

RESEARCH

Open Access



Eutrophication factor analysis using Carlson trophic state index (CTSI) towards non-algal impact reservoirs in Taiwan

Jr-Lin Lin^{1,2}, Arthur Karangan¹, Ying Min Huang¹ and Shyh-Fang Kang^{3*}

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 influential factors of CTSI-based eutrophication by using Pearson correlation analysis and principal component analysis 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, around 45.5% of statistical data fall within non-algal turbidity with surplus phosphorus, especially in the spring and winter season. Besides, about 78% of total collected data show that TSI chlorophyll-a (Chl-a) is less than TSI Secchi depth (SD) due to the small particulate predominance. On the other hand, three TSI variables (SD, total phosphorus (TP) and Chl-a) of CTSI exhibits insignificant correlation to each other in most cases. Under such conditions, the probability of eutrophication (TSI > 50) based on TSI (SD) is 63%, while it is 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 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 state of drinking water reservoirs in Taiwan in the presence of sustainable non-algal turbidity comparative Chl-a that specifically represents the potential of algal growth.

Keywords: Trophic state index, Reservoirs, Eutrophication, Principal component analysis

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 increases algae growth rapidly [1]. Macronutrients such as phosphorus and nitrogen are stored in reservoirs by runoff from anthropogenic activities from nearby watersheds [2]. 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 [3]. Unfavourable anthropogenic impacts are known to discharge a massive amount of untreated wastewater [4], and then it is strengthened as the change in temperature is caused by global climate changes. This influences the increase in total organic production and the degree of saprobity, which predominates the occurrence and dynamics of eutrophication [5]. Eutrophication-related microorganisms can pose serious health risks to consumers by causing respiratory irritation [6], and cause an environmental problem with water supply interruption [7]. Hence, it is crucial to evaluate the eutrophication potential in the

* Correspondence: kangsf@mail.tku.edu.tw

³Department of Water Resources and Environmental Engineering, Tamkang University, New Taipei City 251301, Taiwan
Full list of author information is available at the end of the article



© The Author(s). 2022, corrected publication 2022. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

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 [8]. The strategy to assess and control these systems are using a standardized index based on the trophic state classification. 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. This approach is helpful for classifying and communicating environmental changes (e.g., change of water bodies) to the public, especially for temperate lakes [9]. Lately, an issue on the misapplication of the original TSI approach developed by Carlson for tropical/subtropical countries has been concerned regardless of the type of environmental system (e.g., reservoirs) [10, 11]. Nevertheless, the relationships among each TSI and the equations for the TSI analysis should be considered for aquatic systems with distinct ecological conditions and functional patterns. Otherwise, the conclusion of the TSI index application may lead to a misidentification of the trophic state [11]. The adaptations may also be related to new parameters such as new nitrogen-based or the modified equations of the original Carlson approach [12]. A previous case study has confirmed that the CTSI overstates the trophic state where it is frequently categorized as either eutrophic or hyper-eutrophic [10].

Abiotic and biotic factors influence the trophic states of reservoir are still challenging [13]. Hence, further study of which factors related to the TSI variables are still required for well-managed trophic states [14]. A previous study has identified that Chl-a concentration of the eutrophicated reservoirs in Taiwan is an insignificant contributor to the CTSI level because of predominant suspended solids (SS) [15]. Likewise, one study has confirmed that SS exhibits a better correlation with TSI (SD) over Chl-a for Shihmen Reservoir in Taiwan, and its level is more pronounced than TP and Chl-a level [14]. The TSI (Chl-a) and TSI (SD) should have a strong correlation for considering the light attenuation influenced by the preeminence of algae [16]. Besides, there is a strong association between intense rainfalls and eutrophication potential. Heavy rainfalls would cause sediment discharge into reservoirs, increasing inorganic SS along with the reduced SD level [17]. Thus, the quantity of inorganic SS (non-algal turbidity) increases in reservoirs during rainfall seasons, which causes significant SD variations over Chl-a [14]. Under such conditions, high TSI (SD) value could frequently appear for most of non-algal impact reservoirs, but it is not caused by

eutrophication process with fast algae growth, which would overestimate the CTSI level. At present, the prioritized algae management strategy for most reservoirs in Taiwan is to minimize the loading of nutrients (e.g., TP) in the eutrophicated reservoirs rated by CTSI. Although numerous studies have hitherto evaluated the misconception about trophic state application using the CTSI approach [10, 11, 15], the implication of CTSI remains unclear for non-algal impact reservoirs. The misconception about CTSI application should be explicitly evaluated and explained. Besides, previous studies have provided limited information about eutrophication factors because only short-term data analysis was conducted. The applicability of CTSI should be further clarified by under long-term investigations for various reservoirs. The correlation between three TSI values based on CTSI using Pearson analysis with long-term data obtained from 2008 to 2019 on 21 drinking water reservoirs in Taiwan was evaluated for this study. The influencing factors of TSI towards non-algal impact reservoirs and their deviations were also identified. Lastly, 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 is located off the southeast coast of China. Taiwan's geographical position is between 21° 45' 25" to 25° 56' 31" north latitude and 119° 18' 3" to 124° 34' 30" east longitude [18]. Average annual rainfall in Taiwan is about 2515 mm, around 2.6 times higher than the global average, which frequently occurs between May and October [19]. Tropical storms regularly occur in Taiwan during typhoon seasons and significantly increase the quantity of sediments and nutrients in the reservoirs [20]. The total storage capacity of 61 major reservoirs in Taiwan is 2.2 billion m³ for public water supply, power generation, industrial, and irrigation [21]. So far, there are 21 reservoirs operated for drinking water supply in Taiwan.

Expansion of agricultural land is intimately associated with increasing population growth in Taiwan [22]. Phosphorus is an essential nutrient for the fertilizer processes in the agricultural sector [23]. A previous study has clarified that phosphorus and other nutrient could be obtained from municipal wastewater or sewage [24]. Taiwan Environmental Protection Administration (EPA) has published an annual report on wastewater pollutions in Taiwan. The total volume of wastewater discharged is about 634 m³ d⁻¹ into water bodies (i.e., rivers). It consists of 65 m³ d⁻¹ from the agricultural sector, 55 m³ d⁻¹ from the manufacturing industry, and 514 m³ d⁻¹

from urban wastewater discharged [25]. Based on the collected data of 21 reservoirs from 2008 to 2019 in this study, TP and total nitrogen (TN) contributed up to 1.58 and 3.66 mg L⁻¹, respectively. A previous study also has reported that phosphorus is the primary limiting nutrient in most of reservoirs in Taiwan [18]. Thus, nutrient pollution predominately causes seasonal eutrophication for most reservoirs in Taiwan.

