphorus simultaneously mitigate lake eutrophication. It was reported that around 10% of the world's lake and reservoir eutrophication is associated with nitrogen, and

80% is linked to phosphorus enrichment. Also, the composition and growth of phytoplankton biomass are affected by the ratio of nitrogen and phosphorus (Reynolds 2006). As indicated in Hodgkiss and Lu (2004), if the ratio of N to P is 16:1, P is likely the limiting agent for algal growth, but lower ratios imply that N is limiting one in the protoplasm ($C_{106}H_{263}O_{110}N_{16}P$) molecular representation. Recent studies also indicated that certain harmful algal taxa thrive and are even potentially more toxic in the aquatic environment, in conditions where N is disproportionately available relative to P (USEPA 2015). So even if the significance is not like that of phosphorus reduction, reduction of nitrate has its own contribution in controlling eutrophication in lakes and estuaries.

In general, controlling external loading of the nutrient can be practiced in different mechanisms: The first one is catchment management to control diffused sources of nutrients from runoff water from fertilized lands. This can be possible by regulating the nutrient sources, reducing the use of fertilizers or using less phosphate-rich fertilizers, proper soil management practices, altering land use practices in the watershed, and constructing vegetative buffer zones and wetlands in the peripheries of the lake and reservoirs. The second one is restructuring industrial layout to control point sources including sewage treatment facility. This can be practiced by implementing environmental impact assessment studies before any industry is planted. And, if there is also wastewater/sewage treatment plant in the peripheries of the lake and reservoir, it should be controlled and discharged based on the permissible limit of surface water quality standards. The same rules should have to apply also for industrial waste discharges. The third one inhabits human intervention in the catchment of the lake or reservoir perspires. This would be possible awareness campaign to keep the balance of the ecosystem like curbing deforestation because of land use changes from forest to cultivated land, overgrazing of animals, overfishing, and related activities which upset natural biodiversity of the lake ecosystems and the perspire.

Mechanical methods

Permanent restoration of lake eutrophication can effectively be achieved by reducing the external loading of nutrients sufficiently (Lewtas et al. 2015). But this may not be effective sometimes due to the continuing of internal loading of nutrients from the lake itself and atmospheric deposition of nitrogen from the atmosphere. Thus, it is suggested to use multiple lake restoration techniques like mechanical methods to prevent the lake from further eutrophication. Mechanical methods of lake restoration include mainly physical and some chemical applications techniques. However, this one also has limitation since it is applied more to small surface area lakes in addition to having some negative side effects of the chemical application methods. The physical methods have no negative

side effects rather it is not easy for application at a larger scale. This method involves both strategies that involve before eutrophication and post-eutrophication. In case of pre-eutrophication, optimize the use of fertilizer based on crop requirement supported with regular testing of soils. Because some soils may have naturally high P status which can be used for a longer period so further addition of phosphorus is not relevant in such case. Moreover, we can use also alternative sources of fertilizer which have slow release tendency of phosphorus.

Dilution and increasing flushing rate, aeration and oxygenation, artificial circulation, dredging and removal of sediment, and mechanically removal of phytoplankton biomass are the strategies to restore the lake and reservoir to its original trophic status in the post-eutrophication case. However, these techniques are not liable to address problems in the larger surface area lakes and reservoirs like Lake Tana with a lake surface area of 3041 km² and watershed of 15,100 km². According to Mitrovic et al. (2003), in hydrological cycle of a water body, flushing rate is related to purification capacity, i.e., flushing rate increment decreases the residence time of water to provide less time for the slow-growing cyanobacterial blooms that may be used to restore eutrophic water bodies. However, it is limited to small size lakes, and it does not effectively recover the lake in the long run alone unless it has to be done with a supplement of reduction of external loading of nutrients. So, the mechanical methods shall be undertaken in parallel to the reduction of external loading of nutrient. We can take as an example Lake Trummen, a small size lake in Sweden with lake area of ~1 km², mean depth of 1.6 m, and watershed of ~13 km². So, this lake experienced CyanoHAB water quality deterioration in response to domestic effluent and industrial discharge nutrient inputs during the mid-1900s. To recover this lake, removal of nutrients stored in the sediments using suction dredging of the upper half meter of sediments during a 2-year period has been utilized (Cronberg 1982).

