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THUAN, Ta Dang
Division of Environmental Engineering Technology, Faculty of Chemical and Environmental Technology, Hung Yen University of Technology and Education

LAP, Bui Quoc
Division of Environmental Management, Faculty of Chemistry and Environment, Thuyloi University

THANH, Le Minh

HARADA, Masayoshi
Laboratory of Water Environment Engineering, Division of Bioproduction Environmental Sciences, Department of Agro-environmental Sciences, Faculty of Agriculture, Kyushu University

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Eutrophication Status of Lakes in Inner Hanoi and a Case Study of Cu Chinh Lake

Ta Dang THUAN[1], Bui Quoc LAP[2]*, Le Minh THANH, Masayoshi HARADA[3], Kazuaki HIRAMATSU[3] and Toshinori TABATA[3]

Laboratory of Water Environment Engineering, Division of Bioproduction Environmental Sciences, Department of Agro–environmental Sciences
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Many lakes in inner Hanoi have been affected by eutrophication, which commonly leads to uncontrolled growth of algae, generation of cyanobacteria and toxic algae, increased water–treatment costs, and lake shallowing. This study presents an overview of the recent eutrophication status in Hanoi lakes and compares the lakes with Cu Chinh Lake based on a case study performed from April 2017 to March 2018. The eutrophication was mainly assessed by comparing the nutritional parameters (phosphorus and nitrogen) with values of poor nutrition and the concentration of algal biomass with concentrations found in hypereutrophic lakes. In addition, we investigated which nutrients contribute to limiting the growth of algae based on the total nitrogen/total phosphorus ratio, and we identified groups of algae that contained typical species in Cu Chinh Lake. The nutrient levels and algal biomass in many lakes were maintained between the eutrophic and hypereutrophic limits and underwent seasonal changes throughout the year. In Cu Chinh Lake, phosphorus is the predominant limiting nutrient for the development of algae. Thus, some typical algae genera, such as *Microcystis, Anabaena* of cyanobacteria, and *Scenedesmus* of green algae, are biological indicators of eutrophication in the lake.

Key words: Algae, Cyanobacteria, Eutrophication, Hanoi lakes, Nutritional Status Index

INTRODUCTION

Recently, the amount of pollutants in the lakes of Hanoi, including nutrients derived from domestic wastewater and urban runoff, has been increasing owing to the rapid economic development and urbanization of Hanoi. Hanoi has more than 100 large and small–sized lakes, which regulate rainwater, shape landscapes, harmonize the climate, and accommodate many water plants and animals. Most lakes in Hanoi are medium and small–sized, and relatively shallow. These lakes are facing many water quality problems, especially owing to eutrophication. Eutrophication leads to the uncontrolled growth of algae, including blue–green and toxic algae, which increases water–treatment costs and causes lake shallowing.

To overcome these problems, Hanoi has recently invested in wastewater–treatment projects that aim to control discharge sources, limit the direct discharge of wastewater into the lakes, and protect natural landscapes and surface water. The water quality in Hanoi lakes, especially in the inner–city areas, is being monitored more synchronously and regularly. However, the monitoring and analysis of the water quality mainly focus on comparing and evaluating various parameters with the national standards for specific uses of surface water. Most assessments of the eutrophication status of the lakes follow qualitative methods and avoid the quantitative evaluation of parameters that are closely related to eutrophication. However, recent studies on the eutrophication process have performed quantitative evaluations and followed the methods of Hakanson and Carlson (Nguyen *et al.*, 2016; Nguyen *et al.*, 2017; Pham *et al.*, 2018).

MATERIALS AND METHODS

Study area

In this research, we evaluated the eutrophication status of ten typical lakes in inner Hanoi and investigated a case study on Cu Chinh Lake. Hanoi is the capital city of Vietnam, and it is located in northern Vietnam. It covers an area of 3328.9 km^2 with an estimated population of 8.1 million (2019). Hanoi is the second largest city in Vietnam after Ho Chi Minh City, which is located in southern Vietnam. According to a report on Hanoi lakes (Nguyen, 2015), inner Hanoi has 112 ponds with a total water surface area of 6959305 m^2; this area decreased by 72540 m^2 since 2010 owing to urbanization. Among over 100 lakes in inner Hanoi, we selected ten typical lakes to overview their eutrophication state and Cu Chinh Lake for a more detailed investigation. The locations of all studied lakes are shown in Fig. 1.

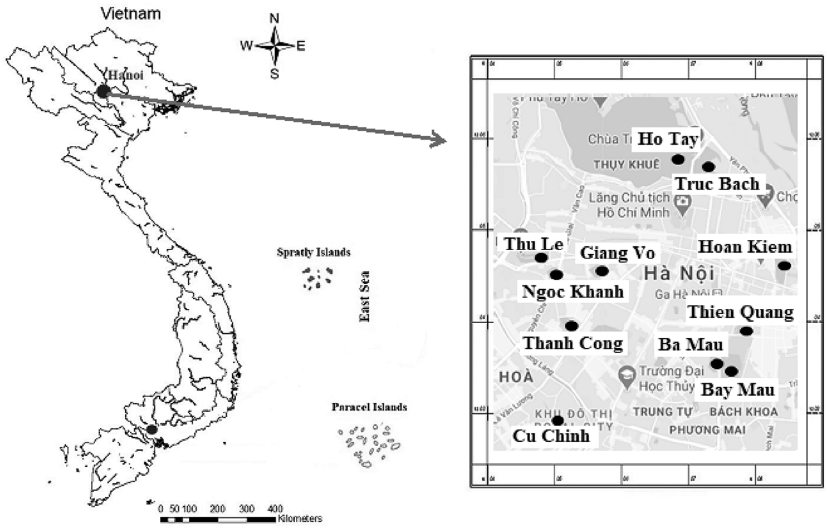
Many lakes in Hanoi have partially or permanently disappeared owing to the urbanization. The lakes in inner Hanoi are mainly shallow with depths of 1.5–4.0 m (Nguyen, 2015); thermal stratification occurs in the

