Eutrophication Factor Analysis Using Carlson Trophic State Index (CTSI) Towards Non-Algal Impact Reservoirs in Taiwan

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Abstract

Carlson trophic state index (CTSI) has been commonly adopted to assess the eutrophication potential of reservoirs or lakes in water quality management. This study aims to analyze the influencing factors of CTSI-based eutrophication by using Pearson correlation analysis and principal component analysis (PCA) with long-term data from 2008 to 2019 on 21 drinking water reservoirs in Taiwan. The trophic state index (TSI) deviation indicates that most drinking water reservoirs in Taiwan, around 45.5% of statistical data fall into non-algal turbidity with surplus phosphorus, especially in the spring and winter season. Besides, there are about 78 % of total collected data show that TSI (Chl-a) is less than TSI (SD) due to the small particulate predominance. On the other hand, three TSI variables (Secchi depth (SD), total phosphorus (TP) and chlorophyll-a (Chl-a)) of CTSI exhibits insignificant correlation to each other in most cases. At such a condition, the probability of eutrophication ($TSI > 50$) based on TSI (SD) is 63%, while it is only as low as 20% based on TSI (TP) and TSI (Chl-a). The influencing factors of eutrophication variables by suspended solids (SS) composition and turbidity have shown that the SD is strongly influenced by non-algal SS. The deviations of three TSI have shown that the highest algae-induced eutrophication potential occurs in the summer season. In addition, the TP is the most significant loading factor of algae-induced eutrophication for drinking water reservoirs. It is concluded that the CTSI has limited applicability to identify the trophic status of drinking water reservoirs in Taiwan in the presence of sustainable non-algal turbidity comparative Chl-a that completely represents algal growth potential (AGP).

1. Introduction

Water quality issues in drinking water reservoirs have attracted worldwide attention. Eutrophication is one of the most challenging water quality issues in drinking water reservoir management, which is exacerbated by the accumulation of macronutrients that increase algae growth rapidly [1]. Macronutrients such as phosphorus and nitrogen are stored in reservoirs by runoff from anthropogenic activities nearby watersheds [2, 3]. Nutrients can contaminate the surface waters in reservoirs in various ways, which can be attached or adsorbed to particles like clay or dissolved in water [4]. Unfavourable anthropogenic impacts are known to discharge a massive amount of untreated wastewater [5], and then it is strengthened as the change in temperature caused by global climate changes. This influences the increase in total organic production and the degree of saprobity, which predominate the occurrence and dynamics of eutrophication [6]. Eutrophication-related microorganisms can pose serious health risks to consumers by causing respiratory irritation [7] and cause an environmental problem with water supply interruption [8]. Hence, it is crucial to evaluate the eutrophication potential in the water quality management of reservoirs for drinking water supply.

Carlson trophic state index (CTSI) has been adopted to assess the eutrophication potential in the reservoirs as an early warning of environmental changes [9]. The strategy to assess and control these systems is by using a standardized index based on the trophic continuum division. This index classifies the reservoirs into different categories, which are oligotrophic, mesotrophic, and eutrophic. It focuses on the measurement of Secchi disk transparency (SD), total phosphorus (TP), and algal biomass through

the form of chlorophyll-a (Chl-a) present in all green algae species. Initially, this approach is helpful for classifying and communicating environmental changes to the public, especially for the temperate lake [10]. Lately, an issue on the misapplication of the original TSI approach developed by Carlson for tropical/subtropical countries and regardless of the type of environmental system such as reservoirs have been concerned [11]. Nevertheless, it must be understood that the relationships and the equations for analysis of the index should be considered to the water bodies systems with different ecological structure and functional patterns. Otherwise, the conclusion of the index application may lead to a misidentification of the trophic state [12]. The adaptations may also be related to new parameters such as new nitrogen-based or the modified equations of the original Carlson approach [13]. A case study of the Paranapanema Reservoir confirmed that the CTSI overstated the trophic condition where the trophic state is mainly categorized as eutrophic and hypereutrophic [11].

