Vietnam Journal of Earth Sciences, 43(4), 509-523, https://doi.org/10.15625/2615-9783/16562

Vietnam Academy of Science and Technology
Vietnam Journal of Earth Sciences
http://www.vjs.ac.vn/index.php/jse

Assessing trophic status of Suoi Hai Reservoir using Carlson's Trophic State Index

Nguyen Thuy Linh[1], Nguyen Thi Thu Ha[1*], Nguyen Thien Phuong Thao[1], Pham Quang Vinh[2]

[1]*Faculty of Geology, University of Science, Vietnam National University, Hanoi, Vietnam*
[2]*Institute of Geography, VAST, Hanoi, Vietnam*

Received 13 April 2021; Received in revised form 24 August 2021; Accepted 13 September 2021

ABSTRACT

The water quality of Suoi Hai reservoir, the largest reservoir in Hanoi city, is being threatened by human activities of the surrounding area, as reported by the press. The trophic status of the reservoir is the result of both natural eutrophication and nutrient inputs from anthropogenic sources, particularly the leachate from a lakeside waste treatment plant. This study aims to identify the trophic status of the Suoi Hai reservoir and the changes of water trophic state over space and time. Data of chlorophyll-a concentration, total phosphorus, and Secchi disk depth from 51 sites during three field campaigns in October 2019, August 2020, and March 2021 was used to calculate Carlson's trophic state index (CTSI). Resultant CTSI (ranged from 60 to 72) allows classifying Suoi Hai reservoir as highly eutrophic water. Its variations in space and time provided evidence for an influence of anthropogenic activities on the reservoir trophic state. Analysis of the trophic state index deviations suggested that total phosphorus is the key factor that influenced the reservoir trophic state. Therefore, managing the anthropogenic nutrient inputs load to the reservoir should be a critical task to control eutrophication in Suoi Hai Reservoir at present.

Keywords: Eutrophication, TSI, chlorophyll-a, Secchi disk depth, Suoi Hai Reservoir.

1. Introduction

As in many parts of the world, lake eutrophication has been a serious problem in Vietnam. Eutrophication has caused a series of water quality problems for freshwater ecosystems, such as the blooms of Microcystis/Cyanobacteria in many lakes in Hanoi (Nguyen et al., 2015; Duong et al., 2014), in Tri An and Dau Tieng Reservoirs (Pham et al., 2015; Dao et al., 2015) and in small ponds in Southern Vietnam (Trung et al., 2018); the oxygen depletion in lakes in Hanoi (Hoang et al., 2020); and summer fish-kills in lakes and rivers over the country. Lakes, which can be classified as eutrophic and hypertrophic in Vietnam, have increased dramatically during the past decades. Therefore, assessing and monitoring eutrophication in lakes has been a hot topic in the water science community for decades.

Eutrophication is a process of the movement of the lake trophic state in a direction from oligotrophy towards eutrophy

[*]Corresponding author, Email: hantt_kdc@vnu.edu.vn

(Carlson & Simpson, 1996). Therefore, eutrophication can be assessed and monitored by determining the lake's trophic state and changes in space and time. The trophic state is defined as the total weight of the biomass in a water body at a specific location and time. It reflects the biological response for nutrient additions to the water bodies (Nauuman, 1929). The trophic status of a water body, which indicates the stability of the trophic state within a certain period, can roughly be assessed by the value of the trophic state index (Istvánovics, 2010). The most widely accepted trophic state index (TSI) for assessing lake trophic state is the one suggested by Carlson (1977), which was computed using information about the concentration of the limiting nutrient (phosphorus), chlorophyll an (an indicator of phytoplankton biomass), and transparency (dependent on both algal biomass and sediment resuspension, expressed as Secchi disk depth). Carlson's TSI (CTSI) has been widely used due to its simple data requirement and understanding (Prasad & Siddaraju, 2012). Furthermore, deviations among Carlson's trophic state indices, TSI(x), provide adequate information to identify factors limiting phytoplankton growth (Okech et al., 2018; Kuma et al., 2019).

In Vietnam, CTSI and the trophic classification system proposed by Carlson & Simpson (1996) have been used widely to assess the trophic state of many inland lakes and reservoirs across the country. For example, lakes in the Hue Imperial Citadel had CTSI > 70 and therefore were classified as hypertrophic waters (Hop et al., 2012); the Blue Lake in An Son, Thuy Nguyen, Hai Phong was classified as an oligotrophic lake with CTSI = 28.9 (Tuan et al., 2017); the trophic state of Cao Van reservoir (Cam Pha, Quang Ninh) was ranked at the eutrophic condition with CTSI = 57.25 by Ha et al. (2018); three reservoirs, Dai An, Khe San, and Khe May in Quang Trị were considered as highly trophic waters with CTSI ranged from 50 to over 60 (Hai et al., 2019); with the CTSI values ranged from 66.32 to 75.9 in the dry season and 73.33 to 84.86 in the wet season of the year 2016, Tri An reservoir was classified as hypertrophic water in the study of Yen et al. (2019); lakes in the urban areas of Hanoi capital and Da Nang city were also ranked as highly eutrophic and hypertrophic waters with the CTSI over 50 (Ngoc et al., 2017; Thuan & Lap, 2018; Hop & Trung, 2020). Other trophic classification systems, i.e., those were suggested by the Organization for Economic Co-Operation and Development, OECD (Vollenweider & Kerekes, 1982), Vollenweider et al. (1998), and Håkanson et al. (2007), have also been used in several domestic studies to assess the trophic state of lakes and reservoirs (Hung & Huyen, 2010; Hop et al., 2012; Tien et al., 2018; Thuan & Lap, 2018; Hai et al., 2019; Hop & Trung, 2020). However, it is noticed that all these studies calculated CTSI and used it as a referenced index for their assessments. Consequently, using CTSI and the trophic classification system proposed by Carlson & Simpson (1996) is the most appropriate method to assess the trophic status of lakes and reservoirs in Vietnam because it is simply in data collection and more suitable for comparing results obtained to historical records.

The reservoir is an artificial ecosystem that is a combination of natural phenomena and human manipulation. These ecosystems exist because they support human demands, such as drinking and irrigation water, energy production, aquaculture, flood management, touristic and leisure activities. Identifying the environmental characteristics of reservoirs, including their trophic state, seasonal variations, and the factors that influence eutrophication in reservoirs are indispensable tasks for water resource management and ecological quality improvement. Like other reservoirs in the Red River Delta, Suoi Hai reservoir was first constructed for irrigation and daily life water supply. Along with the reservoir aging process, eutrophication has occurred naturally and is accelerated by surrounding anthropogenic pollution. Up to the present, there has been no scientific study addressing the water quality or trophic status of Suoi Hai reservoir, despite impacts of the lakeside waste treatment plant, Xuan Son Waste Treatment Plant, on the surrounding environment was reported (Toan, 2012). It is time to assess and control eutrophication in the reservoir to improve their economic, ecological, and environmental services. This study aims at identifying the trophic state of the Suoi Hai reservoir using the datasets of chlorophyll-a concentration (Chla), total phosphorus concentration (TP), and Secchi disk depth (SDD) obtained in three campaigns during the period from October 2019 up to the present (March 2021). Spatial distribution maps of CTSI over the reservoirs in three surveyed times indicated the reservoir's trophic state variation in space and time. Furthermore, they suggested anthropogenic factors that speed up eutrophication in the reservoir.