2.2 Water quality data collection

The designated physicochemical data in terms of Chl-a, TP, SD, SS, turbidity, ammonia (NH₃), and chemical oxygen demand (COD) were obtained from 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 m. All the designated data were stored and processed once per month. 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 reservoirs using the CTSI method. All water quality data collected in this research were analyzed following the Standard Methods proposed by Taiwan EPA.

2.3 CTSI for eutrophication potential calculation

CTSI [8] was used to assess the eutrophication potential of reservoirs in Taiwan for this study. All three indices were used to calculate the value of CTSI, including Chl-a, TP, and SD based on the following equations:

$$TSI (SD) = 60 - 14.41 \ln(SD) \tag{1}$$

$$TSI (Chl - a) = 9.81 \ln(Chl - a) + 30.6 \tag{2}$$

$$TSI (TP) = 14.42 \ln(TP) + 4.15 \tag{3}$$

$$CTSI = \frac{TSI (SD) + TSI (Chl - a) + TSI (TP)}{3} \tag{4}$$

Three variables of TSI were first calculated by using Eqs. (1), (2), (3), then CTSI calculated with Eq. (4). Taiwan EPA has launched the CTSI involving an average of three TSI variables since 1994 due to its comprehensiveness in water quality assessment. The limits for reservoir trophic state levels according to the original CTSI were classified as oligotrophic (0 < CTSI ≤ 30), mesotrophic (30 < CTSI ≤ 50), eutrophic (50 < CTSI ≤ 70), and hypereutrophic (70 < CTSI ≤ 100). Eutrophication potential was used in this study in order to evaluate the frequency of eutrophication occurrence (i.e., eutrophication ratio) for each drinking reservoir in Taiwan. The definition of eutrophication potential is the probability that CTSI value exceeds 50 in all investigating data for 21 reservoirs from 2008 to 2019. As the eutrophication

potential value is higher than 50%, it represents the predominance of eutrophic state. Eutrophication potential was calculated with 1432 available data by the following equation:

$$Eutrophication\ potential = \frac{Number\ of\ CTSI > 50}{Number\ of\ CTSI} \times 100\% \tag{5}$$

The relationship between “TSI (Chl-a)–TSI (SD)” and “TSI (Chl-a)–TSI (TP)” was used to interpret the deviations of three indices based on the two-dimensional analysis. This approach is generally used to indicate the degree of light penetration relative to the size of particulates 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 [26]. As shown in Fig. S1, points lying to the right of the y-axis indicate situations where the TSI (SD) is lower than expected from TSI (Chl-a). These deviations may occur if the Chl-a is packaged in large particulates, such as colonial blue-green algae or large filamentous, and the less light is attenuated than an equal biomass of smaller algal particles (Region II). Deviations to the right may also occur if zooplankton grazing removes smaller particles and leaves only large particulates (Region IV). Alternatively, points to the left of the y-axis would be related to situations where TSI (SD) is dominated by non-algal factors such as color or turbidity or the occurrence of very small particles predominance (Region III). If TSI (Chl-a)–TSI (TP) is plotted on the vertical axis, then points below the x-axis would be associated situations where Chl-a is under-predicted by TP, i.e., situations where TP may not limit Chl-a. As points go above the zero axis, it would suggest increasing possibility of phosphorus limitation (Region I). Points lying on the diagonal to the left of the origin indicate situations where TSI (TP) is correlated to TSI (SD) instead of TSI (Chl-a). Points on or near this line would be found in turbid situations where phosphorus is bound to clay particles and therefore turbidity and phosphorus are related, but Chl-a is not related to phosphorus.

2.4 Statistical analysis on influencing factors of eutrophication

Influencing factors analysis of CTSI was identified using Pearson’s correlation analysis. CTSI variables, including TSI (Chl-a), TSI (SD), TSI (TP), and other water quality parameters such as SS and turbidity were used for this approach to evaluate the correlation between all variables. The Pearson correlation coefficient is given as Eq. (6):

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

Pearson’s product-moment correlation coefficient is symbolized as “γ” and it is commonly used when two variables

are normally distributed. It can be interpreted as $-1 \leq \gamma \leq +1$. There is no linear relation between the variables x and y if γ is about zero. Otherwise, γ is close to -1 or $+1$ means that strong negative correlation or strong positive correlation between the variables, respectively [27]. High, medium and low correlations among parameters are indicated by $\gamma > 0.7$, $0.4 < \gamma < 0.7$, and $\gamma < 0.4$, respectively.

PCA was used on a set of data including TSI (Chl-a), TSI (TP), TSI (SD), SS, Chl-a, SD, TP, turbidity, NH₃, and COD. The PCA was calculated mathematically using covariance to determine the factor loads of the selected parameters. Besides, the PCA was used to determine the parameters which act as driving factors.

3 Results and discussion

3.1 CTSI evaluation on eutrophication potential of reservoirs

The results of eutrophication potential by using TSI assessment are shown in Fig. 1. Five reservoirs have exhibited the eutrophication potential as high as more than 50%, including Feng-Shan, Ming-Te, Ching-Mien, Cheng-Ching-Hu, and Pai-Ho Reservoir. Feng-Shan reservoir is the most severely eutrophicated reservoir in Taiwan and classified as hypereutrophic based on CTSI value, as shown in Fig. S2. It has the highest potential than other reservoirs, approximately 100% followed by Ming-Te, Ching-Mien, Cheng-Ching-Hu, and Pai-Ho reservoirs.

This finding is consistent with a previous trophic state classification study [18]. High eutrophication levels affected by nonpoint source pollution from fertilizers and farm drainage cause excessive algal growth [28]. 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 where it is rich in organic matter, nitrogen, and phosphorus. In Taiwan, the main watersheds are mostly fragile slates, and poor soil conservation induces sand and gravel upstream to be easily flushed down to the reservoir by high precipitation [18]. The adverse effects of eutrophication induce loss of dissolved oxygen in the reservoir [29] and the rapid growth of harmful phytoplankton [30]. Therefore, eutrophication assessment is still necessary in order to prevent the detrimental impact on reservoirs, especially from the anthropogenic influences. 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 for CTSI application

The analysis of TSI deviations was used following a previous study reported by Carlson and Havens [26], as shown in Fig. 2. This form of graph places the deviations of the TSI (SD) onto the graph of the other deviations, allowing simultaneous viewing of the deviations of all three indices. The spatial location of the data for a single lake or for a