Some factors such as abiotic and biotic that influence trophic states of the reservoir are still challenging [14]. Hence, further study of which factors related to the TSI variables are still required for the well-managed trophic states [15]. A previous study has identified that Chl-a in the eutrophicated reservoirs in Taiwan is not the most significant contributor to the CTSI level [16]. Another study has confirmed that suspended solid had a better correlation with TSI (SD) over Chl-a, and it is more significant than those of TP and Chl-a level [15]. While the value of TSI (Chl-a) and TSI (SD) should have a strong correlation for considering the light attenuation is highly influenced by the preeminence of algae [17]. Besides, there is a strong association between intense rainfall and eutrophication potential [18, 19]. Heavy rain causes sediment discharge into the reservoir, increasing inorganic suspended solids and reducing the SD level [20]. Hence, the inorganic suspended solids (non-algal turbidity) increase as rainfall intensity increases, affecting SD variations over Chl-a [15]. This condition could not be associated with the eutrophication process. An algae management strategy is inappropriate to be the primary strategy.

Although numerous studies have hitherto evaluated trophic status misconception using the CTSI approach [11, 12, 16], the implication and application of CTSI remain unclear for non-algal impact reservoirs. The evaluation of CTSI misconception should be explicitly explained in which condition of CTSI can be implemented. Besides, those studies provided limited information about eutrophication factors because only short-term data analysis was conducted. The misapplication of CTSI should be clarified by using long-term correlation data for various reservoirs to ensure the accuracy of CTSI evaluation. The correlation between three TSI values based on CTSI using Pearson analysis with long-term data obtained from 2008-2019 on 21 drinking water reservoirs in Taiwan was evaluated for this study. The influencing factors of TSI towards non-algal impact reservoirs and its deviation were also identified. Finally, the principal component analysis (PCA) was conducted to determine the loading factors to water quality and eutrophication.

2. Materials And Methods

2.1 Description of the study area

Taiwan is categorized as a tropical and subtropical area and located off the southeast coast of China. Taiwan's geographical position is between $21^{\circ} 45' 25''$ to $25^{\circ} 56' 31''$ north latitude and $119^{\circ} 18' 3''$ to $124^{\circ} 34' 30''$ east longitude [21]. The average annual rainfall in Taiwan is 2515 mm, around 2.6 times the global average, which frequently occurs in the period between May and October [22]. Tropical storms regularly occur in Taiwan during typhoon seasons and significantly increased sediments and nutrients in the reservoirs [23]. Twenty-two reservoirs have been constructed since 1970 to satisfy the growing demand for freshwater due to rapid economic and population growth [21]. The total sufficient storage capacity of all human-made reservoirs in Taiwan is $2.2 \times 10^9 \text{ m}^3$ and used for public water supply, power generation, industrial, and irrigation [24].

There has been a massive overlap between forested and agricultural land since 1956. Expansion of agricultural land is intimately associated with increasing population growth in Taiwan [25]. Phosphorus is an essential nutrient for the fertilizer processes in the agricultural sector [26]. Another study clarified that phosphorus and another nutrient could be obtained from municipal wastewater or sewage [27]. Taiwan Environmental Protection Administration has published the annual data on wastewater pollution in Taiwan. The total volume of wastewater discharged about 634 metric tons into water bodies. Consisting of 65 metric tons from the agricultural sector, 55 metric tons from the manufacturing industry and 514 metric tons from urban wastewater discharged [28]. These conditions cause eutrophication or contamination in the reservoir water.

2.2 Physicochemical data collection

The designated physicochemical data in terms of chlorophyll-a (Chl-a), total phosphorus, Secchi disk (SD), suspended solids (SS), turbidity, ammonia (NH_3), and chemical oxygen demand (COD) were obtained from Taiwan Environmental Protection Administration (Taiwan EPA) for 21 drinking water reservoirs from 2008 to 2019. The water samples were collected from the epilimnion with a depth of less than 1 meter. All the designated data were stored and processed once per month. For spring season is from March to May, the summer season is from June to August, the autumn season is from September to November, and the winter season is from December to February. Data collection aims to provide a detailed understanding of water bodies by using the CTSI method. All the data in this research were collected using the newest version of APHA Standard Methods proposed by the Taiwan Environmental Protection Administration.