2. Materials and methods

2.1. Study reservoir

Suoi Hai is an artificial reservoir located on the Tich River in Ba Vi piedmont area, which belongs to four communes, i.e., Cam Linh, Ba Trai, Thuy An, Tan Linh, Ba Vi district, northwest Hanoi city (Fig. 1). The reservoir was constructed in 1958 to store water for irrigation, daily life, and regional ecological improvement. At present, the water surface area of the reservoir is approximately 5.11 km^2 wide, with the average depth ranges from 5 m to 10 m and the total water accumulation capacity greater than $45 \times 106\ m^3$. The reservoir stores water in the rainy season, mainly from April to September, and releases water in the dry season from October to March of the following year. There are two main streams from Ba Vi mountain that flow into the reservoir: Yen Cu and Cau Rong stream (Fig. 1). The reservoir serves as an irrigated water source for 4,500 ha of agricultural land in surrounding areas. Recently, the discharges of wastewater in the surrounding area into Suoi Hai Reservoir causing pollution has been reported in the press (Doan Tuan & Dang Tien, 2018; Dat Le & Gia Bach, 2019) that requires the participation of the scientific community in providing evidence to better management of the reservoir.

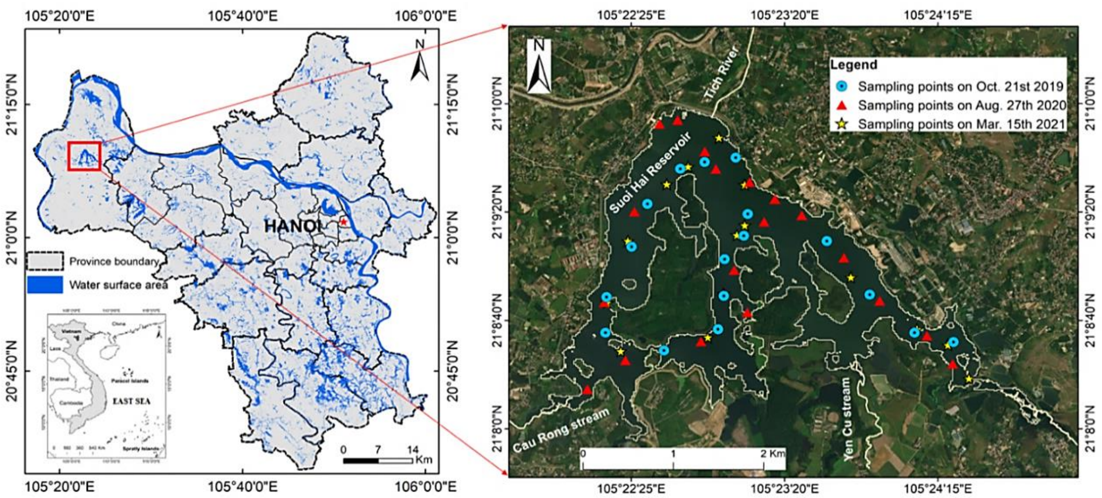

Figure 1. Locations of Suoi Hai Reservoirs in Hanoi and sampling points

2.2. Methods

2.2.1. Water sampling and field measurement

Data were collected during the three field campaigns on October 21st, 2019 (corresponding to late of the rainy season in 2019), August 27th, 2020 (corresponding to the middle of the rainy season in 2020), and March 15 th, 2021 (corresponding to the end of the dry season in 2021). Water samples and SDD measurements were recorded at a total of 51 sites in three trips by boat. There are 17 sites on October 21st, 2019, 19 on August 27th, 2020, 15 sites on March 15th, 2021. Water sampling and measurement sites were designed randomly throughout the water surface to ensure the environmental representativeness and the spatial balance of obtained data. The number and the location of sampling sites were adjusted slightly during each field campaign to conform to actual conditions. The location of sampling sites was georeferenced using a hand-held GPS receiver and shown on the local map as in Fig. 1. Two liters of water were taken at a depth of 0–50 cm using a Van Dorn water sampler, preserved in 1 L cleaned, dark-color bottles, and then refrigerated and transported to the laboratory for the determination of Chla and TP.

SDD was measured in the field using a standard 20 cm diameter plastic Secchi disk (U.S. Wildco, model 3-58-B10). To avoid direct sunlight reflections from the water, SDD was measured on the shaded side of the ship and determined by the arithmetic average of the total three readings. SDD was measured overall water sampling sites and united in meters.

2.2.2. Water sample analysis

In the laboratory, the water samples were analyzed to determine Chla based on the standard spectrophotometric method (10200-H and 4500-P) of the American Public Health Association (APPH, 1998), which used a DR 5000 UV-VIS Laboratory Spectrophotometer (Hach, Colorado, U.S) with a 1 nm spectral bandwidth resolution over the region from 200 nm to 900 nm. This technique uses acetone 90% as the solvent. Accordingly, Chla was extracted in 90% acetone, and the absorption at 664 nm and 665 nm of the solvent with the extractant before and after the acidification, respectively, were read in a spectrophotometer. The amount of Chla was calculated using the following equation:

$$Chla = \frac{26.7(664_b - 665_a) \times V_1}{V_2 \times L} \quad (1)$$

Where V_1 and V_2 are volume of extract (L) and volume of sample (m^3); L is with of cuvette unit in cm; 664_b and 664_a are optical densities of the 90% acetone extract before and after acidification. Chla resulted in mg/m^3 or μg/L. Due to the high dependence of resultant Chla in water sample on the analyzed technique, this study used the APHA standard method to determine Chla in water sample which was suggested by Carlson and Simpson (1996) to ensure that the Chla data fits the relationship between Chla and CTSI using historical data. TP in water sample was determined using the ammonium molybdate spectrometric method as the description in TCVN-6202:2008 (Vietnam Ministry of Science and Technology, 2008).

2.2.3. Trophic state determination

For the identification of the trophic status of Suoi Hai reservoir, the TSI based on data of Chla, SDD, and TP was calculated as TSI(Chla), TSI(TP), and TSI(SDD) using the following formulations of Carlson and Simpson (1996), respectively:

$$TSI(Chla) = 9.81\, ln(Chl\, a) + 30.6 \quad (2)$$

$$TSI(TP) = 14.42\, n(TP) + 4.15 \quad (3)$$

$$TSI(SDD) = 60 - 14.41\, ln(SD) \quad (4)$$

From the resultant TSI(Chla), TSI(TP), and TSI(SDD), CTSI was computed by averaging these values by the equation:

$$CTSI = [TSI(Chla) + TSI(TP) + TSI(SDD)]/3 \quad (5)$$

Based on the values of CTSI, the reservoir is classified according to the category as showed in Table 1.

Table 1. The trophic state index category suggested by Carlson and Simpson (1996)

CTSI	Chla (µg/L)	SDD (m)	TP (µg/L)	Attributes
< 30	< 0.95	> 8	< 6	Oligotrophy: Clear water, oxygen throughout the year in the hypolimnion.
30–40	0.95–2.6	8–4	6–12	Hypolimnia of shallower lakes may become anoxic.
40–50	2.6–7.3	4–2	12–24	Mesotrophy: Water moderately clear; increasing probability of hypolimnetic anoxia during summer.
50–60	7.3–20	2–1	24–48	Eutrophy: Anoxic hypolimnia, macrophyte problems possible.
60–70	20–56	0.5–1	48–96	Blue-green algae dominate, algal scums and macrophyte problems.
70–80	56–155	0.25–0.5	96–192	Hypereutrophy: (light limited productivity). Dense algae and macrophytes.
> 80	> 155	< 0.25	192–384	Algal scums, few macrophytes

2.2.4. Mapping of the trophic state index

The final resultant CTSI determined at all sampling sites within a field campaign was used as the primary input dataset to map the spatial distribution of CTSI over the reservoir. The "thin-plate spline" with the third-order polynomial Kernel function was demonstrated as the best interpolation method to conduct the map with the determination coefficients (R^2) of the predictions are 0.98, 0.88, and 0.71 of the dataset on October 21st, 2019, August 27th, 2020, and March 15th, 2021, respectively. The standard errors of all three interpolations are approximately 1 (i.e., 1.16, 0.70, and 1.46), which are less than 5 % of mean CTSI, indicating this method's suitability for mapping the distribution of CTSI. The Geostatistical analyst tools in ArcGIS 10.5 software were employed for this mapping.

