Dynamics of Eutrophication and Its Linkage to Water Hyacinth on Lake Tana, Upper Blue Nile, Ethiopia: Understanding Land-Lake Interaction and Process

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Abstract. The increasing population has put an immense pressure on our natural resources leading to water pollution and land degradation. The need for new agricultural areas, urbanization and industrial development have been responsible for resources degradation and pollution. Eutrophication can be resulted due to substantial driven enrichment of seasonal cycle of nutrients like phosphorus and nitrogen. So, this study is aimed at evaluating the (1) spatial and temporal dynamics of eutrophication on Lake Tana, (2) linkage between eutrophication and water hyacinth infested area (3) lake-land linkage of nutrients and water hyacinth infestation. To evaluate the dynamics of eutrophication, the samples were taken from 143 points at 0.5 m depth of the lake in August (2016), December (2016) and March (2017). To see the lake-land linkage of nutrients, two major nutrients (P and N) were collected at the major tributary rivers. The trophic status index of TP, SDD and Chl-s was determined by adopting Carlson's model by using spatial analyst tool of ArcGIS. The result of this study showed that the trophic status index of the lake is shifting from mesotrophic to eutrophic condition. The growth of the invasive weed in the northeastern part of the lake is caused by the spatial distribution of nutrient and eutrophication as well as the depth, wind direction

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and the extent of large floodplain. This study will help to manage and control the pollution of Lake Tana and the expansion of water hyacinth.

Keywords: Eutrophication · Spatial distribution · Trophic sate index · Geographic information system (GIS) · Lake Tana · Water hyacinth

1 Introduction

Increasing population is the main cause of water pollution through the increased sewage and garbage, expanding agriculture practices (application of pesticides, herbicides and fertilizer) and rapid industrialization (effluents and hazardous waste) (Sheela et al. 2011). Water can play a great role in transformation energy within an ecosystem, facilitate the weathering process of rocks during the formation of soil, transport nutrients, regulate temperature in the atmosphere and used as a detergent of pollutants and particulate matters (Khan and Ansari 2005). The basic pollutants of water bodies, which can be extracted from different sources of water bodies are Phosphorus and Nitrogen (Penelope and Charles 1992; Hinsely and Jones 1990; Cunha et al. 2013; Teshale et al. 2002).

In etymology, eutrophic meant "good nourishment" and eutrophication meant the process by which water bodies being more productive for the growth of phytoplankton (Ferreira et al. 2011). Eutrophication is the sum of the effects of the excessive growth of phytoplankton caused by nutrient enrichment through runoff that carried down excessive application of fertilizers in agroecosystem and human wastes from settlements or it is a plant growth facilitating process resulting from accumulation of nutrients in lakes or other water bodies (Khan and Ansari 2005; Harper et al. 2008). Eutrophication changes the status of water quality parameters substantially and significantly (Penelope and Charles 1992).

Eutrophication is caused by enrichment of seasonal cycle of nutrients like P and N in water bodies (Bricker et al. 2003). Chlorophyll-a is a biological indicator of eutrophication in coastal and deep-water bodies (Bricker et al. 1999, 2003, 2005, 2008; Kowalewska et al. 2004). Turbidity affects the eutrophication and its process of water bodies. The reduction of water transparency can shift macrophyte communities from submergent to canopy forming, to floating leaved and then to emergent vegetation (Chambers 1987; Moss 2009; Niemer and Hubert 1984; Sand-Jensen 1997; Van Den Berg et al. 1999). Lakes in turbid stable state can shift from dominant of submergent species and clear water to dominant of emergent species and high turbidity (Scheffer et al. 2001). High total dissolved solids (TDS) indicates the cultural eutrophication which is the process that speeds up natural eutrophication because of human activity (Vijayvergia 2007). According to Vijayvergia (2007), lakes which have less than 100 mg l-1 TDS could be classified as Oligotrophic whereas lakes which have more than 100 mg l-1 TDS could be classified as Eutrophic lakes.

The release of phosphorus from aerobic sediment surface to the trophogenic zone in summer, which is made up the major fraction of the total phosphorus load in shallow lakes can be influenced by temperature and pH (Jensen and Andersen 1992). The internal loading of phosphorus is an important mechanism in delaying the recovery of shallow lakes which is followed by reduced external loading of phosphorus (Ryding 1985).