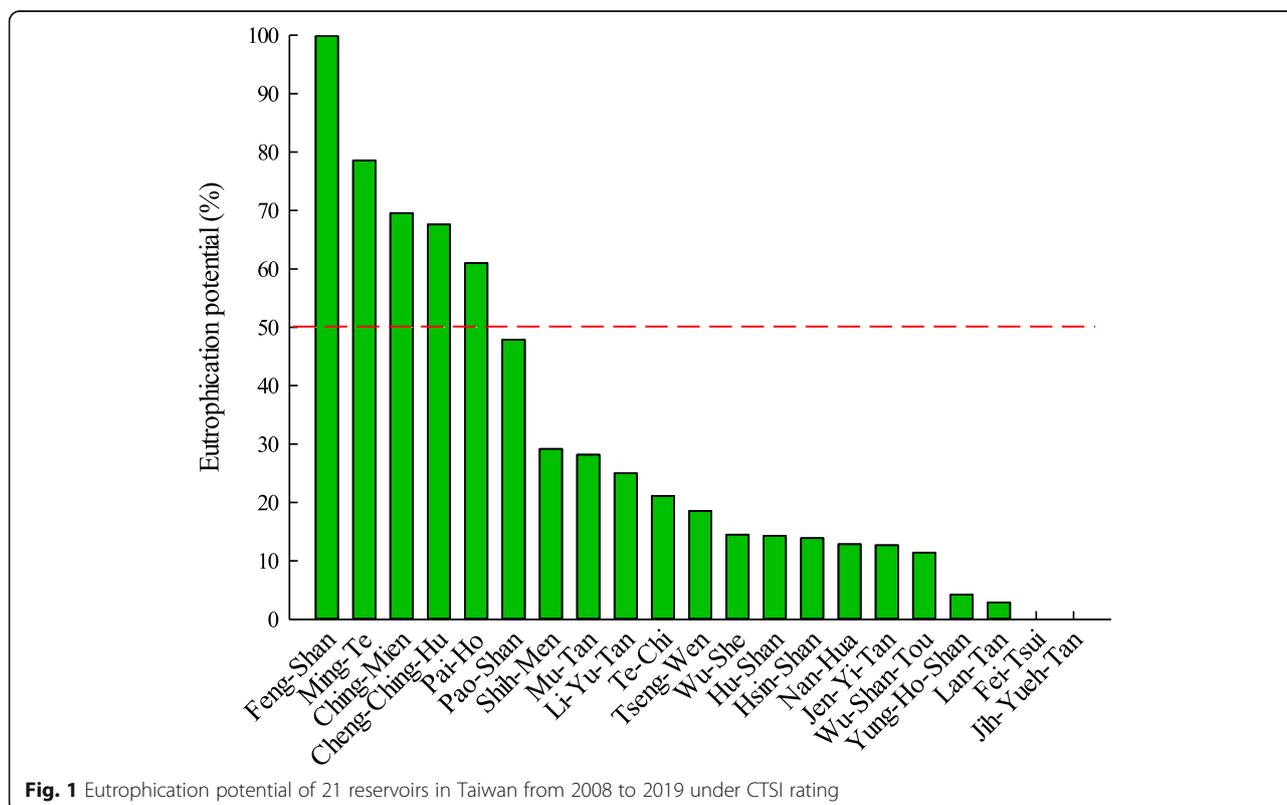
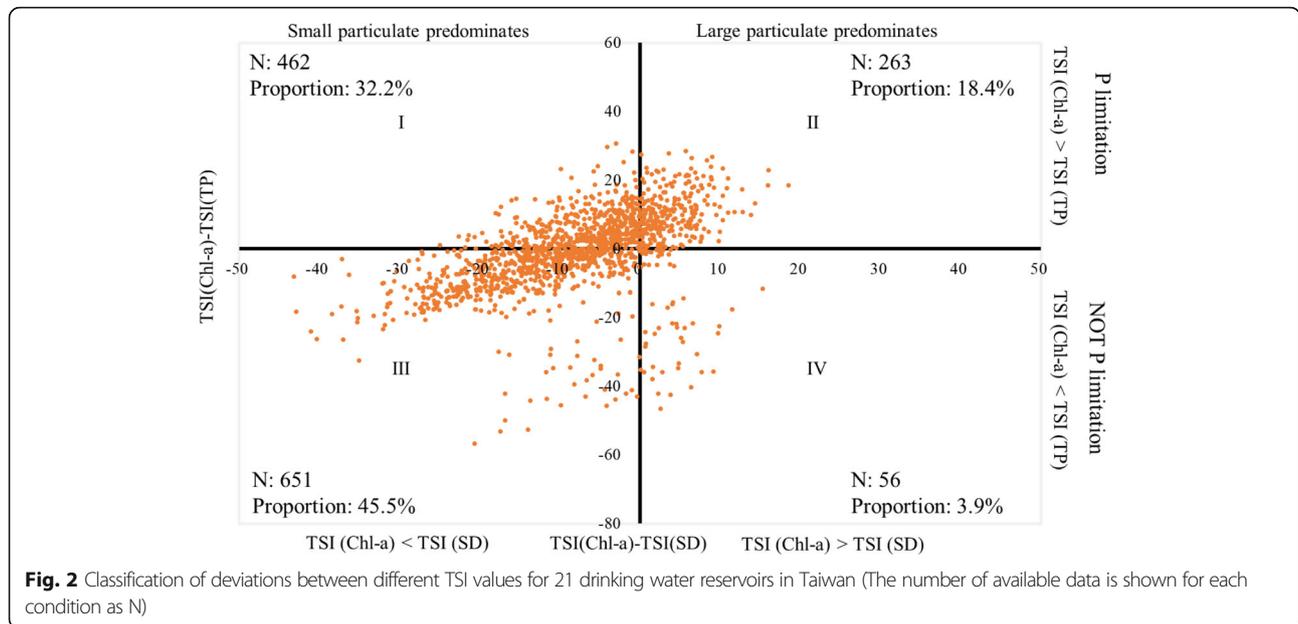
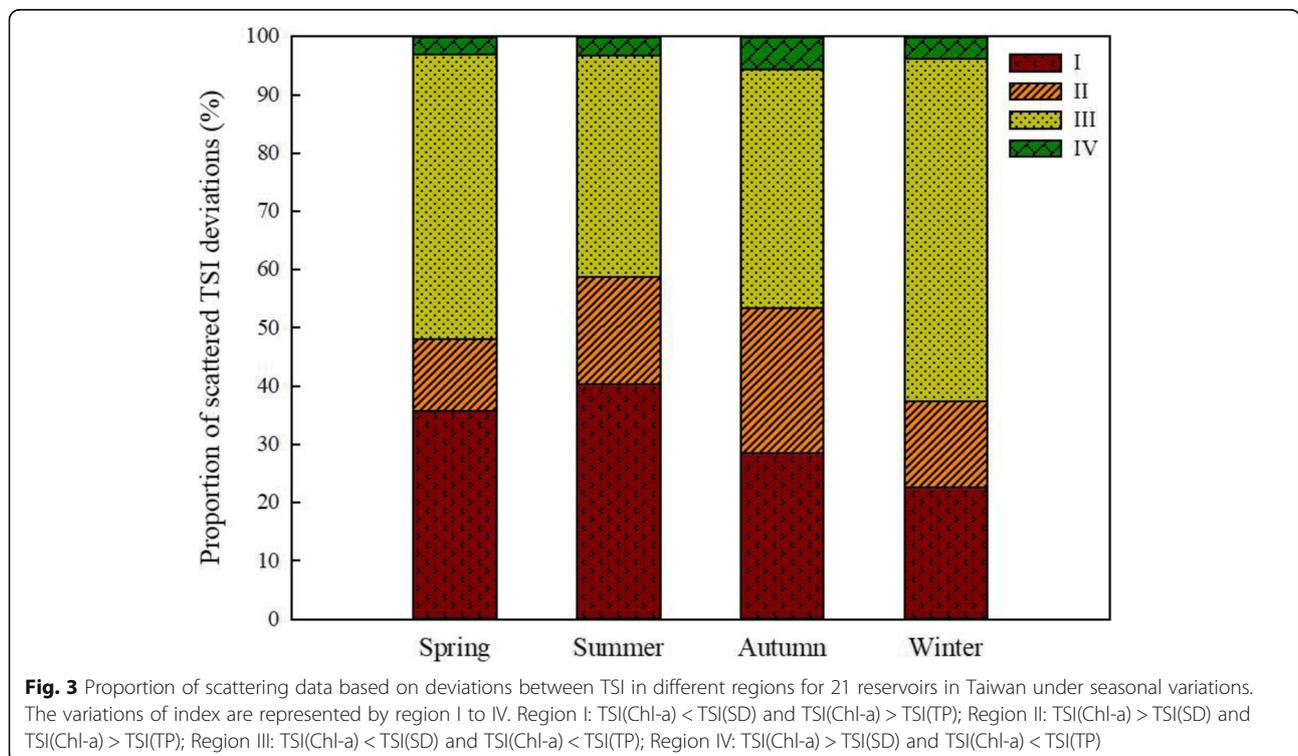