2.3 Carlson trophic state index for eutrophication potential calculation

Carlson trophic state index [9] was used to assess the eutrophication potential of the reservoirs in Taiwan in this study. Three variables were used to calculate the value of CTSI such as chlorophyll-a (Chl-a), total phosphorus (TP), and Secchi disk transparency (SD) based on the following equations:

$$TSI(SD) = 10 \times [6 - \ln(SD) / \ln 2] \quad (1)$$

$$TSI (Chl - a) = 10 \times [6 - (2.04 - 0.68 \ln(Chl - a)) / \ln 2] \quad (2)$$

$$TSI (TP) = 10 \times [6 - \ln(48/TP) / \ln 2] \quad (3)$$

$$CTSI = [TSI(SD) + TSI(Chl - a) + TSI(TP)]/3 \quad (4)$$

Three variables of trophic state index (TSI) which first calculated by using Eqs. (1), (2), (3), then calculated with Eq. (4). The limits for reservoir trophic state levels according to the original Carlson trophic state index were classified as oligotrophic ($0 < CTSI \leq 30$), mesotrophic ($30 < CTSI \leq 50$), eutrophic ($50 < CTSI \leq 70$), and hypereutrophic ($70 < CTSI \leq 100$). Eutrophication potential was used in this study in order to evaluate the overall status of each reservoir in Taiwan. Eutrophication potential was calculated by the following equation below:

$$Eutrophication\ Potential = \frac{\text{number of } CTSI > 50}{\text{All number of } CTSI} \times 100\% \quad (5)$$

The relationship between "TSI (Chl-a) – TSI (SD)" and "TSI (Chl-a) – TSI (TP)" was used to interpret the deviation of the trophic state index based on the two-dimensional analysis. This approach is generally used to indicate the degree of light penetration relative to the size of particles based on the deviations of TSI (Chl-a) from TSI (SD), while the deviations of TSI (Chl-a) from TSI (TP) identify nutrient limitation in reservoirs [29].

2.4 Statistical analysis

Influencing factors analysis of Carlson trophic state index (CTSI) was identified using Pearson's correlation analysis. CTSI indicators such as TSI (Chl-a), TSI (SD), TSI (TP), and other water quality parameters such as suspended solids and turbidity were used for this approach to evaluate the correlation between variables. The Pearson correlation coefficient is given as Eq. (6):

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{[\sum_{i=1}^n (x_i - \bar{x})^2] [\sum_{i=1}^n (y_i - \bar{y})^2]} \quad (6)$$

Pearson's product-moment correlation coefficient is symbolized as " r " and commonly used when two variables are normally distributed. It can be interpreted that $-1 \leq r \leq +1$. There is no linear relation between the variables x and y if r is about zero. Otherwise, if r is close to -1 or $+1$ means that there is a strong linear relationship between the variables [30]. High, medium and low correlations among parameters are indicated by $r > 0.7$, $0.4 < r < 0.7$, and $r < 0.4$, respectively [31].

Principal component analysis (PCA) was used on a set of data including TSI (chl-a), TSI (TP), TSI (SD), SS, Chl-a, SD, TP, turbidity, NH_3 , and COD. PCA was calculated mathematically using covariance to determine the factor loads of the selected parameters. Besides, PCA was used to determine the parameters which act as driving factors.

3. Results And Discussion

3.1 Eutrophication potential of drinking water reservoirs by CTSI assessment

The results of eutrophication potential by using trophic state index assessment are shown in Fig. 1. In Taiwan, there are 5 reservoirs that have a eutrophication potential of more than 50%, namely Feng-Shan, Ming-Te, Ching-Mien, Cheng-Ching-Hu, and Pai-Ho reservoirs. Feng-Shan reservoir is the most severely eutrophicated reservoir in Taiwan and classified as hypereutrophic based on CTSI value, as shown in Fig. S1. It has the highest potential than other reservoirs, approximately 100% followed by Ming-Te, Ching-Mien, Cheng-Ching-Hu, and Pai-Ho Reservoirs, respectively. This present finding is consistent with a previous trophic state classification study [21]. High eutrophication levels affected by nonpoint source pollution from fertilizers and farm drainage cause excessive algal growth [32]. Feng-Shan reservoir is fed by a river tributary that is downstream from hundreds of pig farms. Farmers discharged their pig manure massively into the river [33], rich in organic matter, nitrogen, and phosphorus [34]. In Taiwan, the main watersheds are mostly fragile slate, and poor soil conservation induces sand and gravel upstream are easily flushed down to the reservoir by high precipitation [21]. The adverse effects of eutrophication induce loss of dissolved oxygen in the reservoir [35] and the rapid growth of harmful phytoplankton [36]. Eutrophication assessment is still necessary in order to prevent the detrimental impact on reservoirs, especially in the anthropogenic influences [37]. The results have shown a significant divergence of eutrophication level for 21 drinking water reservoirs based on CTSI evaluation.