3. Results

3.1. Trophic Status of Suoi Hai Reservoir

Figure 2 shows the ranges of Chla, SDD, TP, and CTSI in Suoi Hai Reservoir water obtained from three field campaigns, in October 2019, August 2020, and March 2021, respectively. Accordingly, Chla ranged from 10.47 µg/L (in October 2019) to 74 µg/L (in March 2021) with an increasing trend of the mean value over three surveys. The mean value of Chla was 15.53 µg/L in October 2019, then increased to 38.18 µg/L in August 2020 and 37.83 µg/L in March 2021 (Fig. 2A). Conversely, TP averaged at 83.53 µg/L in October 2019, increased slightly to 86.53 µg/L in August 2020, then decreased to 65.53 µg/L in March 2021. The highest and lowest concentrations were found in March 2021 (169 µg/L and 45 µg/L) (Fig. 2B), demonstrating a vast range of TP over the reservoir space in the dry season. SD varied slightly in August 2020, from 0.46 to 0.58 m, but ranged widely in March 2021, from 0.67 m to 1.20 m. The mean SDD in March 2021 was approximately 1 meter on average, which is double higher than in August 2020 and October 2019 (Fig. 2C). This result shows an opposite trend to the variations of Chla and TP over August 2020 to October 2019. While Chla and TP decreased, the increase in SD indicates that algae and phosphorus concentrations are not the main factors influencing the seasonal variation of water clarity. The ranges of Chla, TP, and SD datasets obtained in March 2021 are higher than those obtained in August 2020, demonstrating that the wet season's water exchange is better than in the dry season.

The trophic indices based on Chla, TP, and SDD were presented in Figs. 2D, E, F, respectively. The deviation among the mean values of three indices in a survey can be up to 10, as shown in Fig. 2D. Mean TSI(Chla) increased from 57 in October 2019 to 66 in August 2020 and March 2021, demonstrating the significance of algal biomass in raising the trophic level of the reservoir. Mean TSI(TP) and TSI(SDD) showed a slightly decreasing trend over three surveys, from 68 (in October 2019 and August 2020) to 64 (in March 2021) and from 69 to 62, respectively. It may be because water clarity and phosphorus concentration mainly depend on the discharge from the surface runoffs in the catchment. In the dry season, the discharge from the surface runoffs is negligible, leading to a decrease in TP and turbidity in the water.

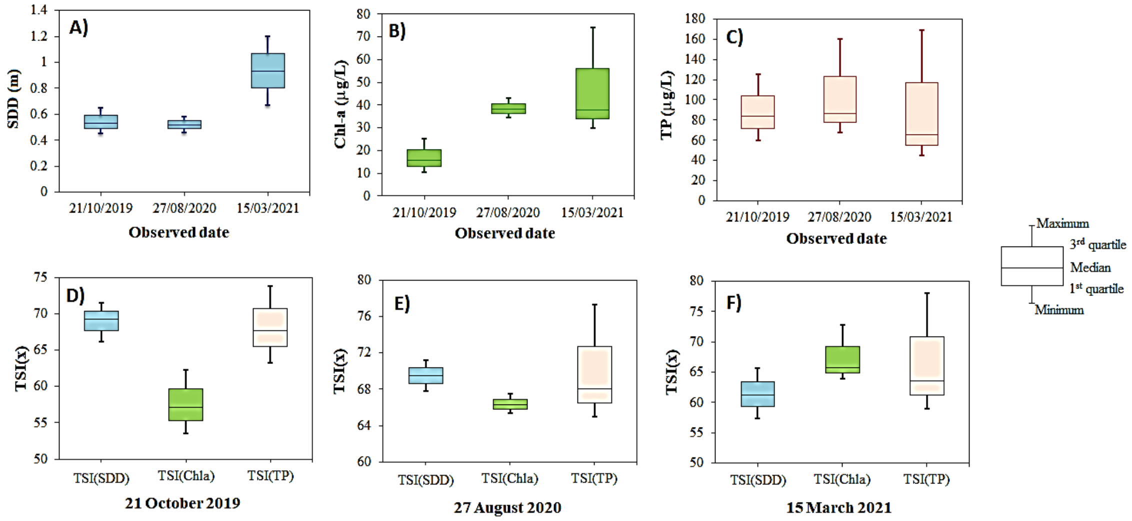

Figure 2. Variations of water clarity (A, SDD), chlorophyll-a concentration (B, Chla), total phosphorus (C, TP), and their based trophic indices (D, E, F)

The resultant CTSI showed in Fig. 3 demonstrated the trophic level of the reservoir and the possible change of the trophic state with the seasons. Accordingly, the reservoir is classified at a highly eutrophic level, with the averaged CTSI value ranged from 63.5 (in March 2021) to 68 (in August 2020). This result agreed with the assessment using the trophic classification system suggested by OECD (Vollenweider, Kerekes, 1982). The eutrophic level in the OECD's system is defined by five thresholds, i.e., mean TP (35–100 µg/L), mean Chla (8–25 µg/L), maximum Chla (25–75 µg/L), mean SDD (1.5–3.0 m), and minimum SDD (0.75–1.5 m). The obtained data in the present study consistently fits these thresholds, thus confirming the reservoir water at the eutrophic level. Moreover, using CTSI as demonstrated in this study helps better understand how far the reservoir presents status to hypertrophy. Indeed, the maximum CTSI in August 2020 and March 2021 were over 70, indicating the hypertrophic level appeared in the reservoir. According to possible attributes of the high eutrophic level described by Carlson and Simpson (1996), the reservoir's water quality worsens the aquatic ecosystem.

3.2. Limiting factors

Nutrient availability is a primary factor influencing the lake’s ability to support the ecosystem, and thus identifying factors that limit phytoplankton growth is essential to understand the lake’s ecology. Although nutrient availability in lakes is not uniform, phosphorus and nitrogen have been recognized as the key nutrients influencing phytoplankton growth in most aquatic ecosystems (Vollenweider, Kerekes, 1982).

Therefore, the total nitrogen ratio versus TP is often used to determine the trophic limiting factor in domestic studies (e.g., Tien et al., 2018; Thuan & Lap, 2018). To identify the trophic limiting factors in Suoi Hai Reservoir, we analyzed the relationships among three variables (Chla, TP, and SDD). The correlations among Chla with TP and SDD were examined and showed in Fig. 4A. Accordingly, Chla was moderately correlated to TP in the wet season (the coefficient of determination, R^2 = 0.30 in October 2019 and R^2 = 0.50 August 2020) and strongly correlated to TP in the dry season (R^2 = 0.87). Consequently, phosphorus is considered as a main limiting factor for algae growth in the reservoir. Chla was not correlated to SDD (R^2 = 0.08–0.36), implying that algae are not the main factor that decreases water clarity. In other words, non-algae suspended matters. The diagram in Fig. 3B shows the deviations of three indices: TSI(Chla), TSI(TP), and TSI(SDD) and indicates both the degree of nutrient limitation and the composition of suspended matters (Carlson and Simpson, 1996). Most of the data points lie on the diagonal, indicating that non-algal suspended matters are a key factor in deciding the CTSI of the reservoir. In the diagram, data obtained in the wet season (October 2019 and August 2020) was mainly located in the lower-left quadrant, in which TSI(Chla) << TSI(SDD) and TSI(Chla) << TSI(TP), indicating that non-algae suspended matters dominated the reservoir in this season. Additionally, TSI(Chla) obtained in the wet season was less than TSI(SDD) (Figs. 2D, E), which suggests that non-algae suspended matters were dominated in the water, induced the light diminution, and limited algal production. Data obtained in March 2021was located in the upper right quadrant, in which TSI(Chla) >> TSI(SDD) and TSI(Chla) >> TSI (TP), indicating that relatively large algae dominated the reservoir water in the dry season, which is nutrient-limited by phosphorus concentration.