Fig. 1 Eutrophication potential of 21 reservoirs in Taiwan from 2008 to 2019 under CTSI rating



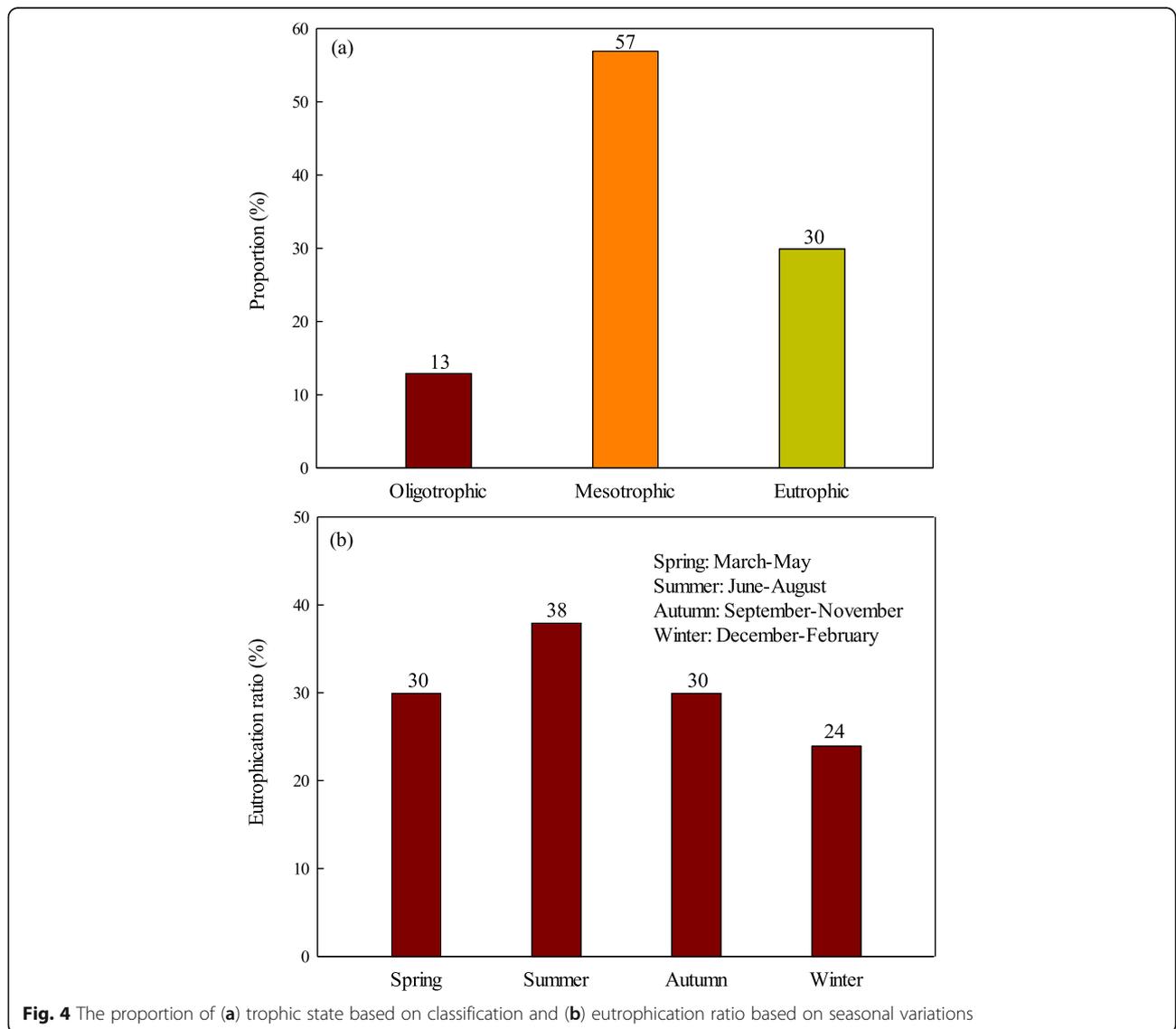
number of lakes can therefore be used to infer possible relationships between the three indices. Figure 2 describes that approximately 78% of the studied reservoirs are categorized into a small particulate predominance based on the relations between “TSI (Chl-a)–TSI (SD)” and “TSI (Chl-a)–TSI (TP)” during all seasons. The influence of larger particulates in relation to algal growth is insignificant. A non-algal turbidity effect has occurred in most reservoirs, as