Previous studies showed that substantial amount of sediment is transporting from its catchments to the lake (Setegn et al. 2010; Zimale et al. 2016; Lemma et al. 2018).

According to Lemma et al. (2018), the rate of sedimentation of Lake Tana is 11.7 ± 0.1 kg m-1 yr-1 and its trap efficiency is estimated about 97%. The sediment load transported from the to the lake and flood plains has implications on nutrient transportation and facilitates the eutrophication process of the lake.

Lakes can be classified as Oligotrophic, Mesotrophic and Eutrophic with sub classifications within each class according to the Trophic Status Index (TSI) of Total phosphorus (TP), Chl-a and Secchi Disc Depth (SDD) (Carlson 1977; Sheela et al. 2011). According to Carlson (1977); Sheela et al. (2011), lakes can be classified in to three main categories (Oligotrophic, Mesotrophic and Eutrophic) and four possible classes (Oligotrophic, Mesotrophic and Eutrophic and hypereutrophic). The classification of lakes based on the values of Trophic State Index (TSI) is oligotrophic for TSI $<30-40$, Mesotrophic for TSI $40-50$, Eutrophic for TSI $50-70$ and Hypereutrophic for TSI 70–100+. In the other hand, the trophic status of water bodies can be classified based on the numerical values of TP and Chl-a concentration of lakes (Jolankai and Biro 2008).

The dynamic nature of the trophic status of Lake Tana and its linkage with water hyacinth infesting area was not well known. Even though the data was limited, a few previous studies showed that the trophic status of the lake was in transition condition from Oligotrophic to Mesotrophic (Moges et al. 2017; Nagelkerke 1997; Teshale et al. 2002; Wondie et al. 2007; Wubneh 1998). The study will play a great role in designing strategic plan to control and manage the infestation of water hyacinth in Lake Tana. The objectives of this study were to (1) valuate the spatial and temporal dynamics of eutrophication on Lake Tana (2) evaluate the linkage between eutrophication and water hyacinth infested area and (3) evaluate the lake-land linkage of nutrients and water hyacinth infestation using the nutrient concentration of major rivers.

2 Materials and Methods

2.1 Study Area

The Lake Tana region is situated in the northern part of the Ethiopian Highlands in Amhara National Regional State, Ethiopia. Lake Tana is the largest lake in Ethiopia and is the third largest lake in Africa. The Lake is registered as a World Natural Biosphere Reserve Heritage by UNESCO in June 2015. Its basin has a total area of 1.5 million hectares and out of this, 55% is cultivated, 21% is water, 10% is grassland and 1.6% is the wetland (Heide 2012). Geographically it is situated between latitude 10°58′–12°47′N and longitude 36°45′–38°14′E (Fig. 1), the watershed consists of 347 Kebeles and 21 Woredas (districts) in four administrative zones (IFAD 2007). The surface area of the lake is approximately 3078 to 3080 km^2 and stretching approximately 84 km north-south and 66 km east-west. Located at an elevation of 1840 masl it is also the highest lake in Africa. Its maximum depth is 15 m with a decreasing trend due to siltation and lowering water level.

Lake Tana Basin accounts for 50% of the inland water to the Blue Nile. The lake basin has a drainage area of approximately 15,096 km^2. The lake has 40 tributaries (rivers and streams), on which Gilgel Abay, Ribb, Gumara and Megech account for 93% of the total inflow (Setegn et al. 2008). According to UNESCO 2011, the lake was formed 20 million years ago by a lava extrusion that functions as a natural reservoir.