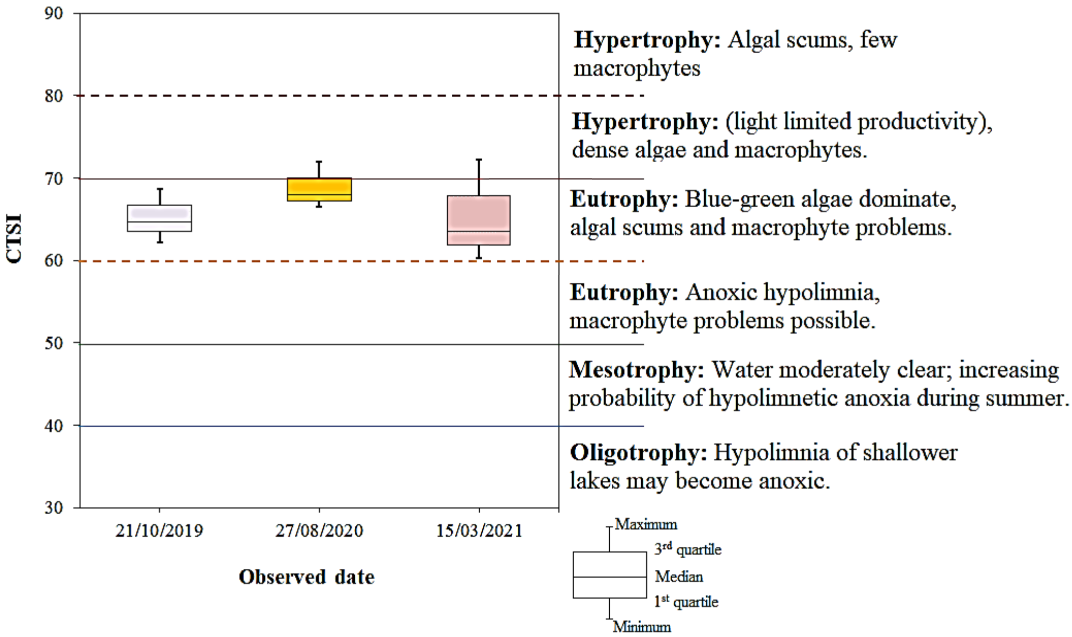

Figure 3. Carlson's trophic state index (CTSI) of Suoi Hai reservoir water in October 2019, August 2020, and March 2021 compared to the TSI category (Carlson and Simpson, 1996)

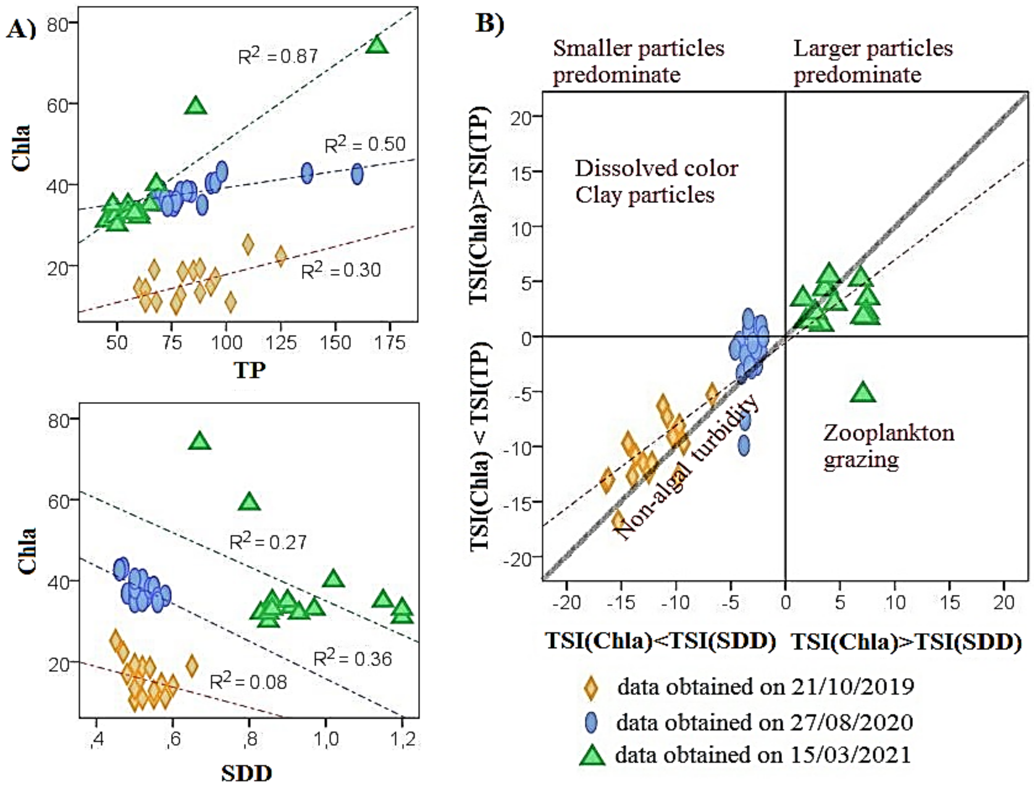

Figure 4. Relationships between Chla and TP, SDD (A) and the deviations of three indices: TSI(Chla), TSI(TP), and TSI(SDD) (B). R^2 denotes the coefficient of determination

Figure 5 presents the crossly relationships of CTSI with TSI(SDD) (Fig. 5A), TSI(Chla) (Fig. 5B), and TSI(TP) (Fig. 5C) based on total data obtained in all three field campaigns (N = 51). Accordingly, CTSI is correlated strongly with TSI(TP) (the Pearson coefficient, R = 0.86), while is correlated relatively to TSI(SDD) (R = 0.68) and TSI(Chla) (R = 0.48). These relationships indicate that the trophic state of the reservoir is much dependent on the nutrient input than the inner water characteristics (transparency and biomass). Therefore, eutrophication control in the reservoir must correspond to the control of nutrient loads.

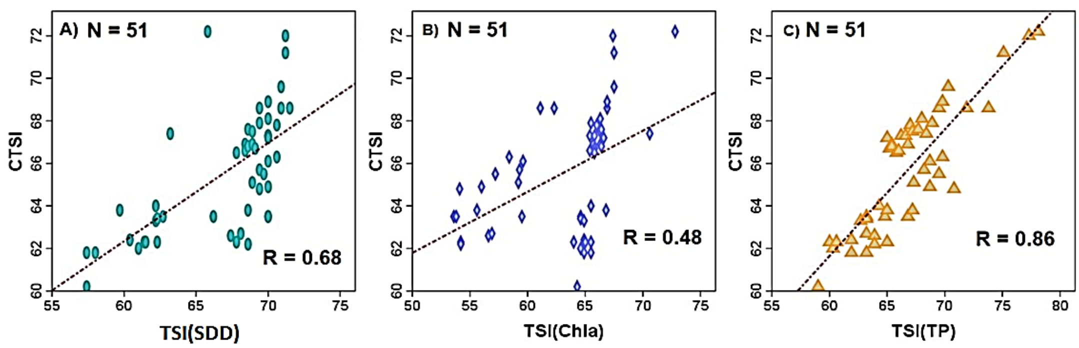

Figure 5. Relationships between CTSI and TSI(SDD) (A), TSI(Chla) (B), TSI(TP) (C). R denotes the Pearson coefficient

3.3. Seasonal and spatial variation of the Trophic State Index

Figure 6 shows the spatial distribution of CTSI across the reservoir using the data obtained on October 21st, 2019, August 27th, 2020, and March 15th, 2021, respectively. The trophic state of Suoi Hai Reservoir showed heterogeneity among sites and seasons. Accordingly, the CTSI ranged from 61 to 69 in October 2019, risen to 66–72 in August 2020, and then fell to 60–72 in March 2021. Based on the resultant CTSI, the highly eutrophic state (60 ≤ CTSI < 70) covered most of the reservoir from October 2019 up to the present. Remarkably, the reservoir's southeast inflow was recognized at the hypertrophic level from August 2020 to March 2021 with CTSI >70 (Table 1). CTSI at the inflows of Cau Rong and Yen Cu streams was lower than the mean CTSI in October 2019 but was higher than the mean CTSI in August 2020 and March 2021. The CSTI pattern changes seasonally in space, from presenting high CTSI in the reservoir center part (as in October 2019) to inflows in August 2020 and March 2021.