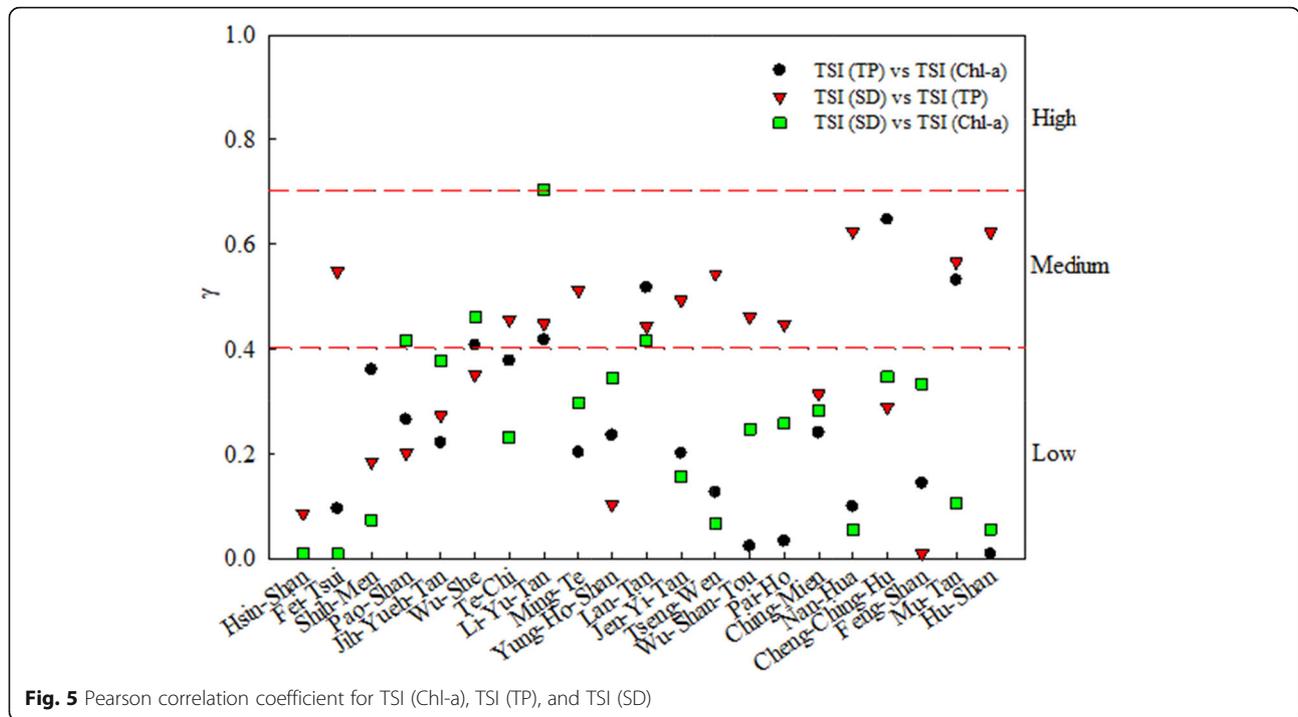
evidenced in Fig. S1. Non-algal particulates such as turbidity, which are derived from external or internal sources, produce sufficient light extinction to limit algal productivity [16]. These findings also suggest that phosphorus is not the dominant factor limiting the trophic state for non-algal impact 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 [31]. This discrepancy could be caused by a low water transparency level of most reservoirs in Taiwan due to the shading effect of small inorganic particulates, which inhibits algae growth along with pronounced TP uptake. The probability is only 18.4% in all cases with a large particulate predominance condition where the potential of algal growth is dominant, as shown in Region II of Fig. 2. Instead, the proportion of phosphorus surplus (i.e., without P limitation) is as high as 45.5% with a small particulate predominance in Region III, while only 32.2% cases occur with a small particulate predominance at the condition of P limitation in Region I, as illustrated in Fig. 2. It indicates that a small particulate predominance condition occurs in most investigated reservoirs (around 78%) in Taiwan. Therefore, it does not show that a predominance of larger particles and P limitation occur at high algal growth in our study.

To further understand the effect of seasonal variations on TSI values of 21 drinking water reservoirs in Taiwan, the TSI deviations at various seasons were identified. Figure 3 shows that non-algal turbidity (Region III) predominates during every single season. However, small particulates predominance and P limitation (Region I) are markedly formed in summer and autumn seasons. It could be attributed to fast algal growth at such a high temperature (28–29 °C). This finding is also supported by a previous study in which it has confirmed that high temperature deteriorates water quality and increases cyanobacteria occurrence and diatom blooms in reservoirs to cause significant eutrophication [32]. Another study also has proven that wind speed in summer has a substantial impact on algal growth. In addition, wind speed in different seasons could gradually induce the occurrence of turbulent water bodies, resulting in high





phosphorus level in overlying *water* column where algal growth is accelerated tremendously [33]. It can be concluded that seasonal variations affect the eutrophication level for drinking water reservoirs, especially in summer season.

Taiwan is categorized as a tropical/subtropical area with more algal productivity in the presence of a moderate nutrient pollution during summer season. For this reason, most drinking water reservoirs in Taiwan are classified as mesotrophic, with approximately 57% cases, as shown in Fig. 4a. The occurrence of mesotrophic level for most drinking water reservoirs could be resulted from high temperature and rainfall intensity during summer season in which the potential of algal growth is more pronounced, as evidenced in Figs. 2 and 3. It has indicated that higher proportion (50.6%) of cases with TS (Chl-a) > TSI (TP) (Region I and Region II). A higher temperature and rainfall intensity can affect the TSI significantly in tropical/subtropical area [11]. Besides, approximately 30% cases were categorized as eutrophic (Fig. 4a) based on the averaged CTSI values higher than 50 from 2008 to 2019, and the highest eutrophication ratio (i.e., 38%) occurs in summer season (Fig. 4b). It could be associated with intensive rainfalls in subtropical/tropical areas where the release of sediments (i.e., inorganic particles) is induced significantly. In addition, the increased temperature in summer also improves Chl-a level attributed by pronounced algal growth. Therefore, the trophic state level is much higher in summer season.