Even though Cook et al. (2005) suggested that chemical methods are harmful to the ecosystem and may not be considered as a long-run solution, chemical methods which involves the addition of flocculants like aluminum sulfate and addition of algaecides like copper sulfate have been practiced in small surface area lakes and reservoirs to restore the lake from eutrophication. For example, the addition of algaecides like copper sulfate controls algae by the destruction of the phytoplankton cell in the water body practiced in some lakes and reservoirs even though the algaecides may pose a threat to human health as well to the lake and reservoir ecosystem (Hudnell 2010). Chemical flocculants like aluminum sulfate are applied in lakes to reduce soluble phosphorus from eutrophic water. However, it needs repeated addition as this makes the addition of aluminum sulfate flocculent to be expensive in addition to that it creates an acidified environment in the body of water that is toxic and fatal to fish community and other organisms

(River and Region 2016). In general, both the physical and chemical mechanical methods may be used as a strategy to relieve the stress of eutrophication in small size and shallow lakes temporarily, but it is not a solution for a long run unless it is associated with a reduction of external loading of nutrients.

Biological and ecological methods

The biological and ecological methods include different approaches with natural bases. It is considered as ecological management strategies in general that leads to ecological solutions. This set of methods includes periphyton photosynthesis, phytoremediation, seaweed plantation, predators of phytoplankton, and restores shellfish. The first three are done by manipulation of plant species in water body whereas the latter two approach introduction of animal species in the water bodies (Wagner and Erickson 2017). Theories which base in biological methods suggest that this method would be good if it is applied in site-specific cases rather than it is applied uniformly to all lakes or reservoirs experience eutrophication (Xiao et al. 2017). Periphyton photosynthesis is a method employed to reduce P from the waterbody including P uptake, P deposition, and filtering particulate P from the water during the photosynthesis process. In parallel, in this process, due to an increment of pH with one-unit precipitation of calcium phosphate, the formation of and deposition of carbonate-phosphate complexes increment will enhance retention and deposition of P so that phytoplankton growth is inhibited in the water body. Seaweed farming like that of periphyton absorbs phosphorus and nitrogen from the water body, and it is also useful to remove nutrients from over-fertilized parts of the sea (Xiao et al. 2017). The phytoremediation follows the same approach as the above-mentioned, aquatic macrophytes species such as *Eichhornia crassipes* and *Salvinia auriculata* that cause the considerable decline of phosphorus and nitrogen compounds in the water body. For example, plantation of aquatic higher plant, the common duckweed that effectively reduces (up to 60%) the content of nutrients (N, P) in municipal effluents, was observed before the effluent enters the water system in Lithuania and served as biological assay water treatment (Arias et al. 2016). Jiang et al. (2007) indicated that harvesting of the species *Phragmites communis* and *Zizania latifolia* in wetlands receiving nonpoint source pollutants remove 463–515 kg hm⁻² N and 127–149 kg hm⁻² of P each year.

On the other side, animal introduction such as predators of phytoplankton and restore shellfish in lake or reservoirs are approaches which are practiced by employing animals to decline phytoplankton bloom in the water bodies. For example, restore shellfish populations such as oysters and mussels have a tendency to remove nitrogen from the waterbody and filter out suspended solids subsequently reducing the likelihood occurrence of harmful algal growth used as a proposed