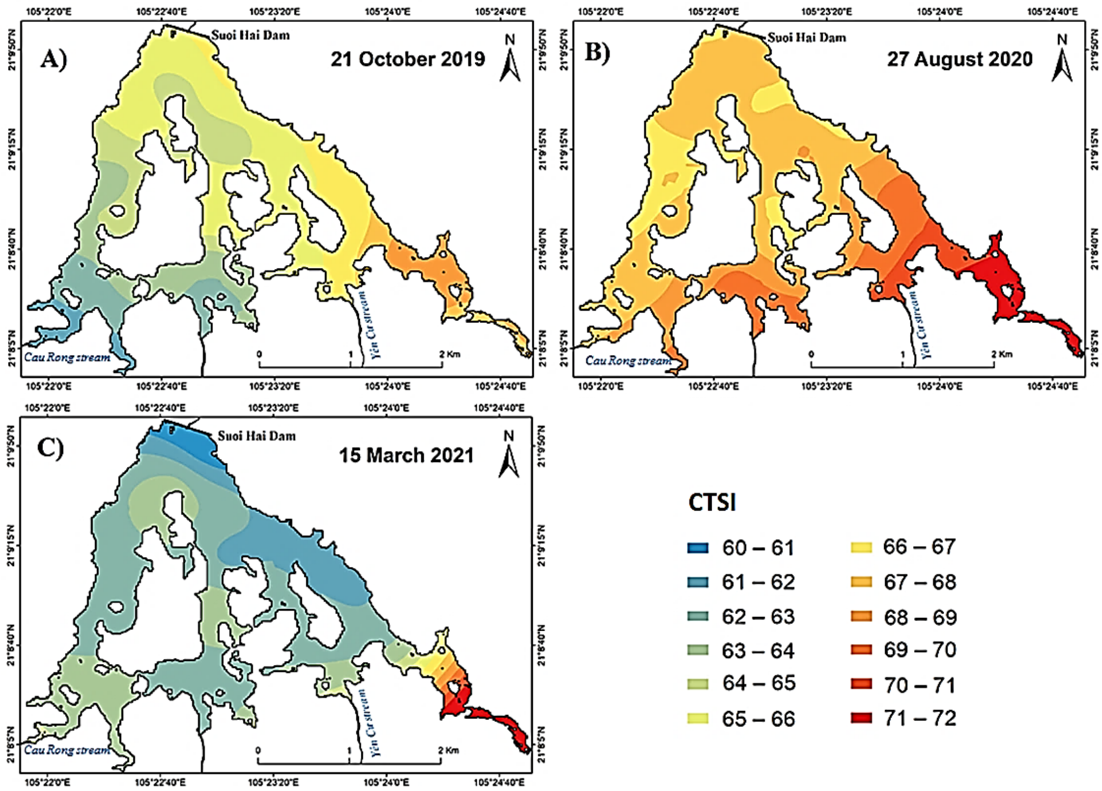

Figure 6. Spatial distribution of CTSI across Suoi Hai reservoir on three measured times: A) on October 21st, 2019; B) on August 27th, 2020; C) on March 15th, 2021

Because Chla and SDD both change seasonally due to various factors, including nutrients, light, water temperature, mixed regime, and hydrodynamic condition (Carlson & Simpson, 1996), the lake trophic state changes seasonally. In Fig. 6, the mean CTSI presented the highest value in summer (August 2020) and the lowest in spring (March 2021). However, the spatial deviation of CTSI in August 2020 (from 63 to 68, corresponding to 5 CTSI units) was not as high as the spatial deviation in March 2021 (from 60 to 72, corresponding to 12 CTSI units). The supper high CTSI value shown in the southeast inflow both dry and wet seasons, suggesting a strong impact of anthropogenic activities within the inflow's catchment on the reservoir's water quality.

According to guidelines of several countries, such as the United States and Korea, the lake water's trophic state must remain oligotrophic to mesotrophic for drinking water purposes (Mamun et al., 2021). Considering the study results, the water quality of Suoi Hai Reservoir does not meet the requirement for drinking water supply. The high eutrophic level of the reservoir's water indicates that the reservoir is facing substantial bloom problems and impeding local tourism. Therefore, appropriate measures should be taken to control eutrophication in Suoi Hai Reservoir.

4. Discussions

A variety of indices have been used for assessing the lake trophic status, and they can be divided into two distinguished groups, i.e., (1) the group of trophic status indices, which focuses on the primary production potential; (2) the group of indices that reflect the complexity of trophic relations between organisms (Pavluk & Bij, 2013). In the first group, indices based on level of Chla, total nitrogen concentration (TN), TP, and SDD such as TRIX Index, Carlson's Trophic State Index, Trophic Level Index have been more widely used. The present study used the most well-known index created by Carlson (1977) to assess the trophic status of Suoi Hai Reservoir, the largest reservoir in Hanoi (Vietnam) but has been rarely mentioned in published studies. The trophic status of the Suoi Hai Reservoir obtained in this study was compared to different lakes and reservoirs located in Northern Vietnam. Accordingly, the CTSI of Suoi Hai Reservoir is higher than the CTSI of lakes and reservoirs in mountainous and rural areas, such as the Thac Ba Reservoir (Chla = 15.3–17 μg/L (Vinh et al., 2019), TSI(Chla) = 57.4–58.4), Ba Be Lake (Chla = 1.5–6 μg/L (Ha el al., 2017), TSI (Chla) = 34–48), Cao Van Reservoir (CTSI = 57.25; Ha et al., 2018), Blue Lake (CTSI = 28.9; Tuan et al., 2017) and Dai Lai reservoir (TSI(TP) < 65; Hung & Huyen, 2010). Compared to lakes in the urban areas of Hanoi city, Suoi Hai Reservoir has a lower CSTI value because most of them were classified as hypertrophic waters with CTSI, TSI(Chla), and TSI(SDD) > 70 (Ha et al., 2016; 2017; Thuan & Lap, 2018; Linh et al., 2019; 2020; Thao et al., 2021).

Carlson's TSI presents the trophic condition on a continuous numeric scale, from 0 to 100, that helps easily classify approximately the trophic state and rank lakes with the same trophic level. For example, Dai Lai and Suoi Hai reservoirs both have been classified as eutrophic waters (Hung & Huyen, 2010 and the present study), but Suoi Hai Reservoir is ranked as higher trophic than Dai Lai Reservoir because it has the higher TSI values (Dai Lai: TSI(TP) < 65; Suoi Hai: TSI(TP) > 65). In addition, in Carlson's trophic scale, a change of 10 CTSI units within a trophic level indicates a significant difference in trophic ecology; therefore, using TSI helps users understand how far or near the lake trophic state is the possible ecological attribute. As demonstrated in this study, the variation of CTSI within a trophic level is large enough to create a spatial distribution map of CTSI (Fig. 6), providing scientific information to identify possible pollution sources and related human activities.