3.3 Correlation of TSI variables

The correlation of TSI variables was quantified to understand the relationship between all three indices of CTSI. Figure 5 shows a low correlation ($\gamma < 0.4$) among three TSI variables. Only some reservoirs have a medium correlation between TSI (SD) and TSI (TP). It is similar to a previous study that has reported that the correlation between TSI variables is insignificant for drinking water reservoirs in Taiwan [14]. Theoretically, it is inappropriate to use TSI variables when their correlations are not normally distributed [34]. The correlation results have indicated that the application of CTSI could not show a real trophic state of drinking water reservoirs without strong algal impact in Taiwan. In other words, the CTSI does not make sense as it is calculated by averaging three indices (i.e., TSI (SD), TSI (Chl-a) and TSI (TP)). To further investigate the contribution of independent TSI to CTSI level, the calculations of TSI higher than 50 on 21 reservoirs in Taiwan are presented in Table 1. It has revealed that the proportion of TSI variables is

Table 1 Proportion of CTSI variables higher than 50 for 21 drinking water reservoirs in Taiwan

Variables	Proportion of TSI > 50 (%)	Proportion of TSI > 50 as CTSI > 50 (%)
TSI (SD)	63	96
TSI (Chl-a)	24	60
TSI (TP)	20	58

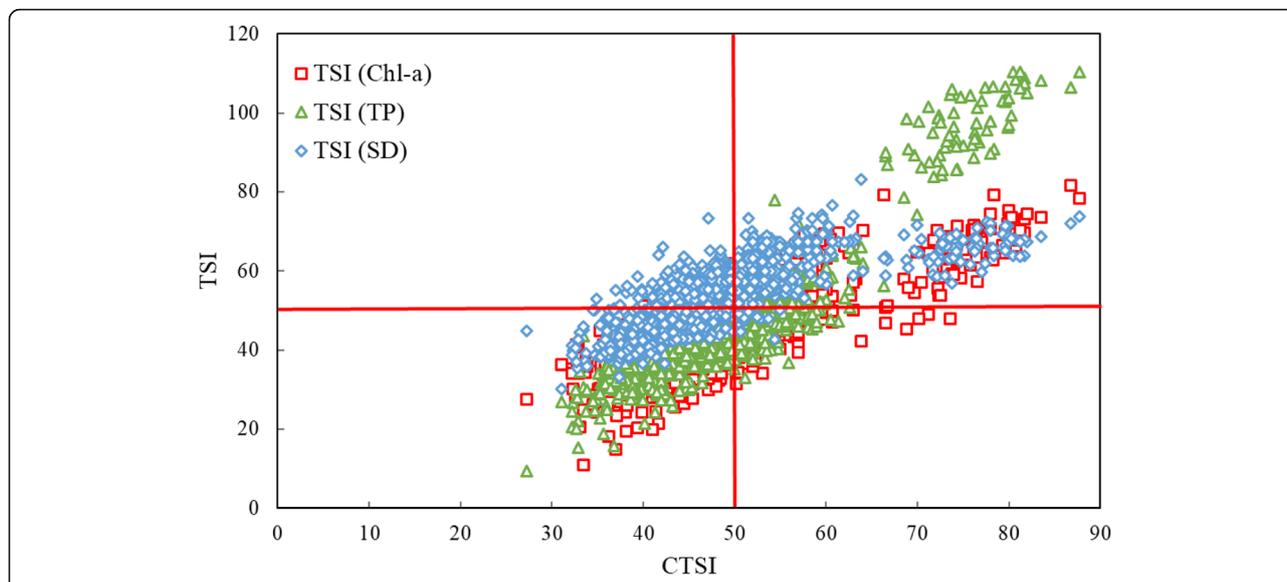


Fig. 6 The scatter of TSI values on 21 reservoirs in Taiwan from 2008 to 2019

dominated by TSI (SD), approximately 63% over TSI (Chl-a) and TSI (TP). TSI (Chl-a) and TSI (TP) only contribute 24 and 20% to the CTSI level, respectively. In addition, the ratio of each TSI more than 50 at the same sampling time is only about 9%, as shown in Fig. S3. In the specific case of CTSI higher than 50, TSI (SD) more than 50 significantly contributes as much as 96%, which is higher than that contributed by other TSI variables, as

shown in Fig. 6 and Table 1. However, the proportion of TSI (Chl-a) or TSI (TP) greater than 50 is only around 60% as CTSI is higher than 50. The result of dominant TSI variables evaluation has indicated that TSI (SD) is the primary influencing factor towards CTSI determination for most drinking water reservoirs in Taiwan, which echoes the previous study [15]. Other studies also have suggested that TSI (SD) plays a dominant role in the CTSI

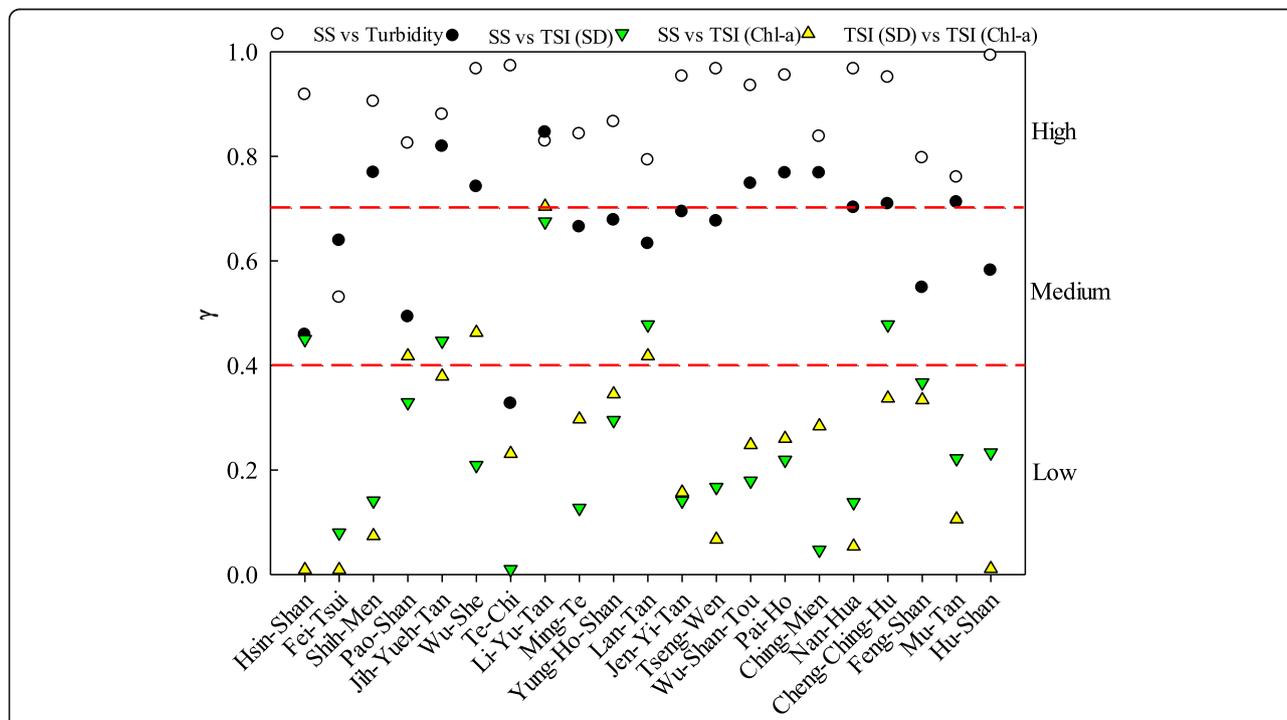


Fig. 7 Pearson correlation coefficient for SS, turbidity, TSI (SD), and TSI (Chl-a)

level for turbid reservoirs due to high rainfall rate, heavy storm runoff and direct nutrient discharges [20, 35]. The deviations of three TSI variables have indicated that the CTSI is of limited applicability on water quality management for most reservoirs in Taiwan.