solution to eutrophication especially in estuaries and reservoirs (Jiang et al. 2007). As reported in Carpenter et al. (2010), bio-manipulation lake eutrophication management technique changes the food web, to favor large zoo planktonic grazers that control algal biomass. According to this technique, the food web manipulation is done by removing planktivorous fishes that consume grazers or by stocking piscivorous fishes that consume planktivores. However, in this technique, the whole lake experimental result designed to test the contention that grazer control alone was ineffective with increasing in P loading. For instance, we can consider the result of this experiment as a case example to elaborate on this method by taking the two situations: “the chlorophyll concentration of the Planktivore lake rose as predicted by the Vollenweider model, whereas, the chlorophyll concentration of the Piscivore lake was less than half the prediction of the Vollenweider model. Chlorophyll in the Piscivore Lake was significantly less than that of the Planktivore lake, even though the concentration of phosphorus (P_m) in Piscivore lake was almost twice as high as that of the Planktivore lake. However, the biomass of the blue-green algae increased markedly in both lakes upon enrichment of P in the Planktivore lake and Piscivore lake. In both P enriched lakes, mean biomass of blue-green algae exceeded 2 g/m³, a level symptomatic water quality problems” (Conform et al. 1995). Thus, this experimental result implied that the biological methods should be associated parallel with external loading phosphorus reduction to be fully effective. Hence, we have to look for an approach which is holistic and integrated, and ease of application for the larger surface area with the complex ecosystem as well as for the small surface area with the simplified ecosystem as the conclusion of this paper. Table 4 summarizes the measures taken to prevent lake eutrophication, their advantages, limitations, and the ecological impacts they have.

Lake Tana and its present condition

According to Singh et al. (2006), the major treats of Africa’s lakes include but not limited to land use/cover changes due to rapid population growth, depletion of water resources through pollution, deforestation, overgrazing, soil erosion, and invasive alien species. For example, Lake Chad which is located on the border of Nigeria, Chad, and Cameroon over the past four decades has reportedly shrunk from 22,000 to 300 km². Eutrophication of Lake Victoria is clearly linked to the rapid population growth and changes in land use pattern which were happened in the lake catchments that constitute 250,000 km² of total area. To mention one specific case related to this lake, about 150,000 km² of the catchment has been exposed and affected by soil degradation since 1980 due to this land has been utilized for agriculture. Moreover, in Lake Victoria, nearly much of the land has diverse and fragile ecosystems

Table 4 Measures to prevent lake eutrophication

Method category	Measure taken	Ecological impact	Advantage	Disadvantage	References
Controlling nutrient loads targeted on phosphorus Reduction	Diversion of municipal wastewater and	Reduction of TP, algal biomass and phytoplankton	Very simple	Has no visible disadvantage	(Edmondson 1994; Edmondson and Lehman 1981)
	Catchment management	It is attractive and improves water quality	Simple	It needs community engagement, long time process and expensive	(Arheimer et al. 2005)
	Dilution and flushing	Improves water quality and slow-growing cyanobacterial blooms, fish abundance will increase	Simple and fast	Expensive; availability of the clean source water is required; limited to small size with shallow lakes	(Mitrovic et al. 2003; Zhang et al. 2020)
Mechanical methods	Sediment dredging	Unwanted toxic substance may expose to the lake from the sediment; disturb the sediment's natural environment	State forward	Not applicable for long-term control; very expensive	(Fan et al. 2004)
	Mechanical removal of phytoplankton	Leftover dead phytoplankton pollutes the water body unless completely removed	Simple	Incur high cost; limited to small size lakes	(Zhang et al. 2020)
Biological and ecological methods	Use of copper CuSO ₄ , aluminum sulfate, herbicides, and algicide	Harmful to the ecosystem; accelerate the aging of the lake	Simple and quick effects	Cannot be used for long-term solution (used for immediate solution); expensive; results in secondary pollutant or residues; suitable for small-scale lakes only	(Hudnell 2010; O'Dell et al. 1995; Schindler et al. 2008; Zhang et al. 2020)
	Periphyton photosynthesis, phytoremediation, seaweed plantation, predators of phytoplankton and restores shellfish	–	Maintain a stable ecological environment; do not generate secondary pollutant; less risky; significantly reduce pollutants; sustainably effective	Suitable for small-scale lakes; needs length of time to establish the system; incurs maintenance cost; the latter two techniques are ineffective with increasing in P loading	(Conform et al. 1995; B. Q. Qin et al. 2013; Schindler et al. 2008; Shan et al. 2009)