3.2 Deviations of three TSI variables in CTSI application

The analysis of trophic state index deviations was followed by a previous study [29]. It describes that approximately 78% of the studied reservoirs were categorized into a small particulate predominance based on the relations between "TSI (Chl-a) – TSI (SD)" and "TSI (Chl-a) – TSI (TP)" during all the seasons as shown in Fig. 2. The influence of larger particulates and the effect of algae growth are negligible. It indicates that non-algal turbidity occurred in most reservoirs, as evidenced in Fig. S2. Non-algal particulates such as color or turbidity, which are derived from external or internal sources, produce sufficient light extinction to limit algal productivity [17]. These findings also suggest that phosphorus is not the dominant factor limiting the trophic state for non-algal impact reservoirs. This outcome is contrary to a recent study which has found that most studied reservoirs show a dominance of larger particles and phosphorus limitation occurs at a high algal growth condition [38]. This discrepancy could be attributed to the dominant nutrient regulating the trophic state. When there is available surplus phosphorus in reservoirs, nitrogen is known to be the dominant factor regulating the trophic state or some other factors that co-varied with nitrogen [29, 39, 40]. In contrast, the small particulates predominance condition indicates that a low water transparency level is dominantly formed by inorganic sediment than Chl-a [41].

For further understanding in TSI deviations at various seasons, this study identified the effect of seasonal variations on the trophic state index values of 21 drinking water reservoirs in Taiwan. Figure 3 shows that non-algal turbidity (Region III) dominantly occurred during all seasons. However, small particulates predominance and P limitation were markedly formed in the summer and autumn season. It could be attributed to the algae growth is likely increased in high temperature. This finding is also supported by some studies which have confirmed that high temperature deteriorates water quality and increases cyanobacteria occurrence and diatom blooms in reservoirs to cause significant eutrophication [42, 43, 44]. Another study also has proven that wind speed in summer has a substantial impact on alga growth. In addition, wind speed in different seasons could gradually suspend the phosphorus and promote algal growth [45]. It can be concluded that seasonal variations affect the level of eutrophication for drinking water reservoirs, especially in the summer and autumn seasons.

Although Taiwan is categorized as subtropical/tropical area, which has a productive season, most drinking water reservoirs in Taiwan were classified as mesotrophic, approximately 57% as shown in Fig. 4a. It could be associated with the residence time in reservoirs, which is very low compared to the lakes. Higher residence time can affect the trophic state index more significantly [12]. However, approximately 30% of trophic state index classification was categorized as eutrophic (Fig. 4a) based on the averaged CTSI values higher than 50 occurs in one-year evaluation, where the highest ratio occurs in the summer season (Fig. 4b). It could be associated with the intense rainfall in subtropical/tropical areas that significantly suspend sediment (i.e., inorganic particles). In addition, the increased temperature in summer also improves Chl-a level attributed to the increasing algae growth. Additionally, the trophic state level is much higher in the summer season.

3.3 Empirical relationship of TSI variables

The correlation of trophic state index variables was quantified to understand the relationship between TSI variables. Figure 5 shows that there is an insignificant correlation among three TSI variables. Only some reservoirs have a medium correlation between TSI (SD) and TSI (TP). It is similar to a previous study in Taiwan, which has shown that the correlation between trophic state index was insignificant [15]. The outliers can be extremely sensitive to the Pearson correlation values cause the strength of a relationship can be exaggerated or diminished by extreme values indicate that the variables are not normally distributed. Therefore, it is inappropriate to use trophic state index variables when the correlations are not normally distributed [46]. This finding has indicated that the CTSI application could not show the actual trophic state of drinking water reservoirs without strong algal impact in Taiwan.