[1] Division of Environmental Engineering Technology, Faculty of Chemical and Environmental Technology, *Hung Yen University of Technology and Education*, Vietnam

[2] Division of Environmental Management, Faculty of Chemistry and Environment, *Thuyloi University*, 175 Tay Son, Dong Da, Hanoi, Vietnam

* Corresponding author (E–mail: buiquoclap@tlu.edu.vn)

[3] Laboratory of Water Environment Engineering, Division of Bioproduction Environmental Sciences, Department of Agro–environmental Sciences, Faculty of Agriculture, *Kyushu University*



No.	Lake name	Location	No.	Lake name	Location
1	Thu Le	21°01'50.0"N ;105°48'32.4"E	7	Thien Quang	21°01'04.9"N 105°50'45.1"E
2	Thanh Cong	21°01'08.8"N 105°48'50.9"E	8	Truc Bach	21°02'46.1"N 105°50'17.7"E
3	Ba Mau	21°00'44.4"N 105°50'24.3"E	9	Ngoc Khanh	21°01'38.9"N 105°48'39.8"E
4	Bay Mau	21°00'42.7"N 105°50'36.1"E	10	Giang Vo	21°01'40.7"N 105°49'10.3"E
5	West Lake	21°02'56.0"N 105°49'53.0"E	11	Cu Chinh	21°00'00.0"N 105°48'00.0"E
6	Hoan Kiem	21°01'50.2"N 105°51'08.6"E			

Fig. 1. Map of the study area.

water column but the level is not significant, especially in shallow lakes. Thus, these lakes retain uniformity in temperature, which ensures the well–mixing of nutrients.

Along with the rapid economic development and urbanization of Hanoi, the amount of pollutants and nutrients derived from domestic wastewaters and urban runoffs has increased.

Cu Chinh Lake is a shallow urban lake located in the inner city with a geographic position of 21°00' North latitude, 105°48' East longitude, in the southwest of downtown Hanoi (Fig. 2).

Cu Chinh Lake borders Thuong Dinh and Nhan Chinh Ward (Thanh Xuan District). The lake is sur-

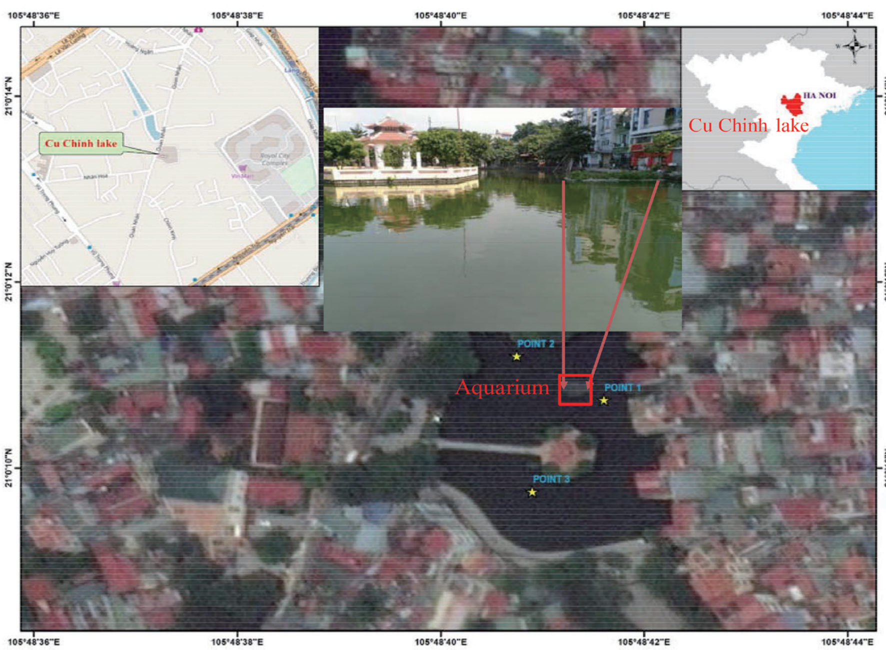


Fig. 2. Location of Cu Chinh Lake.

rounded by a densely populated commercial area. This area includes residential housing, land for commercial areas, offices, schools and hospitals, and roads (e.g., Quan Nhan Street, which has high traffic density). There was almost no direct discharge into Cu Chinh Lake because the domestic wastewater and runoff were largely collected into the city's sewage system. The discharge of groundwater into Cu Chinh Lake was also very limited because the surrounding embankments were made of bricks and reinforced concrete. Rainfall and rainwater flows were the only water bodies that were directly discharged into Cu Chinh Lake.