Table 5 Land use land cover of Lake Tana basin across time

Type of land/use/cover	Percentage of coverage across time		
	1973	1986	2001
Forest land	10.1	9.9	3.6
Built up land	3.5	4.5	7.2
Bush land	8.5	2.6	2.1
Grassland	17.0	20.2	9.0
Cultivated land	60.0	62.3	77.5

that need to be protected and managed. Despite these adverse conditions, however, major population increases have led to in the widespread cultivation of these fragile pockets of land which is a major sign of land use transformation/change accelerating the degradation of the entire lake ecosystem. The infestation of Lake Victoria by water hyacinth in the 1990s is a consequence of both population pressure and land use change in the lake catchments that disrupted transportation and fishing, clogged municipal water pipes, and created a habitat for disease-causing insects in the perspire of the lake (Mitchell 2013; Ebenki 2015; Singh et al. 2006).

Lake Tana (Fig. 2), which has a higher surface area and complex ecosystem lake in east African region and the largest freshwater lake in Ethiopia, nowadays is exposed to dynamic land use/cover shifts across time and also vulnerable to water hyacinth invasion like that of Lake Victoria. The land use or land cover of Lake Tana changed across time significantly as it is presented in Table 5.

(Kidane Biru et al. 2015)

As shown in Table 5, forest and grassland coverage significantly reduced from 10.1 and 17.0% in 1973 to 3.6 and 9.0 in 2001. Beside these, the natural forest which is characterized by dominantly dry evergreen Afromontane and riverine forest in some locations replaced by Eucalyptus species which is the main species of plantation forests (Chuangye et al. 2018). This directly exposed the watershed for erosion and result in nutrient enrichment in the lake. As a result, sign of algae bloom and growth of cyanobacteria over the surface of the lake have been investigated since 2011 in association with an invasive of alien species commonly called water hyacinth (Dersseh et al. 2019a). A 2015 report by Anteneh (2015) indicated that more than 34,500 ha portion of Lake Tana was covered by water hyacinth. The photo which shown coverage of water hyacinth compiled in the report is presented in Fig. 3 and Fig. 4.