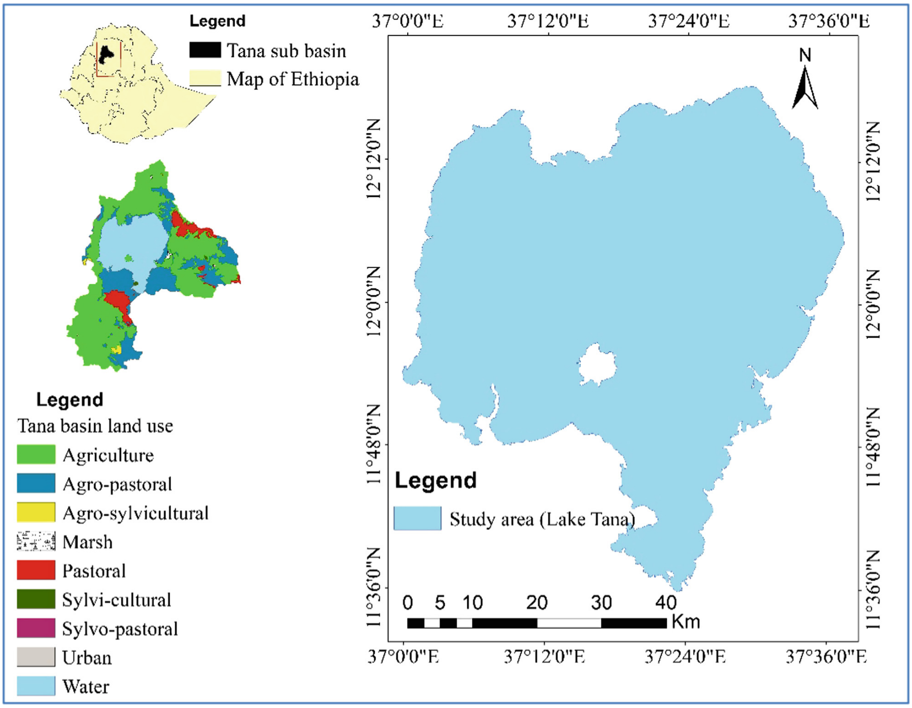

Fig. 1. Lake Tana and the land use map of its Basin in the Upper Blue Nile area, North Western Ethiopia

2.2 Dataset and Data Collection Methods

To achieve the objectives of this study, three water quality parameters such as total phosphorus (TP), Chl-a and Sechi Disc Depth (SDD) on the lake and two water quality parameters (phosphate and nitrate) on major tributary rivers were collected from primary and secondary sources. The water quality data on the lake was collected from 143 sampling points in August, December (2016) and March (2017) in 5 km interval and 0.5 m depth from the surface of the lake.

Transparency of the water was measured by a Secchi disc of 20 cm in diameter. The maximum depth at which the disc can be seen when lowered into the water is marked and measured. Total phosphorus (TP) concentrations were determined using PhosVer®3 based on Acid per sulfate digestion method in the range of 0.06–3.50 PO_4^{3-} $mgP.L^{-1}$. Digestion was realized at 150 °C for 30 min respectively for TP. The absorption was then measured using HACH product DR.2008 and DR.3900 spectrophotometer at the wave length of 410 nm and 890 nm for TN and TP respectively.

Chlorophyll-a concentrations were determined by acetone extraction method after sample filtration on 0.47 μm glass fiber filter (Whatman GF/C) using Gellman polycarbonate filtration towers, under low to moderate vacuum (10–40 cm Hg). Extracts were clarified by centrifugation at 4000 rpm for 20 min. Sample and standard absorbance were read at 750 and 664 nm before acidification (750b and 664b) and 750 and 665 nm after acidification (750a and 665a). Chlorophyll-a concentration in the extract was determined with spectrophotometer using the standard method of Perkin-Elmer Lambda 35 UV/VIS spectrophotometer with a 1 nm spectral band width and optically matched 4 cm plastic micro-cuvettes (APHA 1988).

The number of sampling was determined based on its representativeness and the availability of budget for data collection in the lake and laboratory expenses. Phosphate and nitrate from Gilgel Abay, Gumara, Rib, Megech and Dirma rivers were collected in August, November, January (2011), March, May (2012) and July (2013) by Tana Sub Basin Authority (TaSBo). The aim of the data from the river was to see the land-lake linkage of the major nutrients in the basin and the infested area of the lake by the invasive weed. Additional input data was the shape file of the lake and the geographical coordinates of each sampling points to predict and display the spatiotemporal variability of eutrophication on the lake by using interpolation techniques.