The circumference of the lake is approximately 250 m, and the water surface area is approximately 4000 m^2. The largest length is approximately 75 m, the largest width is approximately 65 m, the average depth is in the range of 1.5–1.7 m, and the average water capacity is approximately 4600 m^3. Cu Chinh Lake harmonizes the microclimate and regulates the rainwater, while it is also a place of entertainment for people in the surrounding area. The campus around the lake had a concrete surface, an area of approximately 1500 m^2, and it was used for parking lots and gyms. Although small, the lake could mix nutrients better than larger lakes.

Water sampling

Water and phytoplankton samples were collected from the study area between April 2017 and March 2018. The sampling occurred one to two times per month from 9:00 am to 10:00 am. Representative samples were attained by mixing samples from three points, 20 cm below the water surface (Fig. 2). In total, 16 representative samples were collected.

Water samples were attained in accordance with the Vietnam standard 5994–1995 (ISO 5667–4: 1987) for sampling in natural and artificial ponds, and they were immediately filtered through a GF/F filter paper (Whitman). The filtered samples were stored separately in plastic bottles (PE) until the analysis of the nutrient concentrations. Unfiltered water samples were used for total phosphorus (TP) analysis. The samples without immediate analysis were refrigerated at 0–4°C. Finally, a certain volume of water was collected and fixed by a Lugol solution to determine the density of the floating plant cells (Duong *et al*., 2012).

Methods of analysis

The parameters NH_4–N, NO_3–N, NO_2–N, PO_4–P, TP, total nitrogen (TN), and chlorophyll a (Chl a) were determined via the colorimetric method using a DR 2800 spectrophotometer (Hach, USA) and a UV–V630 spectrophotometer in accordance with the APHA methods (APHA, 2001). The total organic carbon (TOC) and dissolved organic carbon (DOC) were analyzed using a TOC–V E Total Organic Carbon Analyzer (Shimadzu, Japan). The number of cells was counted on the Sedgewick Rafter counting chamber under a reverse microscope. The species composition was determined using an Olympus BX51 microscope (Duong *et al*., 2012).

Eutrophication evaluation

In this research, the following methods were used:

1) The ratio of TN/TP was compared with the standards of the World Health Organization (WHO) to determine which nutrients were the limiting factors for the growth of algae. According to the WHO standards, phosphorus is a limiting nutrient when the ratio of TN/TP is greater than 6, whereas nitrogen is a limiting nutrient when the ratio is less than 4.5. When the TN/TP ratio ranges between 4.5 and 6, phosphorus, nitrogen, or both can be limiting nutrients (WHO, 2002).

2) Carlson's trophic status indices (TSI), viz. TSI (TP), TSI (Chl a) (Schindler, 1977), and TSI (TN) (Kratzer *et al*., 1981) were calculated based on the formulas:

$$\text{TSI (TP)} = 14.42 \times \ln(\text{TP}) + 4.15 \qquad (\text{TP: } \mu\text{g/l})$$

$$\text{TSI (Chl a)} = 9.81 \times \ln(\text{Chl a}) + 30.6 \qquad (\text{Chl a: } \mu\text{g/l})$$

$$\text{TSI (TN)} = 14.43 \times \ln(\text{TN}) + 54.45 \qquad (\text{TN: mg/l})$$

The eutrophication state of the lake was assessed in accordance with the Carlson and Simpson standards (Carlson *et al*., 1996), in which Carlson's TSI is the average value of TSI (TN), TSI (TP), and TSI (Chl a). The lake is classified as oligotrophic when TSI < 40 (I), mesotrophic when 40 ≤ TSI ≤ 50 (II), eutrophic when 50 < TSI ≤ 70 (III), and hypertrophic when TSI > 70 (IV).

3) The values of the TP, TN, and Chl a parameters were correlated with the classification of nutrients in accordance with the Hakanson standards (Hakanson *et al*., 2007).

RESULTS AND DISCUSSION

Overview of the previous studies

Nguyen *et al.* (2017) (Table 1) showed that ten monitored lakes in inner Hanoi (Fig. 1) were highly polluted with nutrients. Specifically, Ba Mau Lake had the highest level of nutrients, followed by Giang Vo, Ngoc Khanh, Truc Bach, Thanh Cong, Ho Tay, Thien Quang, Bay Mau, Hoan Kiem, and Thu Le. The concentrations of parameters such as TN (1.29–4.63 mg/l) and TP (0.23–1.69 mg/l) in all ten lakes were classified via the Hakason method as the fourth level (IV) of nutrient pollution (hypertrophic). Although all lakes were hypertrophic with respect to TN and TP, most were from oligotrophic to mesotrophic with respect to Chl a, except for Giang Vo Lake which was eutrophic. This suggested that these nutrient–polluted lakes did not have favorable conditions for algae growth. However, this should be studied in more detail. In addition, there was a seasonal variation; i.e., the concentration of nutrients in the dry season was higher than that in the rainy season (Nguyen *et al*., 2017). Carlson's TSI ranged from 56.8 (Thu Le Lake) to 78.1 (Ba Mau Lake). Based on the standards of the US Environmental Protection Agency, the nutritional status in these lakes ranged from eutrophic to hypertrophic, and it followed the order: Ba Mau > Giang Vo > Ngoc Khanh > Truc Bach > Thanh Cong > Ho Tay > Thien Quang > Bay Mau > Hoan Kiem > Thu Le (Nguyen *et al*., 2017). This revealed that the three lakes