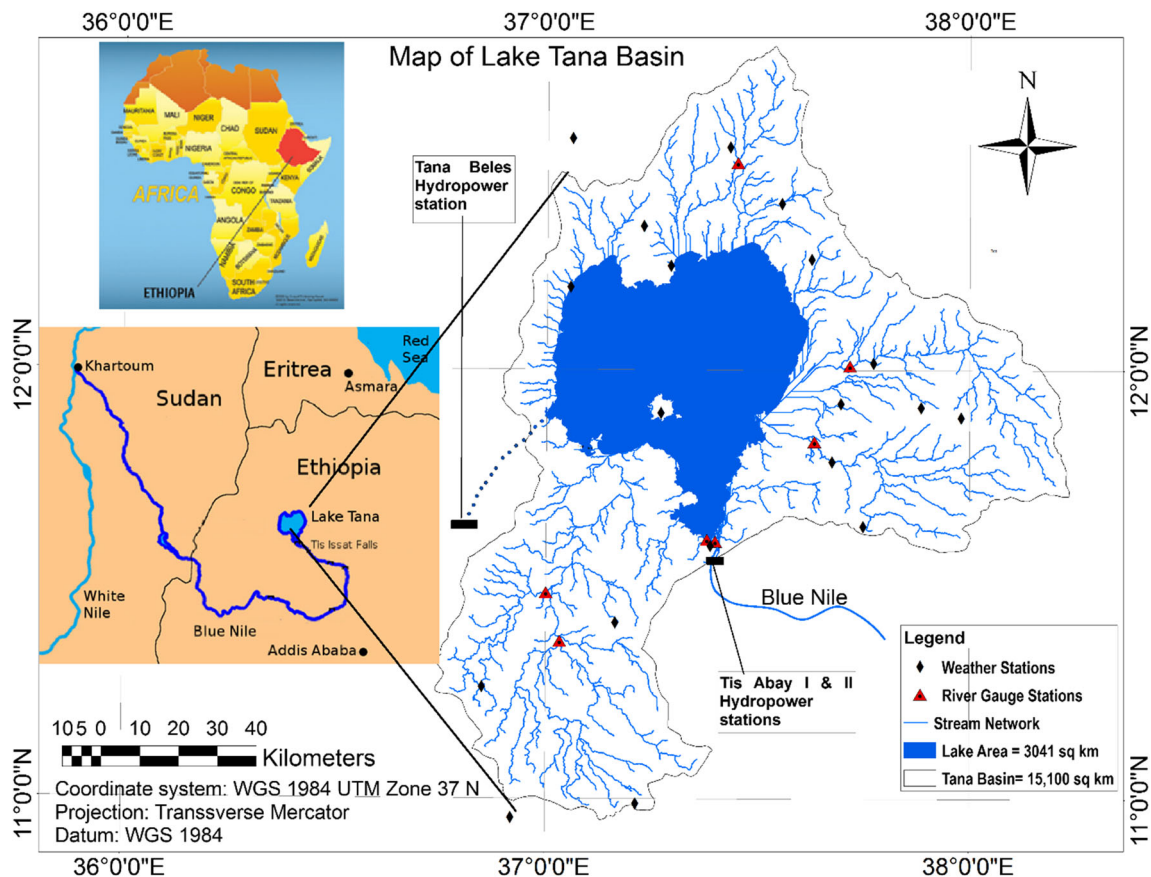


Fig. 2 Lake Tana basin with total area of 15,100 km²

Fig. 3 Thick water hyacinth covered shore in Achera kebele (Anteneh 2015)



Several reports have been made on external loads of nutrient and water quality status of Lake Tana (Alemu et al. 2017; Ewnetu et al. 2014; Tibebe et al. 2019), ecological condition and the coverage of water hyacinth (Dersseh et al. 2019a, 2019b; Wondie 2018), and algal bloom and trophic status of the lake (Moges et al. 2017; Tibebe et al. 2019; Wondie 2018). In summary, the results found by the above reports are presented in Table 6. The reports linked to the surface water quality status of the lake indicated in Table 6 used different indexes. However, all these reports have shown deterioration in water quality of the lake with time which could be associated with non-point sources, sediment, and nutrient inflow and high erosion rate from the watershed especially from the agricultural sector (Alemu et al. 2017; Moges et al. 2017). In the same reports, the authors have suggested mechanisms to improve the water quality of the lake, which include but not limited to soil and water conservation strategies, reducing recession agriculture adjacent to the lake and wetland management practices

Fig. 4 Algal blooming particularly in water hyacinth infested areas of Lake Tana (Anteneh 2015)



As indicated in Table 6, the authors (Anteneh 2015; Ayalew 2014; Dersseh et al. 2019b) have reported the water hyacinth coverage and infestation, factors considered as the cause for it and possible solutions for Lake Tana. The water hyacinth coverage was significantly different in the different years as indicated in the table. The difference might be due to variation in the removal mechanisms adopted at that time. Moreover, the data obtained from the office called “Tana and other water bodies protection and development Agency of Ethiopia” indicated that 20,000 ha, 24,090 ha, and 5396 ha were covered by water hyacinth in the year 2012, 2017, and 2018, respectively. The Agency also indicated that in the same year i.e., 2012, 2017, and 2018 respectively of 20,000 ha, 22,286.84, and 4962.5 ha of the weed were removed from the lake by human labor and simple mechanistic machines (Fig. 5). Nevertheless, these efforts did not bring solutions; rather its infestation has been drastically increased (Charitable Organization for Integrated Tana Basin Development 2018; Wondie 2018). Even if its exact sources