For further investigation in the contribution to CTSI at independent TSI, the calculations of trophic state index higher than 50 on 21 reservoirs in Taiwan are presented in Table 1. It has revealed that the proportion of trophic state index variables is dominated by TSI SD, approximately 63% over TSI (Chl-a) and TSI (TP). TSI (Chl-a) and TSI TP only contributed 24% and 20%, respectively to the CTSI level. In the specific case of CTSI higher than 50, TSI (SD) significantly contributed as much as 96%. Figure 6 illustrates that TSI (SD) values had a higher level compared with the other TSI variables. This result is similar to a recent study, which has shown that TSI (SD) plays a dominant role in the CTSI levels [16] due

to the high rainfall rate, heavy storm runoff [23], and direct nutrient discharges [47], leading to increase the high turbidity level of reservoirs in Taiwan. The deviations of three TSI values have indicated that the CTSI has limited applicability on water quality management for Taiwan reservoirs.

Table 1
The proportion of TSI variables are greater than 50 for 21 reservoirs in Taiwan

CTSI variables	The proportion of TSI>50	The proportion of TSI>50 as CTSI is higher than 50
TSI(SD)	63	96
TSI(Chl-a)	24	60
TSI(TP)	20	58

Water transparency in the reservoir system can be controlled by suspended solid [48] and phytoplankton biomass [38]. The correlation between TSI (SD) and influencing water quality parameters such as turbidity and suspended solid were investigated further. For the purpose of comparison, the correlation between TSI (Chl-a) and suspended solid was observed. Figure 7 shows that the correlation of suspended solids and chlorophyll concentration was negligible. On the contrary, there was a significant correlation between turbidity, suspended solids, and TSI (SD). This result is similar to the previous studies in Taiwan, which have confirmed that suspended solid played the biggest TSI (SD) value contribution [15, 16]. These findings suggest that suspended solid strongly influences the water clarity because non-algal turbidity occurred in most reservoirs in Taiwan.

Figure 8a shows that when TSI (SD) values lesser than 50, 2 reservoirs have a significant correlation between TSI variables, namely Jen-Yi-Tan and Hu-Shan Reservoirs. While the other reservoirs have an insignificant correlation. On the contrary, Figure 8b shows that when TSI (SD) values higher than 50, it is highlighted that some reservoirs have a medium correlation between TSI (TP) and TSI (SD). It indicates that particulate phosphorus influenced the water transparency level. While there is an insignificant correlation of other TSI variables. These findings also suggest that putting TSI (SD) in CTSI calculation is unable to show the distribution level of each CTSI variable for non-algal impact reservoirs. It can be concluded that when non-algal turbidity occurs in reservoirs, the use of TSI (SD) data to infer algal biomass and trophic state is inappropriate where even moderate amounts of non-algal turbidity are present [49]. Despite the fact that non-algal turbidity occurs in most reservoirs in Taiwan, the CTSI can still be used for a specific condition. The CTSI application is more reasonable as the TSI (SD) level limitation is lower than 50 or at a low turbidity level (<5 NTU) in Taiwan. Thus, the algae-carried Chl-a is more suitable as a single trophic state index to evaluate the eutrophication potential for Taiwan reservoirs.

3.4 Relationship of eutrophication influencing factors

The result of Carlson's trophic state index based on two-dimensional analysis is shown in Table 2, the first component (C1) obtains 55,87% of the total variances. Based on the trophic state index value, this

study has revealed that TP has the highest factor loading of the main component, while the factor loading of Chl-a, COD and NH₃ are similar. The correlation between TSI (TP) and TSI (SD) or TSI (Chl-a) is improved for most cases where it has a medium Pearson correlation value when the TSI (SD) values are higher than 50 at high turbidity level (Fig. 8b). Furthermore, as seen in Fig. 9, the TSI (Chl-a) has the insignificant factor load of the second component, where the TSI (SD) has the highest factor load along with a close tendency of SS. In addition, there is a negative correlation between Chl-a and SD. It suggests that most drinking water reservoirs in Taiwan are operated under long-term turbid impact with limited algal particulates dominance. The critical finding in this study is total phosphorus is confirmed to be the most significant influencing factor on water quality in terms of COD, NH₃ and Chl-a (as seen in Table 2). Based on PCA inferences, it indicates that CTSI approach could often leads to confusion because the assessment criteria for CTSI can be degraded by factors such as suspended solids, which does not actually reflect the eutrophication potential. Thus, the best strategy for water quality management is proposed to strengthen TP regulation in the upstream catchment area of drinking water reservoirs and minimize TP loading in reservoirs, which could significantly influence the variety of algal growth, ammonia, and organic matter loadings.