Table 1. Eutrophication levels of ten monitored lakes in Hanoi

Parameter \ Lake	Ba Mau	Giang Vo	Ngoc Khanh	Truc Bach	Thanh Cong	Ho Tay	Thien Quang	Bay Mau	Hoan Kiem	Thu Le
Area (ha)	4.6	6	3.5	22	6.5	446	5.5	21.3	12	9.9
Depth (m)	2.5 – 3.0	2.5 – 3.0	2.5	1.5 – 2.0	3.0 – 4.0	2.0 – 4.0	3.0 – 4.0	2.0 – 2.5	1.5 – 2.0	2.0 – 3.0
TN (*mg/l*)	4.63 (IV)	3.22 (IV)	3.12 (IV)	2.72 (IV)	2.20 (IV)	1.72 (IV)	2.47 (IV)	2.23 (IV)	0.82 (IV)	1.29 (IV)
TP (*mg/l*)	1.69 (IV)	1.27 (IV)	1.77 (IV)	0.55 (IV)	0.4 (IV)	0.41 (IV)	0.41 (IV)	0.28 (IV)	0.26 (IV)	0.23 (IV)
Chl.a ($\mu g/l$)	5.0 (I)	7.7 (III)	4.2 (II)	3.1 (II)	2.4 (II)	3.1 (II)	1.4 (I)	1.3 (I)	5.3 (II)	0.9 (I)
Carlson–TSI	78.1	76.4	75.9	68.5	65.2	65.0	64.1	61.6	61.0	56.8
Overall classification[*]	HT	HT	HT	ET	ET	ET	ET	ET	ET	ET

[*] HT – *Hypertrophic*; ET – *Eutrophic*

with the smallest water surface areas (Ba Mau, Giang Vo, and Ngoc Khanh) were the most nutrient–polluted (hypertrophic), whereas the remaining lakes with larger water surface areas tended to be less nutrient–polluted (only eutrophic). This observation can be explained by the fact that lakes with larger water surface areas can dilute nutrients better and decrease their concentrations. More importantly, a larger water surface area implies a larger air–water interface, which means that wind acts on the water surface more effectively and improves the circulation (wind–induced circulation). As a result, the pollutants and nutrients were circulated and mixed better, which favored the decomposition and absorption of nutrients by aquatic plants. This explains why lakes with large water surface areas tended to be less eutrophic than those with smaller water surface areas.

Nguyen *et al*. (2017) researched six lakes in inner Hanoi, viz. Ba Mau, Bay Mau, Truc Bach, Hai Ba Trung, Hoan Kiem, and Dam Tri. Their results showed that most lakes were highly polluted with NH_4–N and PO_4–P, whose concentrations were two to three times higher than the allowable standards of QCVN 08MT: 2015/BTNMT, column A2 (water quality standard for the conservation of aquatic life). The TSI of these lakes ranged from 59.1 to 88.6, indicating that the lakes ranged from eutrophic to hypertrophic Additionally, the lakes had a higher eutrophication level in the dry season. Furthermore, research on Truc Bach, Thu Le, and Linh Dam (Pham *et al*., 2018) showed that the TP and TN concentrations were considered suitable parameters to monitor the eutrophication status of the lakes. The values of TSI (TP) and TSI (TN) of these lakes were greater than 70, which suggested that the nutritional status in the lakes during the monitoring period was maintained at the hypertrophic level.

In addition, eutrophication promoted the growth and development of algae groups in the lakes. Le (2009) studied ten lakes in Hanoi and reported that there were five main groups of algae, viz. green algae, silica algae, ophthalmic algae (Euglenophyta), two–channel algae (Dinophyta), and a group of cyanobacteria; the groups with the predominant density were green algae (51 species) and cyanobacteria (22 species).

Duong *et al*. (2012) reported that the composition of phytoplankton in Hoan Kiem Lake was dominated by cyanobacteria (accounting for 90% of the total phytoplankton). Many cyanobacteria species had the ability to produce toxins, such as species of the *Microcystis* genus, which form a thick scum on the surface of the water during the blooming season and produce hepatotoxins (microcystins). The concentrations of these toxins ranged from 2.1–46 μg microcystins/l with an average density of 386.94 × 10^6 cells/ml. In addition, West Lake exhibited diverse communities of silica algae with six main families of algae, mainly species with a wide distribution of representative tropical and subtropical species, such as *Nitzschia palea, Gomphonema parvulum, Cyclotella meneghiniana*, and *Aulacoseira granulata* (Duong *et al*., 2012).

The results of the previous studies showed that many lakes in inner Hanoi remained eutrophic. The nutrient levels of most lakes were maintained from eutrophic to hypertrophic during the study period. Green algae and cyanobacteria constituted a large proportion of the algae. The *Microcystis* genus of cyanobacteria produces liver toxins that adversely affect the health of animals in the lakes.