The transparency of reservoir water can be substantially influenced by SS and phytoplankton biomass [33, 36]. The correlations among TSI (SD), TSI (Chl-a), turbidity and SS were investigated further to evaluate the influencing factors towards TSI (SD). The correlation between SS and TSI (Chl-a) is insignificant ($\gamma < 0.4$) in most of cases, as shown in Fig. 7. On the contrary, there is a significant correlation ($\gamma > 0.7$) among turbidity, SS, and TSI (SD) for most of reservoirs. This result is similar

to previous studies in Taiwan [14, 15]. These findings have suggested that SS strongly influences water clarity owing to non-algal particulates present in most reservoirs in Taiwan.

In the case of TSI (SD) value lesser than 50, two reservoirs have a significant correlation ($\gamma > 0.7$) of three TSI variables, including Jen-Yi-Tan and Hu-Shan Reservoirs, while most of reservoirs have an insignificant correlation ($\gamma < 0.4$) of three TSI variables, as illustrated in Fig. 8a. On the other hand, as TSI (SD) value is higher than 50, it is highlighted that some reservoirs have a medium correlation ($0.4 < \gamma < 0.7$) between TSI (TP) and TSI (SD), as illustrated in Fig. 8b. This result has suggested that particulate phosphorus influences water

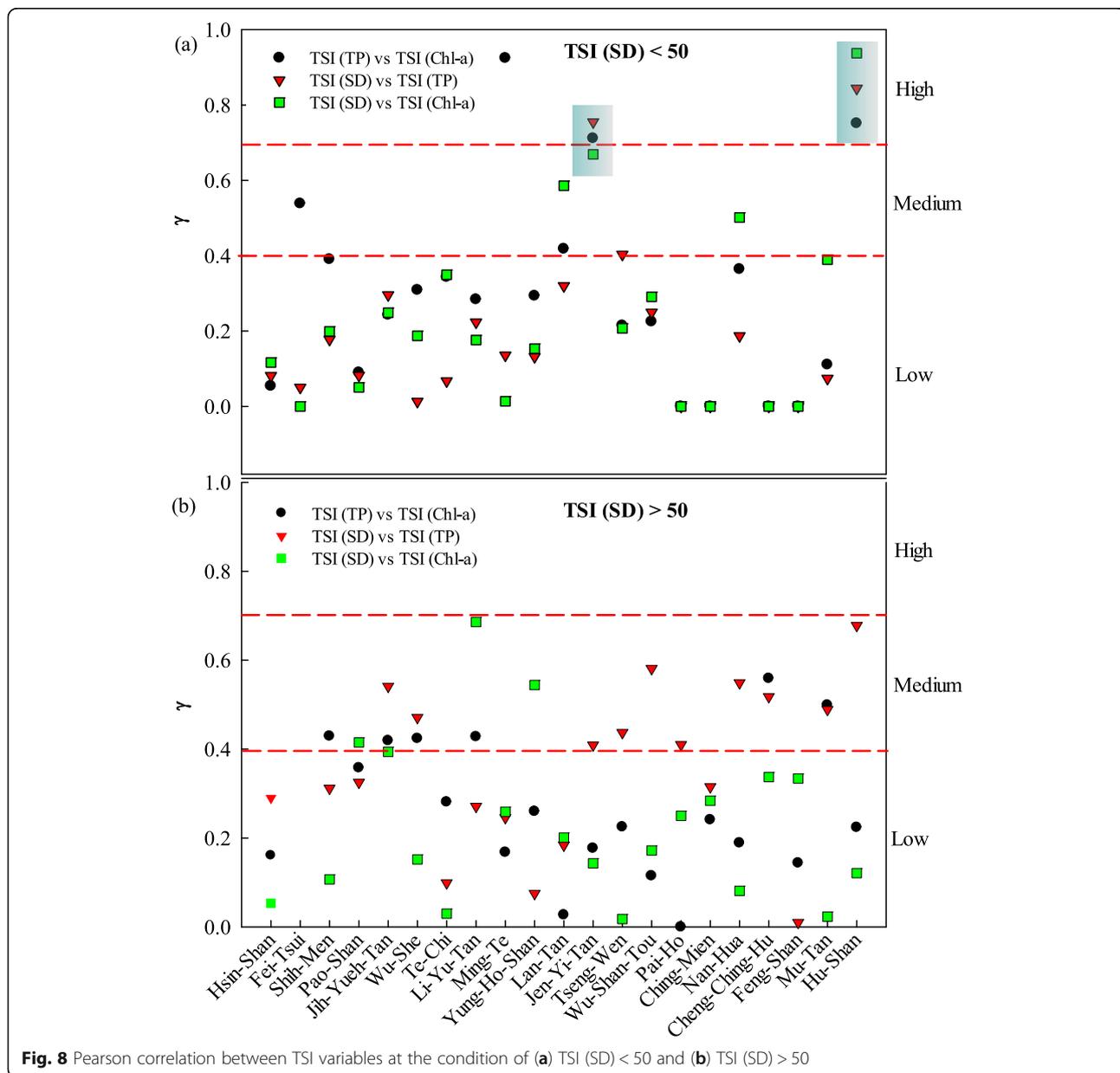


Table 2 Factor analysis results of the significant water quality parameters

Parameters	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 (%)	55.9	16.9
Kaiser-Meyer-Olkin	0.78	
p-value	< 0.001	

Double asterisks (**): a strong factor loading; a single asterisk (*): a medium factor loading

transparency level in a way. In contrast, other TSI variables is insignificantly correlated. These findings have indicated that the CTSI calculation involving TSI (SD) is unable to highlight the contribution of each CTSI variable for non-algal impact reservoirs. It can be concluded that the use of TSI (SD) to infer algal biomass and trophic state for reservoirs is inappropriate in the presence of non-algal turbidity where even moderate amounts of non-algal turbidity are present [37, 38]. Despite the fact that non-algal turbidity occurs in most

reservoirs in Taiwan, the CTSI can still be used for a specific condition. The applicability of CTSI can be improved as the TSI (SD) level 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 specific TSI to evaluate the eutrophication potential for most reservoirs in Taiwan.