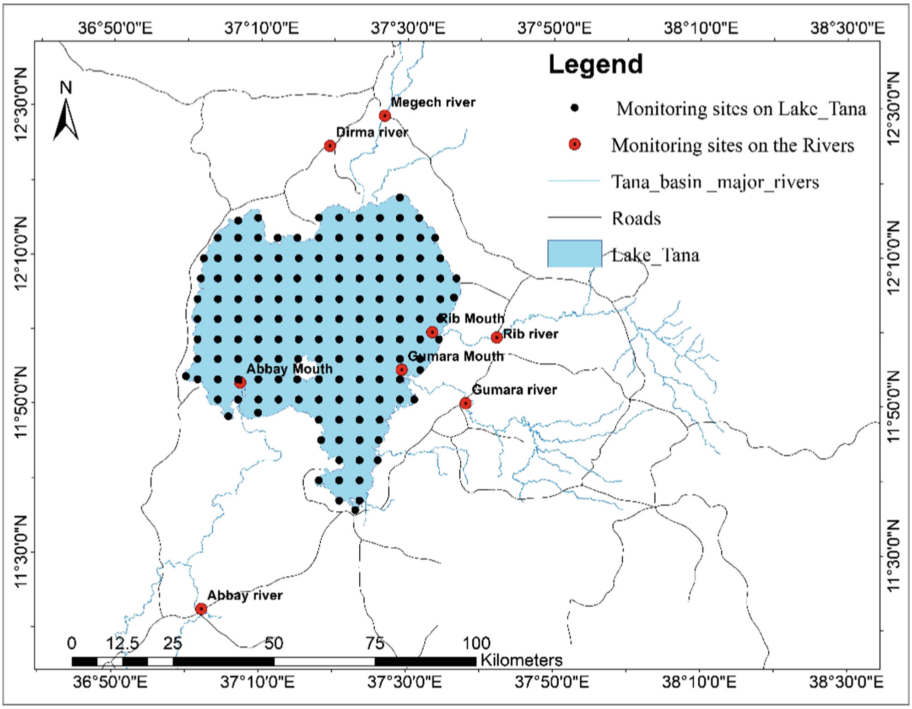

Fig. 2. Data collection sites on the lake (black spot) and on the rivers (red spot) (Color figure online)

The spatial and temporal trophic state index of Lake Tana was computed by using measured data on 143 sampling points all over the lake. To observe the spatial distribution of trophic status of the lake, first we calculated the indexes of the three parameters (TP, SDD and Chl-a) based on the Carlson numerical model which is mentioned in part 2.3.1. Using spatial analyst tool in Arc GIS 10.1, the spatial and temporal values were predicted by interpolation of the measured data using Kriging method.

Carlson's Numerical Model

The trophic state index of the lake was evaluated by using Carlsen's Trophic State Index numerical model applied by (Devi Parasad 2012). The reason we used this model is that its simplicity and good indicator of eutrophication status of lakes in limnology if there is available data. The result of each Trophic State Index (TSI) parameters on each sampling points were interpolated by Arc GIS 10.1. version using surface analyst tools.

$$\text{TSI(Chl-a)} = 9.81\ln\text{Chl-a}\left(\text{mg/m}^3\right) + 30.6 \quad (1)$$

$$\text{TSI (SDD)} = 60 - 14.41\ln\text{SDD(m)} \quad (2)$$

$$\text{TSI(TP)} = 14.42\text{TP}\left(\text{mg/m}^3\right) + 4.15 \quad (3)$$

Where TSI is Carlson Trophic State Index and ln is Natural logarithm. Carlson's trophic state index (CTSI):

$$\text{CTSI} = [\text{TSI(TP)} + \text{TSI(Chl}-\text{a)} + \text{TSI(SDD)}]/3 \quad (4)$$

In addition to Carlson's numerical model, the trophic state classification of the lake also can be evaluated according to numerical values of two parameters (TP and Chl-a) as described in Table 1 (Jolankai and Biro 2008).

Table 1. Eutrophic status classification based on numerical values of TP and Chl-a adopted from (Jolankai and Biro 2008).