Thus, the above studies focused only on the eutrophication assessment through individual aspects, such as the concentration of nutrients, groups of algae, and algae genera appearing in the lakes. Those studies have not shown the effect of nutrients and environmental factors such as water temperature or solar radiation intensity on the growth and development of algae groups, which is typically expressed by the concentration of algae biomass and cell density of algae groups.

In addition, the above studies focused on shallow lakes located in inner Hanoi and most received both point and non–point wastewater sources. However, there are some lakes with well–controlled urban sewage systems that do not experience direct discharge of domestic wastewater, such as Hoan Kiem, Thien Quang, and Thu Le Lakes. Nevertheless, eutrophication proceeded in these lakes as well, suggesting that the eutrophication is not only due to the wastewater discharged directly into the lakes but also due to nutrients added from the atmosphere, runoffs into the lakes, waste excreted by lake plants and animals, and the dispersion of nutrients from lake sediments.

Eutrophication of Cu Chinh Lake

Assessment of the eutrophication level

Eutrophication index (TN/TP)

In addition to assessing the eutrophication level of Cu Chink Lake via the method of Hakanson and Carlson, the study considered which nutrients were limiting the growth of algae. The study also analyzed the cell densities of the algae groups that appeared in the lake and assessed their relationship to dissolved inorganic nutrient concentrations, water temperature, and solar radiation intensity.

Fig. 3 shows the TN/TP ratio of two seasons in the year. Fig. 4 shows the seasonal distribution of the TN/TP ratio, which was used to determine the nutritional factor that limits the growth of algae. As shown in Fig. 3, the average value of the TN/TP ratio was 9.1, the highest value was 17.4 in May, and the lowest was 2.5 in June. Phosphorus was the main limiting nutrient, except during periods of heavy rainfall (from June to August) when nitrogen was the predominant limiting nutrient. This was explained by the fact that when the nutrient concentration in the lake was high, the temperature of the water was also high, while rainy days with few hours of sunshine led to low solar radiation intensity. This was unfavorable for algae growth; therefore, the concentration of TP increased sharply while the TN concentration was stable, resulting in a decrease in the TN/TP ratio.

Fig. 3 and 4 show that the range of the TN/TP ratio in the rainy season (from 2.5 to 17.4) was wider than that in the dry season (from 9.7 to 12.7). The lake's water quality should be monitored regularly to assess and manage the concentrations of limiting nutrients, thereby minimizing the risk of arising eutrophication.

The TSI of the lake was calculated for the monthly values of TSI (TP), TSI (TN), TSI (Chl a), as shown in Fig. 5. TSI (TN) was calculated for June, July, and August when nitrogen was a limiting nutrient. The average values of TSI (TP), TSI (TN), and TSI (Chl a) in Cu Chinh Lake were 77.2, 59.8, and 57.6, respectively. The values of TSI (TN) and TSI (Chl a) suggested that the lake was in the eutrophication state, whereas the value of TSI (TP) suggested that the lake was hypertrophic. Throughout the year, the lake's nutrition status remained eutrophic or even hypertrophic, which was expressed sharply in June and July when the temperature and nutrient concentration were high. The eutrophication status in Cu Chinh Lake was similar to those of the ten monitored lakes in inner Hanoi with a TSI ranging from 59.1 to 88.6 (Nguyen *et al.*, 2017) and somewhat lower than those of the three lakes in Hanoi with TSI ranging from 75.6 to 87.63 in the research of Pham *et al.* (2018).

Table 2 shows a comparison between the annual average and seasonal values of the concentrations of TN, TP, and Chl a (the rainy season was from May to September and the dry season was from October to April of next year) with the nutrient classification of the lake based on the method by Hakanson *et al.* (2007).

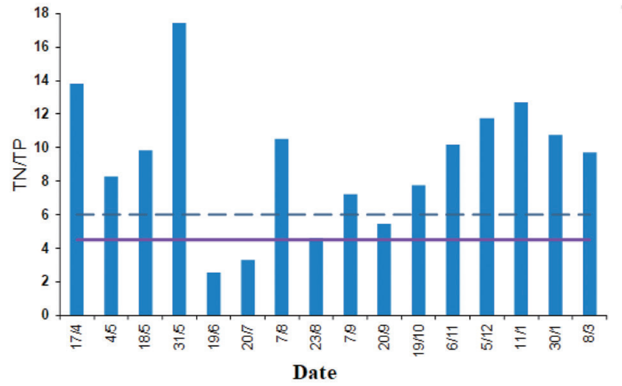


Fig. 3. TN/TP ratios with respect to different observation times.

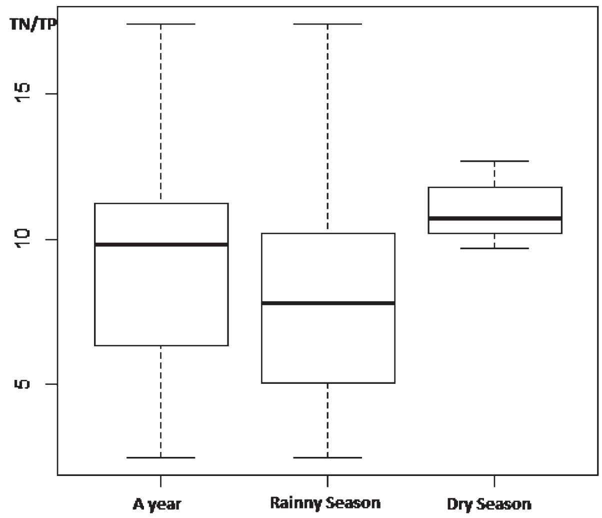


Fig. 4. Seasonal TN/TP ratios of Cu Chinh Lake.