As documented in many studies, aquatic ecosystems in lakes and reservoirs are greatly affected by anthropogenic activities due to population growth and the accompanying development of industry and agriculture. Fig. 7 shows a broad view of Suoi Hai Reservoir's catchment, in which the connection among Ba Vi mountain, local streams, and the reservoir was illustrated clearly. Accordingly, many factors may contribute to the eutrophication of the reservoir presented within the catchment, such as domestic waste and wastewater from the surrounding residential areas (in Ba Trai, Tan Linh, Thuy An, Cam Linh communes); waste and wastewater from lakeside tourism (i.e., 1001 Lakeside Villas; Vuon Hong Villas, Co Moc Coc, restaurants); feces and wastewater from the lakeside livestock and poultry farms (Trai Ga, Dong Tinh Vien, Moncada farms); and, leachate from Xuan Son waste treatment plant (Fig. 7).

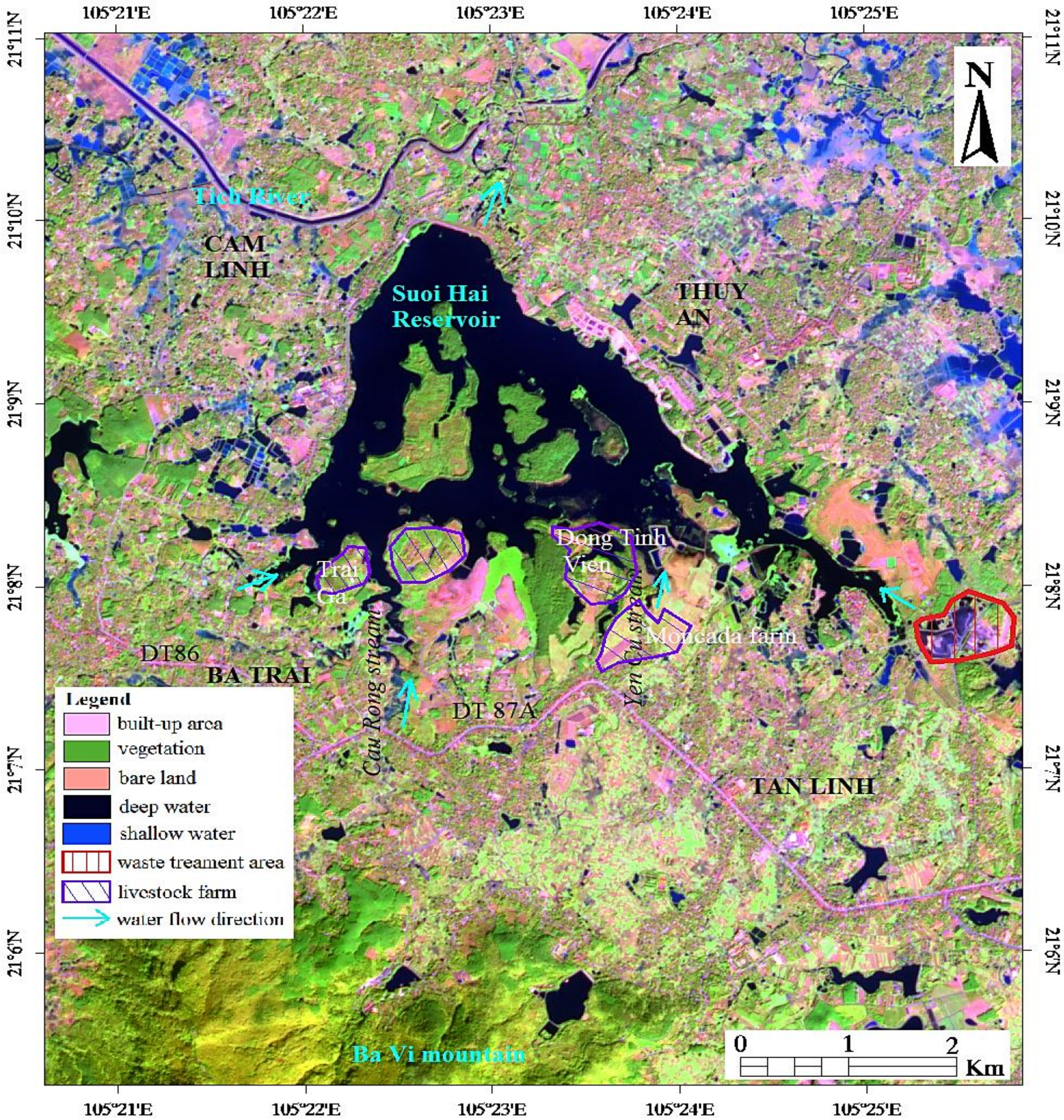

Figure 7. Characteristics of Suoi Hai Reservoir's catchment and lakeside anthropogenic activities that may induce eutrophication (a simulation model based on the Sentinel 2 satellite image taken on January 18th, 2021, the false-color image of band 11, band 8, and band 3)

In this study, phosphorus in water was identified as a primary limiting factor for increasing the trophic state of the reservoir. Phosphorus can enter the water-body in the Earth environment due to human activities like agricultural fertilization, wastewater disposal, and storm-water runoffs from residential areas (Ngatia & Taylor, 2018). The spatial distribution of CTSI, which is highly correlated to TP (Fig. 5C), in the wet season (August 2020) showed higher CTSI in all the inflows (Fig. 6B), proving that phosphorus originated from local anthropogenic activities has influenced the water quality. Therefore, the existence of the above phosphorus-rich anthropogenic activities in the catchment challenges eutrophication control. Measures to control pollution at the source of these activities should be taken to protect lake water quality effectively. Furthermore, the impact of the leachate from the Xuan Son waste treatment plant, which is located on the largest inflow of the reservoir (Fig. 7), was demonstrated through the super high trophic level of this inflow (Figs. 6B and 6C). This study can be considered as a preliminary scientific result on the environmental impacts of the Xuan Son waste treatment plant on the water quality of Suoi Hai Reservoir. It should be noted that leachate from municipal solid wastes often contains various toxic organic pollutants, heavy metals, ammonia nitrogen compounds, and other components (Youcai, 2018). Therefore, a comprehensive investigation on the component and discharge volume of the leachate from the Xuan Son waste treatment plant must be taken urgently to protect the reservoir environment.

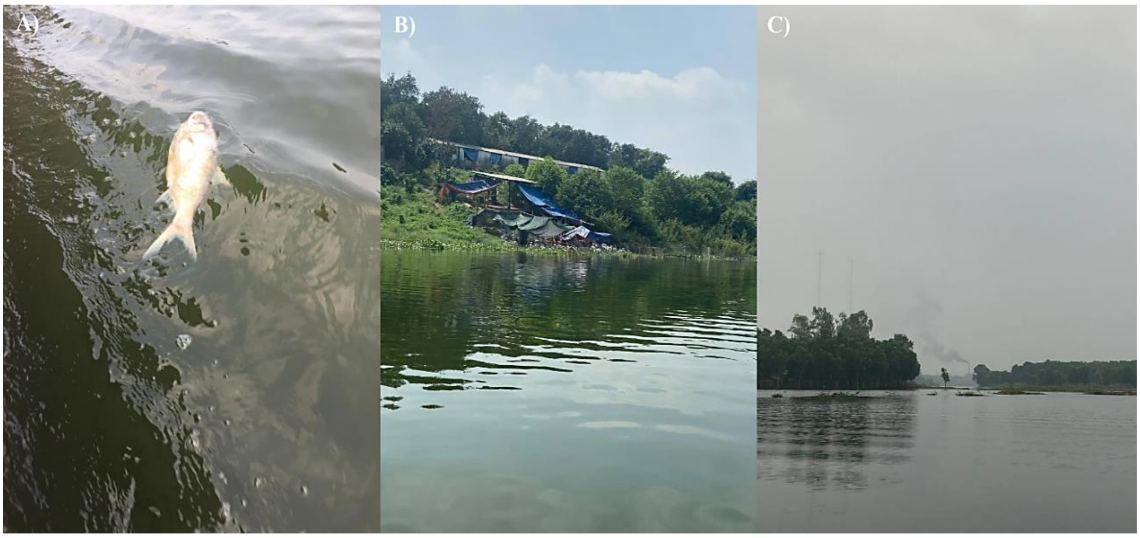

Figure 8. A) Fish-kill in Suoi Hai reservoir (photo taken in October 2019; B) Local livestock on the shoreline of the reservoir, near Trai Ga (photo taken in August 2020); C) The chimney of the Xuan Son waste treatment plant seen from the reservoir (photo taken in March 2021)