Table 2
Factor analysis results of the significant water quality parameters

Water Quality	Component 1	Component 2
SD	-0.103	-0.934
Chl-a	0.768**	0.259
TP	0.907**	0.127
SS	0.378	0.687*
COD	0.748**	0.329
NH ₃	0.810**	0.007
TSI(TP)	0.774**	0.433
TSI(SD)	0.213	0.949**
TSI(Chl-a)	0.625*	0.333
Initial Eigenvalues	55.871%	16.924%
Kaiser-Meyer-Olkin	0.78	
p-value	<0.001	
Double asterisks (**): a strong factor loading; a single asterisk (*): a medium factor loading		

4. Conclusions

In Taiwan, there are 5 reservoirs, namely Feng-Shan, Ming-Te, Ching-Mien, Cheng-Ching-Hu, and Pai-Ho reservoirs, with a eutrophication potential more than 50% based on Carlson trophic state index (CTSI) assessment. The Pearson analysis of trophic state index variables has shown an insignificant correlation, and it also indicates that the proportion of trophic state index variables is dominated by TSI (SD) over TSI (Chl-a) and TSI (TP). It indicates that most reservoirs in Taiwan are under non-algal turbidity impact. Carlson's trophic state index based on two-dimensional analysis has interpreted that the quantity of phosphorus is dominantly responsible for the substantial impacts on reservoir water quality. The use of CTSI to assess algal biomass for strategic management purposes and trophic classification is inappropriate for most reservoirs in Taiwan, while the applicability of CTSI for Taiwan reservoirs is much higher when TSI (SD) is lower than 50. Based on PCA inferences, TP is the dominant eutrophication influencing factor for Taiwan drinking water reservoirs. This study provides the informative approach and reference data for further eutrophication potential evaluation of non-algal impact reservoirs.

Declarations

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare they have no competing interests.

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Authors' contributions

Jr-Lin Lin: Conceptualization, Resources, Visualization, Writing–Original Draft, Writing - Review & Editing, Validation, Supervision. **Arthur Karangan:** Writing–Original Draft, Writing and Editing, Methodology, Formal Analysis. **Ying Min Huang:** Methodology, Formal Analysis. **Shyh-Fang Kang:** Conceptualization, Supervision. All authors read and approved the final manuscript.

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Figures

Figure 1

Eutrophication potential of 21 reservoirs in Taiwan from 2008 to 2019 under CTSI rating

Figure 2

Classification of deviations between different TSI values for 21 drinking water reservoirs in Taiwan. (The number of available data is shown for each condition as N.)

Figure 3

Proportion of scattering data based on deviations between TSI in different regions for 21 reservoirs in Taiwan under seasonal variations. The variations of index are represented by region I to IV. Region I: $TSI(Chl-a) < TSI(SD)$ and $TSI(Chl-a) > TSI(TP)$; Region II: $TSI(Chl-a) > TSI(SD)$ and $TSI(Chl-a) > TSI(TP)$; Region III: $TSI(Chl-a) < TSI(SD)$ and $TSI(Chl-a) < TSI(TP)$; Region IV: $TSI(Chl-a) > TSI(SD)$ and $TSI(Chl-a) < TSI(TP)$

Figure 4

The ratio of (a) trophic state based on classification and (b) CTSI value over 50 based on seasonal variations

Figure 5

Pearson's Correlation analysis based on TSI (Chl-a), TSI (TP), and TSI (SD). The red line indicated a medium and high correlation between TSI variables

Figure 6

The scatter of trophic state index (TSI) values on 21 reservoirs in Taiwan

Figure 7

Pearson's correlation coefficient (r) for SS, turbidity, TSI (SD), and TSI (Chl-a)

Figure 8

Pearson's correlation analysis of trophic state index variables under the condition of (a) TSI (SD) <50 and (b) TSI (SD) >50

Figure 9

Principal Component Analysis (PCA) on various water quality parameters

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