Eutrophication	TP (mg/m^3)	Chl-a max (mg/m^3)	Chl-a mean (mg/m^3)
Ultraoligotrophic	<4	<2.5	<1
Oligotrophic	<10	<8	<2.5
Mesotrophic	10–30	8–25	2.5–8
Eutrophic	35–100	25–75	8–25
Hypereutrophic	>100	>75	>25

3 Result and Discussion

3.1 Spatiotemporal Distribution of Trophic Status of Lake Tana

Spatial and Temporal Distribution of TSI(TP) and CTSI on Lake Tana

Lake eutrophication cannot be evaluated by a single physical, chemical and biological parameter because of its multidimensional nature (Xu et al. 2001). According to Carlson's (1977) range of trophic status index values, the result of TSI (TP) and CTSI from Fig. 3(a and b) the lake laid on eutrophic condition in all the sampling months and/or seasons. This indicates that the lake is becoming enrich with phosphorus and other nutrients which can limit the growth of aquatic plants. In terms of TSI(TP), in August, the north eastern and north western shore of the lake is highly eutrophic whereas the south corridor and the center of the lake in lower eutrophic condition. In December, in the same parameter, all the shore of the lake is highly eutrophic and in March, only the north eastern part of the lake is highly eutrophic. From the perspective of CTSI values, the eutrophication became highest in the western shore of the lake in the rainy season and shifts towards Eastern shore in the dry season.

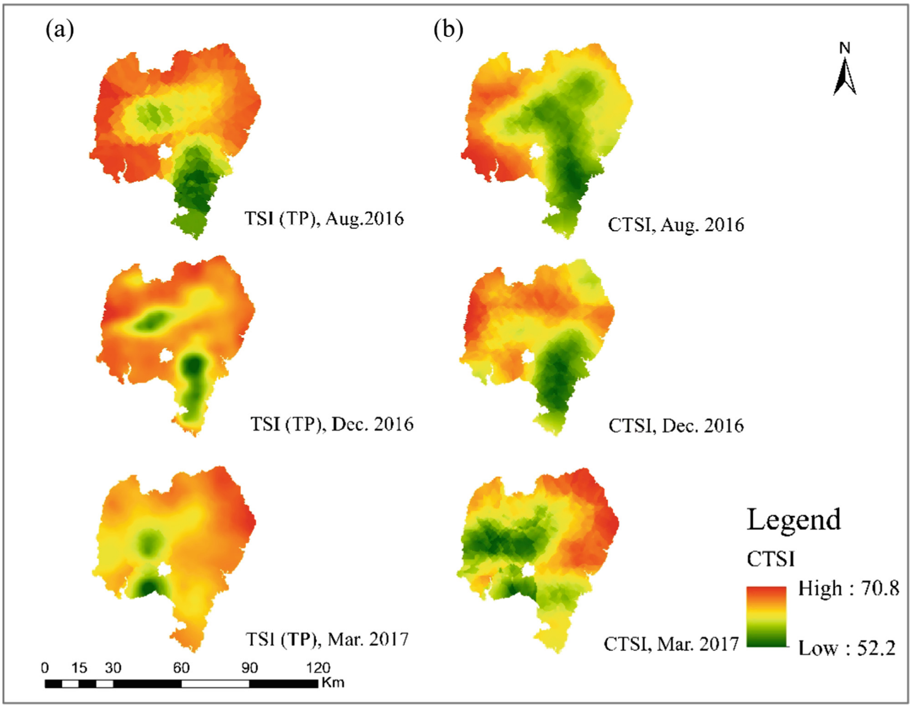

Fig. 3. The spatial and temporal trophic state index of Lake Tana based on TSI (TP) (a) and CTSI (b).

Spatiotemporal Distribution of TSI (Chl-a) and TSI (SDD) on Lake Tana

According to the spatial and temporal values of trophic state index of SDD in Fig. 4(a), the trophic status of the lake in the wet season (August) is eutrophic and in the dry season (December and March), large area of the lake is eutrophic and the north east shore of the lake indicates hypereutrophic condition.

According to the values of trophic state index of Chl-a in Fig. 4(b), in the wet season (August), the north and south western part of the lake is eutrophic whereas the north-east part is mesotrophic. In December, the central and north-west areas of the lake have been eutrophic and the north-east and south corridors of the lake were in mesotrophic condition. In March, the lake was in eutrophic condition except in some areas of the