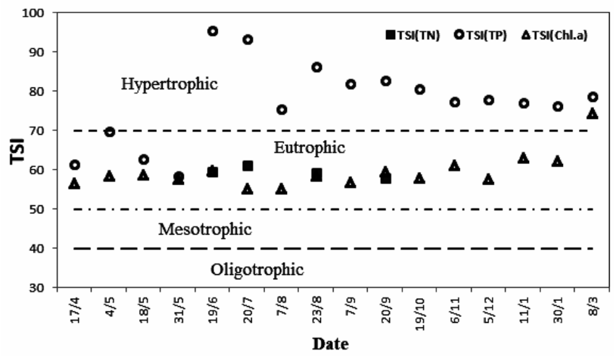


Fig. 5. Lake eutrophication state based on Carlson's trophic status index.

As shown in Table 2, the concentrations of TN and TP indicated that the lake was always hypertrophic in both rainy and dry seasons. This result was similar to those of the ten studied lakes, although the average values of TN and TP in Cu Chinh Lake were slightly lower than those of the ten lakes. The annual and seasonal values of Chl a were significantly greater than those of the

Table 2. Classification of nutrition in Cu Chinh Lake via Hakanson and Carlson's trophic status index methods

Parameter \ Classify	Oligotrophic	Mesotrophic	Eutrophic	Hypertrophic	Cu Chinh Lake		
					Average year	Rainy season	Dry season
TP (mg/L)	< 0.008	0.008–0.025	0.025–0.06	> 0.06	0.2 (Hypertrophic)	0.218 (Hypertrophic)	0.162 (Hypertrophic)
TN (mg/L)	< 0.06	0.06–0.18	0.18–0.43	> 0.43	1.378 (Hypertrophic)	1.12 (Hypertrophic)	1.78 (Hypertrophic)
Chl.a (μg/L)	< 2	2–6	6–20	> 20	17.72 (Eutrophic)	15.5 (Eutrophic)	22.28 (Hypertrophic)
Carlson–TSI	< 40	40–50	50–70	> 70	67.2 (Eutrophic)	65.3 (Eutrophic)	70.4 (Hypertrophic)

ten lakes, (17.72 μg/l, 15.5 μg/l in the rainy season, 22.28 μg/l in the dry season) and the lake was eutrophic to hypertrophic, whereas the ten lakes were oligotrophic to mesotrophic. The concentration of Chl a in Cu Chinh Lake during the rainy season was the lowest, which could be explained by the fact that the environmental factors in this period (water temperature and solar radiation intensity) did not favor algae growth.

In general, the indices used to assess the eutrophication level in the lake via different methods were highly consistent. Most indices indicated that Cu Chinh Lake was eutrophic and hypertrophic throughout the year (although the concentration of nutrients varied). The growth of algae was mainly limited by phosphorus; nitrogen was a limiting nutrient for a short period during the rainy season.

Phytoplankton community

In this study, the phytoplankton community (mainly algae) in Cu Chinh Lake included five groups of algae: Cyanobacteria, Chlorophyta (green algae), Bacillariophyta (silica algae), Euglenophyta (ophthalmic algae), and Dinophyta (two–channel algae). The typical genera of the algae groups are presented in Table 3, the percentage of algae groups is shown in Fig. 6, the cell density of the algae groups is shown in Fig. 7, and the cell density of cyanobacteria and green algae are shown in Fig. 8 and 9.

Table 3 shows that the composition of algae groups in Cu Chinh Lake is commonly found in freshwater ecosystems and some typical algae genera were biological indicators of eutrophication in lakes, such as *Microcystis*, *Anabaena* of cyanobacteria, and the *Scenedesmus* genus of green algae (Tran, 2011).

Fig. 6 shows that the green algae group had the largest average cell density of 50.2% between all phytoplankton present in Cu Chinh Lake (the highest was 67.7% in October and the lowest was 37.2% in August). The second largest group was cyanobacteria with an average cell density of 46.55% (the highest was 58.41% in August and the lowest was 29% in October). Conversely, two–channel, ophthalmic, and silica algae exhibited cell densities of less than 0.32–2.53%.

The cell density of algae in Cu Chinh Lake ranged from 4.9×10^7 to 18.6×10^7 cells/l with an average value of 8.87×10^7 cells/l. The highest value was recorded on December 5, 2017, and the lowest on July 20, 2017. Green algae and cyanobacteria were the two groups of algae with the dominant density and relatively stable growth during the monitoring period.