Zhang and Mei (1996) concludes four negative ecological consequences caused by eutrophication, including: (1) Depletion of fisheries resources and production; (2) Changes in fish community structure; (3) Disappearance of some endemic aquatic species; and 4) An increase in the frequency of algal blooms, elevation in chlorophyll pigment concentration, simplification of species composition. Negative ecological consequences of eutrophication such as fish-kills and stinky waters have also been observed during all three field trips (Fig. 8). If leachate impacts from Xuan Son waste treatment plant and wastewater from lakeside livestock are uncontrolled at present, it is possible to anticipate that phenomena such as fish-kills and algal blooms will occur more frequently in the reservoir soon.

5. Conclusions

Carlson's trophic state index (CTSI) based on Chla, TP, and SDD has been calculated to assess the trophic status of Suoi Hai Reservoir. The resultant CTSI obtained from three field trips in October 2019, August 2020, and March 2021 demonstrated that Suoi Hai Reservoir is at the highly eutrophic level (CTSI ranged from 60 to 72). The trophic state index deviation and the trophic index interrelationships indicated TP's significant role in limiting the reservoir's trophic level (R between CTSI and TP was 0.86). CTSI showed a significant spatial variation due to the effects of anthropogenic activities, particularly the operation of the Xuan Son waste treatment plant. To control the eutrophication in the reservoir, measures must be urgently taken to manage the nutrient inputs from leachate from Xuan Son waste treatment plant, and wastewater from lakeside livestock are pollutants source control, comprehensive environmental investigation, environmental impact assessment, and environmental monitoring. To better understand the seasonal variation of CTSI and other trophic limiting factors, frequent monitoring of CTSI and trophic parameters (Chla, SDD) should be conducted, taking advantage of the remote sensing technology.

Acknowledgements

This work has been funded by the NAFOSTED project code 105.08-2019.329. The authors are grateful for the National Foundation for Science and Technology Development, the Laboratories of Faculty of Geology, University of Science, Vietnam National University, Hanoi.

References

APHA, 1998. Standard Methods for the Examination of Water and Wastewater. 20th Edition, American Public Health Association and American Water Works Association and Water Environment Federation. Washington DC. USA. Available online at: https://www.standardmethods.org/.

Carlson R.E., 1977. A trophic state index for lakes. Limnology and Oceanography, 22(2), 361-369. https://doi.org/10.4319/lo.1977.22.2.0361.

Carlson R.E., J. Simpson, 1996. A Coordinator's Guide to Volunteer Lake Monitoring Methods. North American Lake Management Society, 96pp. Available online at: https://www.nalms.org/product/a-coordinators-guide-to-volunteer-monitoring/.

Dao T.S., Nimptsch J., Wiegand C., 2016. Dynamics of cyanobacteria and cyanobacterial toxins and their correlation with environmental parameters in Tri An Reservoir. Vietnam. Journal of Water and Health, 14(4), 699-712. https://doi.org/10.2166/wh.2016.257.

Dat Le, Gia Bach, 2019. Ba Vi District: A need of an official inspection to assess the impacts of lakeside livestock and poultry farms on Suoi Hai reservoir's environmental quality. Economic and Urban Electronic Newspaper. http://kinhtedothi.vn.

Doan Tuan, Dang Tien, 2018. Who "killed" Suoi Hai Reservoir?. Ho Chi Minh city Police Electronic Newspaper. http://congan.com.vn.

Duong T.T., Jähnichen S., Le T.P.Q., Ho, C.T., Hoang T.K., Nguyen T.K., Dang D.K., 2014. The occurrence of cyanobacteria and microcystins in the Hoan Kiem Lake and the Nui Coc reservoir (North Vietnam). Environmental Earth Sciences, 71(5), 2419-2427. Doi: 10.1007/s12665-013-2642-2.

Ha N.T.T., Canh B.D., Thao N.T.P., Nhi B.T., 2016. First experience in modeling spatial distribution of chlorophyll-a concentration and TSI in the West Lake water using Sentinel-2A image. VNU Journal of Science: Earth and Environmental Sciences, 32(2S). Available online at: https://js.vnu.edu.vn /EES/article/view/3016.

Ha N.T.T., Han V.T., Thao N.T.P., Khanh, D.T.M., 2017. Monitoring the trophic state index of Lake Linh Dam using Landsat 8 Imagery. Journal of Mining and Earth Sciences, 58, 42-50. Available online at: http://tapchi.humg.edu.vn/vi/archives?article =1190.

Ha N.T.T., Thao N.T.P., Koike K., Nhuan, M.T., 2017. Selecting the best band ratio to estimate chlorophyll-a concentration in a tropical freshwater lake using sentinel 2A images from a case study of Lake Ba Be (Northern Vietnam). ISPRS International Journal of Geo-Information, 6(9), 290. https://doi.org/10.3390 /ijgi6090290.

Ha T.D., 2018. Assessment of trophic state of Cao Van water reservoir. Journal of Science and Technology in Civil Engineering, 12(4), 78-85. Available online at: https://stce.nuce.edu.vn/index.php/vn/article/ view/1202.

Hai N.T, Hung N.V., Hop N.V., 2019. Eutrophication concern: A case study on several lakes in Dong Ha city. Hue University Journal of Science, 128(1c), 63-68. Available online at: http://jos.hueuni.edu.vn /index.php/hujos-ns/article/ view/5450.

Håkanson L., Bryhn A.C., Hytteborn J.K., 2007. On the issue of limiting nutrient and predictions of cyanobacteria in aquatic systems. Science of the Total Environment, 379(1), 89-108. https://doi.org/ 10.1016/j.scitotenv.2007.03.009.

Hoang T.H.T., Nguyen V.D., Van A.D., Nguyen H.T., 2020. Decision tree techniques to assess the role of daily DO variation in classifying shallow eutrophicated lakes in Hanoi. Vietnam. Water Quality Research Journal, 55(1), 67-78. https://doi.org/10.2166 /wqrj.2019.105.

Hop N.V., Thi P.N.A., Hoang N.H., Van V.T.B, ToT.C., 2012. Water quality and eutrophic status of the lakes in Hue citadel. Hue University Journal of Science, 73(4), 93-102. Available online at: https://hueuni.edu.vn/portal/data/doc/tapchi/103.pdf.

Hung N.T., Huyen N.T.T., 2010. Studying on water quality of Dai Lai reservoir by one year of field investigation and data collection. Journal of Water Resources and Environmental Engineering, 31, 1-8. Available online at: http://tapchivatuyentap.tlu. edu.vn/portals/10/So% 2030/So%203100010.pdf.

Istvánovics V., 2010. Eutrophication of Lakes and Reservoirs. In: Gene E. Likens, (Editor) Encyclopedia of Inland Waters. Oxford: Elsevier, 1, 157-165. Doi: 10.1016/B978-012370626-3.00141-1.

Kumar P., Mahajan A.K., Meena N.K., 2019. Evaluation of trophic status and its limiting factors in the Renuka Lake of Lesser Himalaya, India. Environmental Monitoring and Assessment, 191(2), 105. https://doi.org/10.1007 /s10661-019-7247-0.