Table 6 Water quality, water hyacinth coverage, and trophic status of Lake Tana

Parameter	Status	Factor	Solutions	Reference
Surface water quality of the lake	Poor (using Canadian water quality index)	External loading of nutrient	Tillage of natural wetland should be inhabited	(Ewvnetu et al. 2014)
Water hyacinth coverage	Moderately polluted in dry and slightly polluted in the wet season (comprehensive pollution index) 50,000 ha 34,500 ha	Excessive agrochemical input from agricultural activities industrial influents from the watershed An infestation of weeds during flood plain through the major tributary rivers Nutrient-rich runoff from the flood plain adjacent to the lake during the rainy season will favor the rapid growth of this deadly weed especially in river mouths	Management of agrochemicals in the lake watershed Integrated method. Applying machines in the deep part of the lake and manual in the shallow Implement the manual removal operation as urgent and purchasing mechanical harvesters, establishing biological control research setup to test chemical applications as long-run solutions Management of agrochemical in the watershed	(Tibebe et al. 2019) (Dersseh et al. 2019b) (Anteneh 2015)
	Eutrophic using Carlson TSI	Excessive agrochemicals inputs from agricultural activities and industrial influents from the watershed		(Tibebe et al. 2019)
	Oligotrophic in spring season and mesotrophic for the other seasons using Carlson TSI	Sediment and nutrient inflow, rapid population growth and agricultural intensification, land degradation	Soil and water conservation moreover reducing recession agriculture around the lake and wetland management	(Moges et al. 2017)



Fig. 5 Removal of water hyacinth with human and simple mechanistic machines. (photo credited to Tana and other water bodies protection and development agency (2018))

is not well-known in Ethiopia, it was observed for the first time in Lake Tana in 2011 (Anteneh 2015), and the factors responsible for the expansion of this weed in the lake could mainly be associated with external loading of nutrient-rich runoff from the upstream watershed agricultural activities during the rainy season (Table 6). And physical camping including human labor and using simple mechanical machines have been implemented as urgent solutions for removal of the weed. Hence, biological control and application of chemical methods with research setup facilities are recommended as long-run solutions.

The trophic status of Lake Tana was reported at different times. The reports by Moges et al. (2017) and Tibebe et al. (2019) had used the Carlson trophic classification index to indicate the state of the lake (Table 6). They also indicated the factors associated with the change of the trophic status and recommend possible solutions for Lake Tana. From the report, Moges et al. (2017) used Carlson trophic state index model focusing on chlorophyll a, total phosphorus, and Secchi depth transparency to estimate the trophic state of the lake for the four seasons. They estimated that the trophic state of Lake Tana was found mesotrophic with TSI ranges from 40 to 60 in autumn, mesotrophic with TSI range 60–70 in winter, oligotrophic with TSI range 30–40 in spring, and mesotrophic

with TSI range 60–70 in the summer season. Whereas Tibebe et al. (2019) estimated the trophic state of the lake using the Carlson trophic state model by manipulating total phosphorus, sech depth transparency, and chlorophyll-a for the dry and wet seasons only. They found that Lake Tana was a eutrophic lake with a value of TSI above the minimum value of eutrophic lake with a TSI value above 69.77. Even if the value of TSI was not indicated, Dersseh et al. (2019b) also shown that Lake Tana was in a state of eutrophic conditions. External loading of nutrients and agrochemicals from the watershed adjacent to the lake via the four major rivers during the wet season was considered the main factor to aggravate the eutrophication of the lake. Wetland management, reducing recession agriculture and management of agrochemicals in the watershed, and constructing buffer zone around the lake were the suggested solutions to change the current trophic status of the lake.