The genus *Microcystis* of the cyanobacteria group produces hepatotoxins such as microcystins, and the genus *Anabaena* produces neurotoxins, saxitoxins (which commonly cause paralytic shellfish poisoning), anatoxin–a, guanitoxin and homoanatoxin–a (Tran, 2011). Fig. 7 shows that the genus *Microcystis* of the cyanobacteria group was dominant with a cell density ranging from 1.97×10^7 cells/l to 9.18×10^7 cells/l (accounting for 28.6–75.5% of the total cell density). This genus appeared in all the samples, with an especially high density during the rainy months. The presence of this genus indicates a high risk of poisoning for aquatic animals and plants in the lake.

The fluctuations in cell density of green algae in Cu Chinh Lake are shown in Fig. 8. The lowest density was 1.87×10^7 cells/l recorded on July 20, 2017, and the highest was 9.15×10^7 cells/l on December 5, 2017. Among the groups of green algae, *Scenedesmus* and *Pediastrum* had cell densities accounting for over 91% during the monitoring period. Although *Pediastrum* adapted to clean water conditions, *Scenedesmus* favored a more nutrient–rich environment.

With an average cell density of up to 80.9% of the total cell density, *Scenedesmus* was predominant during the observation period (always greater than 70%). This indicated that the water in the lake was contaminated with nutrients.

The relationships between the cell densities of algal groups and exogenous variables, such as nutrient concentrations (easily absorbed by algae), dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP), dissolved oxygen concentration, water temperature, and solar radiation intensity were assessed based on the Spearman correlation coefficient and are shown in Fig. 9, 10, and 11.

Fig. 9 shows that Cu Chinh Lake had a higher average cell density of algae during the dry season (from November 2017 to March 2018) than during the rainy season. The algae cell density values increased dramatically in December 2017 and March 2018. Moreover, the concentration of nutrients that are easily absorbed by algae (DIN + DIP) was always maintained at a high

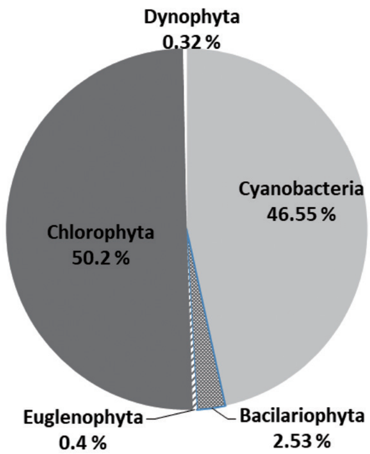


Fig. 6. Percentage of algae groups in Cu Chinh Lake.

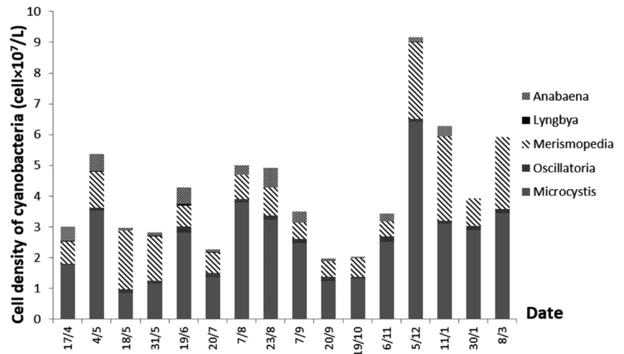


Fig. 7. Changes in cell density of cyanobacteria in Cu Chinh Lake.

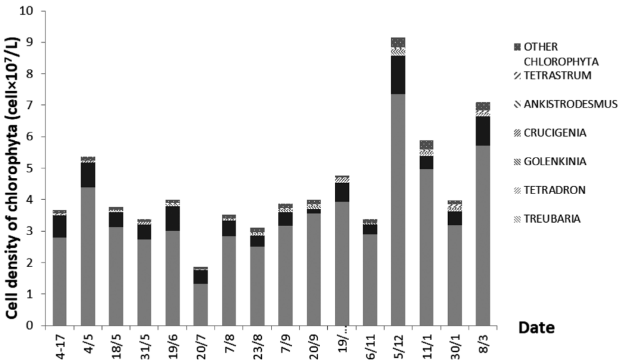


Fig. 8. Fluctuations in cell density of green algae in Cu Chinh Lake.

Table 3. Algae group and typical algae genera

Algae group	Typical algae genera
Cyanobacteria	*Microcystis, Merismopedia, Anabaena*
Chlorophyta	*Scenedesmus,Pediastrum*
Bacilariophyta	*Cyclotella*
Euglenophyta	*Euglena*
Dinophyta	*Glenodinium*

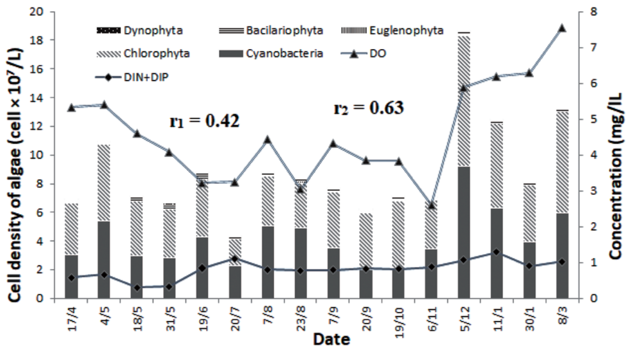


Fig. 9. Relationship between dissolved inorganic nitrogen & dissolved inorganic phosphorus, dissolved oxygen concentration, and cell density.