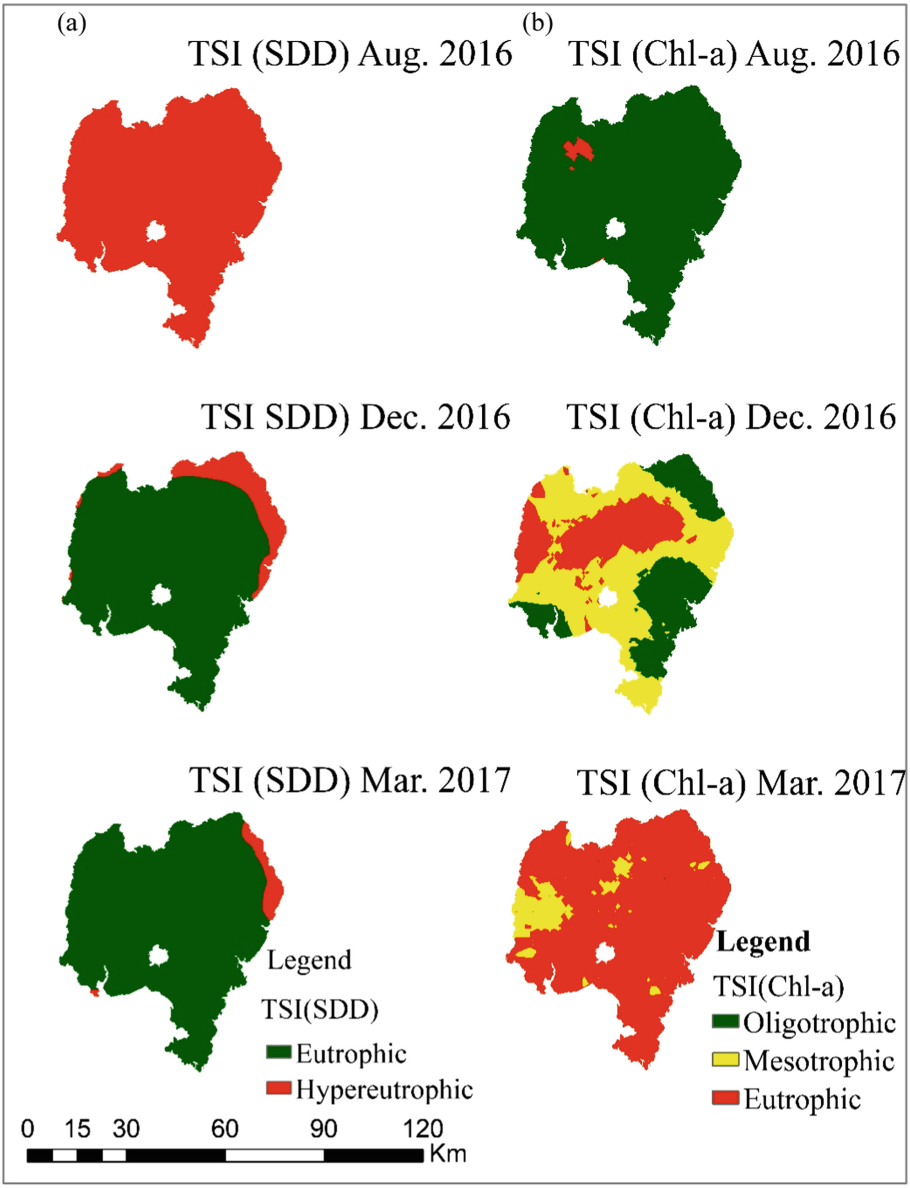

Fig. 4. The spatial and temporal trophic state index of Lake Tana based on TSI (SDD) (a) and TSI (Chl-a) (b).

lake. Generally, according to the values of TSI of Chl-a, the lake's trophic status laid on the range of mesotrophic to eutrophic status in increasing order from wet season to dry season.

This result indicates that in the dry season, the lake is being suitable for microphytes and in the wet season the lake is being suitable for macrophytes (emerging aquatic plants). In the wet season, the lake is turbid (less light transparency) and rich in nutrient which is being favorable for the growth of floating aquatic plants like water hyacinth and in the dry season the lake is less turbid (high light transparency) which is favorable for the growth of submergent species (algae and other micro aquatic plants).

To evaluate the trophic status classification of Lake Tana according to (Jolankai and Biro 2008) fixed scale, the values of determinant parameters (TP and Chl-a) of Lake Tana was summarized in Table 2 below.