Linh N.T., Hoa N.T., Tu D.T., Vinh P.Q., Ha N.T.T., 2020. Evaluating and monitoring eutrophication in Truc Bach Lake in space and time using Sentinel 2A image. Journal of Environmental Economics, 166, 11-17. Available online at: https://kinhtemoitruong.vn/index.php/tap-chi-kinh-te-moi-truong-so-166-thang-92020-50000.html.

Linh N.T., Thao P.T.H., Phuong L.T., Han V.T., Ha N.T.T., Vinh P.Q., 2019. Using Sentinel-2B Imagery to Estimate the Eutrophication Level of Linh Dam Lake, Hoang Mai District, Hanoi. VNU Journal of Science: Earth and Environmental Sciences, 35(4), 88-96. https://doi.org/10.25073/2588-1094/vnuees. 4471.

Mamun M., Kim J.Y., An K.G., 2021. Multivariate Statistical Analysis of Water Quality and Trophic State in an Artificial Dam Reservoir. Water, 13(2), 186. https://doi.org /10.3390/w13020186.

Naumann E., 1929. The scope and chief problems of regional limnology. Internationale Revue der gesamten Hydrobiologie und Hydrographie, 22(1), 423-444. https://doi.org/10. 1002/iroh.19290220128.

Ngatia L., Taylor R., 2018. Phosphorus eutrophication and mitigation strategies. In Phosphorus-Recovery and Recycling. Intech Open. Doi: 10.5772/intechopen.79173.

Ngoc N.T.B., An V.D., Quynh L.T.P., Thuy N.B., Nghia L.D., Thuy D.T., Cuong H.T., 2017. Assessment of the trophic status in some lakes within Hanoi inner city. Vietnam Journal of Science and Technology, 55(1), 84-92. https://doi.org/10.15625/0866-708X /55/1/8575.

Nguyen T.H.H., Pham T.B.D., Dang T.L., Nguyen N.T., Nguyen D.T., Pham T.M., Tran D.K., 2015. Microalgae as indicators of eutrophication in Hoan Kiem lake, Hanoi, Vietnam. Vietnam Journal of Biotechnology, 13(2), 355-365. Available online at: http://thongtinkhcn.vinhlong.gov.vn:81/index.php?option=com_chronoconnectivity&connectionname=tapchikhcn&cf_id=58404.

Okech E.O., Kitaka N., Oduor S.O., Verschuren D., 2018. Trophic state and nutrient limitation in Lake Baringo, Kenya. African Journal of Aquatic Science, 43(2), 169-173. https://doi.org/10.2989 /16085914.2018.1462139.

Pavluk T., Bij D.V.A., 2013. Trophic index and efficiency. In Reference Module in Earth Systems and Environmental Sciences, 1-9. Doi: 10.1016/B978-0-12-409548-9.00608-4.

Pham T.L., Dao T.S., Shimizu K., Lan-Chi D.H., Utsumi M., 2015. Isolation and characterization of microcystin-producing cyanobacteria from Dau Tieng Reservoir. Vietnam. Nova Hedwigia, 101(1-2), 3-20. Doi: 10.1127/nova_hedwigia/2014/0243.

Prasad D., Siddaraju G., 2012. Carlson's Trophic State Index for the assessment of trophic status of two Lakes in Mandya district. Advances in Applied Science Research, 3(5), 2992-2996. Available online at: https://www.imedpub.com/articles/carlsons-trophic-state-index-for-the-assessment-of-trophic-status-of-twolakes-in-mandya-district.pdf.

Thuan T.D., Lap B.Q., 2018. Some characteristics of eutrophication in a shallow lake in Hanoi. Journal of Water Resources and Environmental Engineering, 61, 52-61. Available online at: https://vjol.info.vn /index.php/DHTL/article/view/36470.

Tien N.T.H., Van N.S., Nguyen V.T.H., Thoa K.T., Tuan N.D., Van K.V., 2018. Current status of water quality, sediments of West Lake (Ha Noi) and some solutions for aquatic resources conservation. Vietnam Journal of Agricultural Science, 16(5), 464-472. Available online at: http://tapchi.vnua.edu.vn /wp-content/uploads/2018/10/T%E1%BA%A1p-ch %C3%AD-%E1%BB%91-5.464-4721.pdf.

Toan V.D., 2012. Assess the impact of Xuan Son landfill to water environment and solution proposed. Journal of Water Resources and Environmental Engineering, 39, 28-33. Available online at: http://tapchivatuyentap.tlu.edu.vn/Portals/10/So%20 39/So%203900 005.pdf.

Trung B., Dao T.S., Faassen E., Lürling M., 2018. Cyanobacterial blooms and microcystins in Southern Vietnam. Toxins, 10(11), 471. https://doi.org/ 10.3390/toxins10110471.

Trung N.H., Hop N.V., 2020. Assessment of water quality and eutrophication status at several lakes in Da Nang city. Hue University Journal of Science, 16(2), 31-41. Available online at: http://joshusc. hueuni.edu.vn/upload/vol_16/no_2/568_abstract_5. Hoa%20-%20Hop%20%20Nguyen%20Van%20 Hop.pdf.

Tuan D.H., Mung V.T., Cuong D.M., 2017. Evaluation of water quality of a Blue Lake at An Son commune, Thuy Nguyen district, Hai Phong city by Water Quality Index (WQI), Trophic State Index (TSI) and Heavy Metal Pollution Index (HPI). VNU Journal of Science: Earth and Environmental Sciences, 33(1S), 45-54. https://doi.org/10.25073/2588-1094/vnuees. 4147.

Vietnam Ministry of Science and Technology, 2008. Vietnam National Standards: Water quality - Determination of phosphorus - Ammonium molybdate spectrometric method, code: TCVN-6202:2008 (ISO-6878: 2004). Available online at: https://tieuchuan.vsqi.gov.vn /tieuchuan/view?sohieu=TCVN+6202%3A2008.

Vinh P.Q., Ha N.T.T., Binh N.T., Thang N.N., Oanh L.T., Thao N.T.P., 2019. Developing algorithm for estimating chlorophyll-a concentration in the Thac Ba Reservoir surface water using Landsat 8 Imagery. Vietnam Journal of Earth Sciences, 41(1), 10-20. https://doi.org/10.15625/0866-7187/41/1/ 13542.

Vollenweider R.A., Giovanardi F., Montanari G., Rinaldi A., 1998. Characterization of the trophic conditions of marine coastal waters with special reference to the NW Adriatic Sea: proposal for a trophic scale, turbidity and generalized water quality index. Environmetrics: The official journal of the International Environmetrics Society, 9(3), 329-357. https://doi.org/10.1002/(SICI)1099-095X(199805 /06)9:3<329::AID-ENV308>3.0.CO;2-9.

Vollenweider R.A., Kerekes J., 1982. Eutrophication of waters. Monitoring, assessment and control. Organization for Economic Co-Operation and Development (OECD). Paris, 156p. https://doi.org/10.1002/iroh.19840690206.

Yen T.T.H., Luom L.T., Luu P.T., 2019. Assessing Eutrophic Status and Environmental Factor Regulating Green Algae Community in Tri An Reservoir. Vietnam Journal of Agricultural Science, 17(8), 645-664. Available online at: http://tapchi.vnua.edu.vn/wp-content/uploads /2019/12/so-8.2.6.pdf.

Youcai Z., 2018. Chapter 1 - Leachate generation and characteristics. Pollution Control Technology for Leachate from Municipal Solid Waste. Butterworth-Heinemann, 1-30. https://doi.org/10.1016/B978-0-12-815813-5.00001-2.

Zhang Z.S., Mei Z.P., 1996. Effects of human activities on the ecological changes of lakes in China. GeoJournal, 40(1), 17-24. Available online at: https://www.jstor.org/stable /41146969.