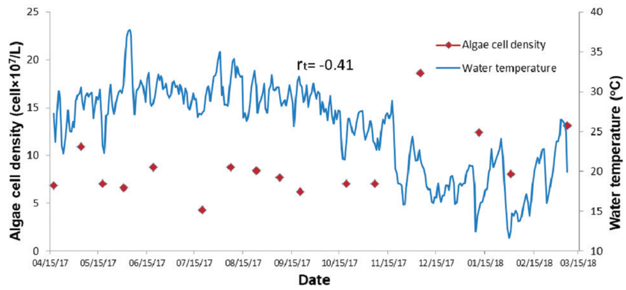


Fig. 10. Relationship between water temperature and algal cell density.

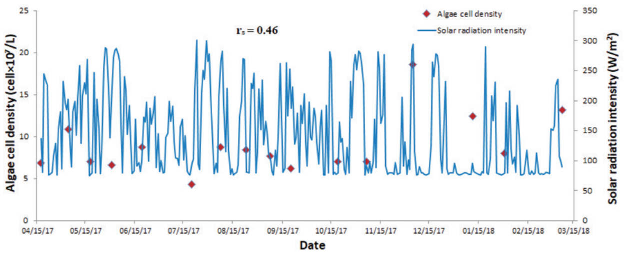


Fig. 11. Relationship between solar radiation intensity and algal cell density.

threshold, and the water temperature and solar radiation intensity underwent strong fluctuations.

At times of high cell density, the water temperature ranged from 20.5°C to 29°C (Fig. 10) and the intensity of solar radiation (Fig. 11) remained at a high level; these were suitable conditions for the overgrowth of algae. For example, on December 5, 2017, the highest cell density was 18.6 × 10^7 cells/l, the water temperature was 21.18°C, and the solar radiation intensity was 300 W/m^2, which favored algae growth.

Conversely, when the cell density was low and the nutrient concentration in the lake was stable, one or both factors (water temperature and solar radiation intensity) would be unfavorable for the growth of algae. Fig. 11 shows that when the solar radiation intensity was low, the algae cell density remained below the average value. For example, on July 20, 2017, a nutrient concentration (DIN + DIP) of 1.14 mg/l and water temperature of 28°C were favorable conditions for algae growth. However, with one sunny hour per day and radiation intensity at a low value of 85 W/m^2, these conditions were not suitable for algae growth; therefore, the cell density of algae was low at approximately 4.9 × 10^7 cells/l. Moreover, high solar radiation intensity and water temperature (≥ 30°C) inhibited the growth of algae. The cell density of algae was inversely correlated with water temperature (r_t = −0.41), and positively correlated with nutrient concentrations (r_1 = 0.42), solar radiation intensity (r_s = 0.46), and dissolved oxygen concentration (r_2 = 0.63). The latter correlation can be explained by the fact that, at the time of sampling, there was a high cell density of algae, which led to an increase in the dissolved oxygen concentration via photosynthesis.

CONCLUSIONS

The following conclusions were drawn from the above results:

1. Almost all lakes in inner Hanoi were between eutrophic and hypertrophic because they received domestic wastewaters and urban runoffs from their surrounding areas without exchanging with external waters. Therefore, it is necessary to apply effective measures for improving the water quality of these lakes.
2. Although almost all lakes were from eutrophic to hypertrophic with respect to TN and TP, most lakes were from oligotrophic to mesotrophic with respect to Chl a. This suggested that the lakes did not favor algae growth.
3. The lakes with the smallest water surface areas tended to be more eutrophic than those with larger water surface areas. This was because the latter can circulate better by wind–induced currents and promote the decomposition and absorption of nutrients by aquatic plants, in addition to the improved diluting capability due to their larger water volume.
4. Cu Chinh Lake was heavily polluted with organic substances and nutrients. The eutrophication level of the lake ranged from eutrophic to hypertrophic. Phosphorus was the main limiting nutrient, except for a short period in the rainy season (June to August) when nitrogen was a limiting nutrient for the growth of algae. Thus, to control the eutrophication state in Cu Chinh Lake, it is necessary to focus on controlling phosphorus.
5. The composition of phytoplankton in Cu Chinh Lake was dominated by green algae and cyanobacteria, which included typical genera such as *Scenedesmus* (biological indicator for organic pollution), *Microcystis*, and *Anabaena* (blooms in water). The cell density of algae in the lake exhibited large fluctuations with a higher value during the rainy season. The fact that cyanobacteria, especially *Microcystis* and *Anabaena*, exhibited the highest density during the monitoring period indicated the risk of toxicity to plants and animals in the lake. Finally, the cell density of algae had a close relationship with the nutrient concentration and environmental factors such as water temperature and solar radiation intensity.

AUTHOR CONTRIBUTIONS

Ta Dang THUAN was resposible for sampling and analizing the water samples. Bui Quoc LAP designed the study, supervised the water sampling and analysis, prepared the manuscript and played the role of the corresponding author. Le Minh THANH supported to the water sampling and analysis as well as manuscript preparation. Masayoshi HARADA and Toshinori TABATA contributed to manuscript preparation, Kazuaki HIRAMATSU contributed to revise the manuscript.

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