Table 2. The numerical values of Total phosphorus and Chl-a concentration on Lake Tana

Parameters	August			December			March		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
TP (mg/m^3)	47	290	140	68	350	180	36	630	210
Chl-a (mg/m^3)	0.05	19.36	2.26	1.38	35.8	13.6	7.99	40.4	20.9

In the fixed scale of Jolankai and Biro which is described in the introduction part of this study, the measured numerical values of the TP showed that the lake is in the range of Eutrophic and Hypereutrophic status in both spatially and temporally. The values of Chl-a showed that the Lake is mesotrophic in wet season (August) and eutrophic in dry season (December and March).

3.2 Nutrient Concentration of the Major Tributaries of Lake Tana and Their Linkage with Water Hyacinth Infested Areas

The nutrient concentration of the major tributaries of Lake Tana can affect the eutrophication process of the lake. To evaluate the lake-land linkage of major nutrients (phosphate and nitrate) and water hyacinth infestation, the contribution of each river had to be analyzed in clusters (North eastern and North western Rivers). The concentration of total phosphorus in the rivers was summarized in Table 3 below.

From Table 3, the highest phosphate concentration was recorded in July in all major rivers. The mean values have been found in the decreasing order of July to August, May, March, November and January respectively. The overall total phosphors concentration of the North Eastern rivers (Megech, Rib, Gumara and Dirma) is higher than the North Western rivers (Gilgel Abay). The concentration of phosphate in the lake was lower in the wet season than the dry season with mean values of 0.14 mg l^{-1} in August and 0.21 mg l^{-1} in March whereas higher in wet season than in the dry season in the Rivers as shown in Table 3. This result showed that the nutrient that comes from the sub basin might sink on the large flood plains or it might sink on the lake bed as in the form of particulate phosphate. The infestation of the lake by water hyacinth has been on the northeastern shores. The northeastern rivers and the large flood plain in this cluster might

Table 3. Phosphate concentration of the Tributaries rivers of Lake Tana

Cluster	Major Rivers	TP (mg/l)					
		2011		2012			2013
		Aug.	Nov.	Jan.	Mar.	May	Jul.
North and south eastern Rivers	Ribb River	9.71	0.65	0.51	1.41	1.02	12.3
	Gumara River	4.4	0.62	0.28	0.40	0.98	8.9
	Megech River	2.2	0.02	0.42	0.32	0.84	7
	Dirma River	6.1	0.02	0.2	0.89	0.54	9.1
North and south western Rivers	G/Abay River	5.01	0.50	0.22	0.43	0.71	7.5

be the main causes for unevenly expansion of water hyacinth and the main source of the phosphate is the sub basin. The other nutrient which is useful for the growth of water hyacinth is nitrate. The concentration of nitrate in the rivers was described in Table 4 below.

Table 4. Nitrate Concentration of the Tributaries of Lake Tana

Clusters	Major rivers	Nitrate (mg/l)					
		2011		2012			2013
		Aug.	Nov.	Jan.	Mar.	May	Jul.
North and south eastern rivers	Rib River	0.64	0.13	0.04	0.07	0.45	3.1
	Gumara River	0.6	0.26	0.07	0.12	0.25	6.17
	Megech River	0.54	0.45	0.24	0.43	0.43	4.52
	Dirma river	0.75	0.22	0.21	0.1	0.09	1.99
North and south western river	G/Abay river	0.53	0.14	0.13	0.22	0.37	3.02

Table 4 shows that the maximum value of the nitrate concentration was observed mainly in July followed by August and it was minimum in the dry season. On the lake, the value of nitrate concentration is higher than phosphate concentration in both the dry and rainy season. The concentration nitrate in the lake was higher in the wet season than the dry season with mean values of 2.73 mg l^{-1} in August and 1.92 mg l^{-1} in march and had the same trend in the rivers. This result indicated that the main source of nitrate is the catchments in addition to the lake process. The overall nitrate concentration of northeast rivers is higher than the northwest and southwest rivers.

Generally, the expansion and growth of water hyacinth in northeast shore of the lake is due to high concentration of phosphate and nitrate in the north and south eastern cluster rivers but further studies shall be done about the other factors which can affect the spatial expansion of the weed such as wind direction and lake morphology.

3.3 Linkage of Eutrophication and Water Hyacinth Expansion on Lake Tana

In the current situation, the lake is severely infested by water hyacinth and the expansion of water hyacinth is on northeast shore of the lake with peak growing rate at the end of the rainy season (September–November) (Fig. 5). In terms of trophic state index of TP, SDD and the average trophic sate index (CTSI), in all the sampling months, the lake was in eutrophic condition with an exception of hypereutrophic condition in the northeast corridor of the lake due to TSI (SDD) in the dry months (December and March). This result indicates that the dynamics of eutrophication process is fundamentally suitable for the growth and expansion of the lake.