Unlike Lake Victoria, Lake Tana is showing a decrease in water quality and worsening in trophic status since 2017 (Moges et al. 2017). However, Lake Victoria has significantly shown an improvement in water quality and trophic state from sever eutrophication which was in the 1980s to less eutrophic in 2010 (Sitoki et al. 2010). Consequently, the biodiversity and millions of people who relied on Lake Tana are as a source of life are endangered because Lake Tana found in a region where the population pressure is increasing over time as a result of its land use and land cover changed significantly across time (Worku and Sahile 2017). Thus, collaborative efforts have to be made in addition to the earlier efforts to fight against this invasive species. Besides, it is better to consider the conclusions driven from this literature review as part of a strategy to save the lake from eutrophication as well as invasive alien species or water hyacinth.

Conclusions

Even though there are several methods and mechanisms to prevent lake eutrophication, identification of strategies that are practically applicable to prevent the problem sustainably for large and complex ecosystem lakes is one of the implications expected to be obtained from this review. Moreover, the similarity of the conditions like population pressure and land use and land cover changes across time in perspiring of some lakes such as Lake Tana and Lake Victoria inspires researcher to drive solutions to save them from further invasion of water hyacinth and eutrophication. Hence, in these regards, most of the mechanical and chemical methods and even some of the biological methods are not easily applicable and viable for such a great lake such as Lake Tana. It has been noted that the traditional eutrophication reduction strategies, including the alternation of excess nutrients, physical mixing of water, and application of powerful herbicides and algacides, have proven futile, expensive, and not viable. As such, it is needed

to propose long lasting and a holistic and integrated approach to prevent lake eutrophication before the lake is eutrophic. Because, restoration of big eutrophic lake is too complex, takes longer time, energy intensive and causes loss of economy. Thus, it is wise to propose strategies which have an integrated and holistic nature and encompass and focuses on preventive measures. Therefore, depending on the literature survey, the following integrated and sustainable strategies are suggested.

External nutrient reduction approach This approach aims at reducing the external input of nutrients into the water basins. This can be done by identification of all nutrient sources and reduce, relocate, and if possible, cut the sources. In that case, some primary information of the catchment area of the water source has to be known in advance. This includes but not limited to knowledge of agricultural practices (fertilizer usage pattern in terms of type and frequency, amount of plant cultivation pattern, and localization), industrial activities, domestic waste type, and discharge practices of the watershed and vegetation type. So, based on the collected information, if possible, relocate sewage discharges to be lined out of the catchment of the lake watershed, use less phosphorus content fertilizers, promote phosphorus-free detergents, and setting permissible limits to industries or sewage treatment plants (if any) to practice in their waste discharges.

Win-win approach Nonpoint pollution is the most difficult source of nutrients to manage, and this pollution is the primary contributors to eutrophication, and when these sources are controlled, eutrophication decreases as suggested in several literatures. Therefore, to decrease their effects, the best mechanism is the win-win approach which advocates the practice of taking preventive measures of lake eutrophication in parallel mutually benefited from the measures taken in the long run. This can be easily practiced through common agricultural practices such as favored horizontal plunging rather than vertical, constructing terracing in the agricultural field, unfertilized grass buffer strips (or broad hedges) along watercourses and ditches, prevention of erosion of sloping soils, use of slow-release fertilizers, afforestation, reduce grazing of animals, constructing buffer zones, and reduce recession agriculture adjacent to the lake by motivating the farmers living around the basin to cultivate permanent fruit trees and bee-keeping activities. In doing these, soil fertility will be enhanced, soil erosion will be reduced, ecosystem of lake biodiversity will be improved, and native and native species of the lake will be maintained. As a result, recreational and esthetic value will be enhanced. As an example, it is better to see the implication of the European WISER project output (Water bodies including lakes and reservoirs in Europe: integrative systems to assess ecological status and recovery of a lake ecosystem (Hering et al. 2013).

Mechanical approach Finally, if the lake or reservoirs are geographically located in which the number of populations is high and faced in risk of intense eutrophication, it is commendable to remove the algae biomass and alien invasive species like water hyacinth found in lakes by mechanical means including human labor as well as simple mechanistic machines.

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Compliance with ethical standards

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