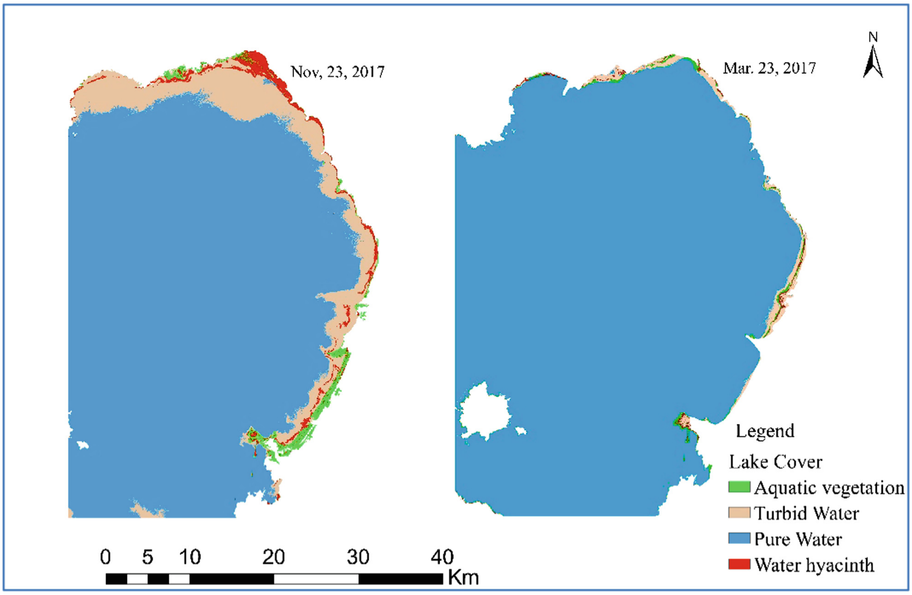

Fig. 5. Water hyacinth infestation at the end of the rainy season and dry season using SENTINEL2 Satellite Imagery and Google Earth Engine for supervised classification at the most infested shore of Lake Tana.

4 Conclusion

According to this study, the lake is being polluted and its trophic state is shifting to eutrophic condition as the result, reduction of dissolved oxygen may occur in the lake and being suitable for the growth of aquatic plants. The lake is turbid in the wet season and this becoming suitable for the growth and expansion of emerged and floating aquatic plants rather than the submerged ones. The infestation of the invasive weed in the north eastern part is the nutrient contribution of north and south eastern cluster rivers but the depth, wind direction, wind induced wave and large flood plain might affect its expansion and growth.

In the rivers, the concentration of phosphorus and nitrogen are higher in the rainy season than in the dry season. The concentration of total phosphorus was higher in the dry season than in rainy season in the lake due to its low flushing rate and high resident time, and wind induced resuspension of the particulate phosphorus in the dry season when the temperature of the water surface is high. The source of phosphorus in the dry season might be the resuspension of particulate phosphorus with sediment which deposits on the lake bed during the wet season or it might be the bed rock and decomposition of residue materials in the lake bed. This needs further investigation by collecting data in depth integration. Whereas the concentration of nitrate was higher in the rainy season than in the dry season in both the lake and in the rivers.

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Author Contributions. Minychl contributed in computation of the overall GIS work, data analysis, writing the manuscript and improving the manuscript based on the comments and suggestions of the coauthors. Aron contributed in the data collection and laboratory work. Fasikaw contributed in improving this manuscript by reviewing and editing the language as well as the images. Assefa contributed in conceptualization of the manuscript, giving comments, suggestions and improving the writing up and result interpretation. Seifu A. contributed in conceptualization of the manuscript, shaping the objectives, the methods and in giving comments and suggestions for the overall work as well. Abeyou played a great role in the GIS part for example in improving the quality of images. Mamaru contributed in shaping the overall contents, English, structure of the paper and giving significant comments. Desalegn Contributed in editing, improving the English and in giving significant comments for the paper.

Conflict of Interest. The authors have declared no conflict of interest.

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