3.4 PCA inference for eutrophication factors

The eutrophication factors were determined based on PCA inference, as shown in Table 2 and Fig. 9. The first component (C1) and second component (C2) obtain 55,87 and 16,92% of the total variances, respectively. As seen in Fig. 9, TP has the highest factor loading (0.907) of the main component, followed by NH₃, Chl-a and COD. However, the TSI (Chl-a) has an insignificant factor loading of the second component, whereas the TSI (SD) has the highest factor loading 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 are operating under long-term SS impact with limited algal particulate predominance. The critical finding in this study is to prove that TP is well correlated with water quality in terms of COD, NH₃, and Chl-a for 21 drinking water reservoirs in Taiwan (as seen in Fig. 9). The PCA inference indicates that the CTSI approach could frequently lead to confusion because its assessment criteria can be degraded by factors such as SS, which is unable to exactly reflect the trophic state or eutrophication potential. To improve the

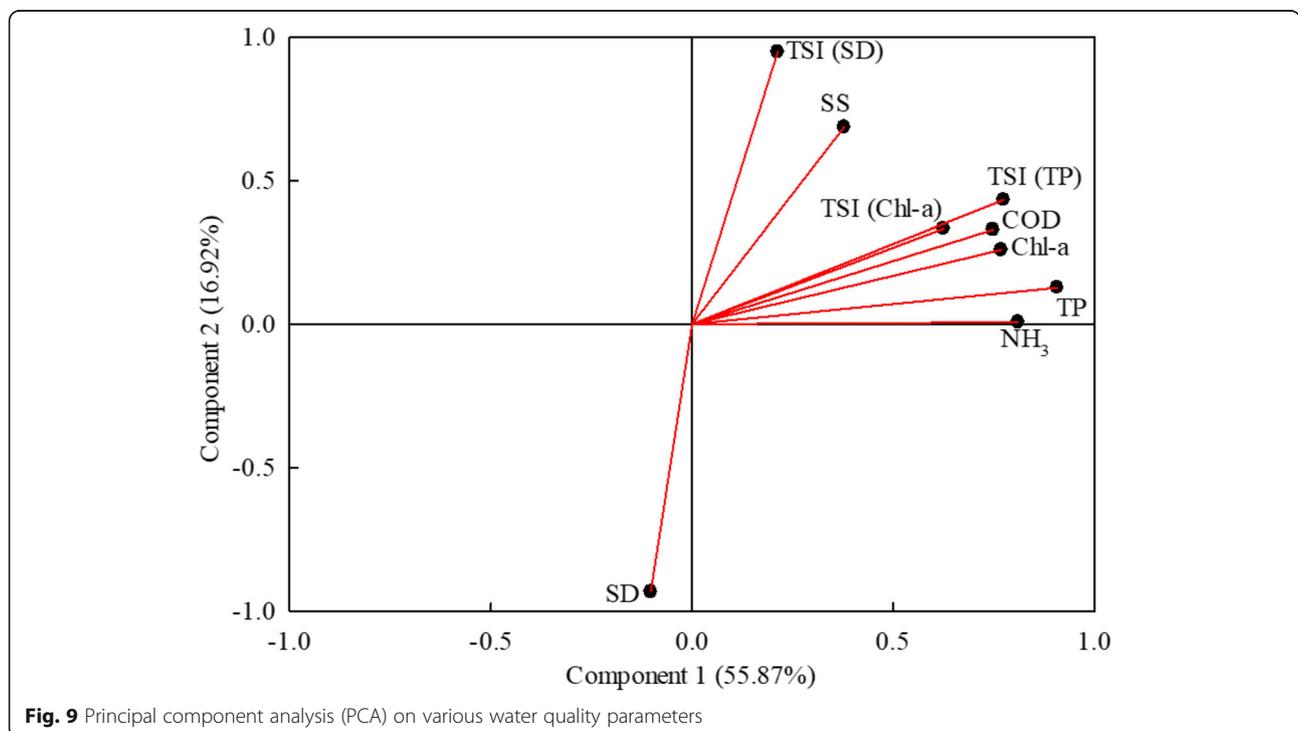


Fig. 9 Principal component analysis (PCA) on various water quality parameters

eutrophication rating, Chl-a is recommended as a single indicator to specifically represent the potential of algal growth for reservoirs in Taiwan and accurately evaluate their trophic state caused by algae regardless of inorganic particulates. Moreover, the best strategy for water quality management is proposed to strengthen TP regulation in the upstream catchment area of drinking water reservoirs, and to minimize TP loading in reservoirs, which could substantially slowdown algal growth rate to prevent the occurrence of algal blooms.

4 Conclusions

Five reservoirs have exhibited the eutrophication potential as high as more than 50% based on CTSI classification, including Feng-Shan, Ming-Te, Ching-Mien, Cheng-Ching-Hu, and Pai-Ho Reservoir. The Pearson analysis of TSI variables (e.g., SD, Chl-a, TP) has shown an insignificant correlation, and it also indicates that the proportion of TSI 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. CTSI based on two-dimensional analysis has interpreted that the quantity of phosphorus is dominantly responsible for the substantial impacts on reservoir water quality. The application of CTSI to assess algal biomass for trophic state classification in water quality management is inappropriate for most reservoirs in Taiwan, owing to high SS impact with limited algal particulate dominance. In contrast, the applicability of CTSI for reservoirs in Taiwan is much higher when TSI (SD) is lower than 50. Based on PCA inferences, TP is the dominant eutrophication factor for drinking water reservoirs in Taiwan. This study provides the informative approach and reference data for further eutrophication potential evaluation on non-algal impact reservoirs.

5 Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s42834-022-00134-x>.

Additional file 1: Fig. S1. The interpretation of trophic state index deviations on 21 reservoirs in Taiwan. **Fig. S2.** CTSI values of 21 drinking water reservoirs in Taiwan from 2008 to 2019. (The number of available data: 1432). **Fig. S3.** The intersection ratio of each TSI more than 50 for 21 drinking water reservoirs in Taiwan from 2008 to 2019.

Acknowledgements

The authors would like to extend their appreciation to the Taiwan Environment Protection Administration (EPA) for assistance in the water quality data collection of 21 reservoirs.

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.

Funding

The authors wish to thank to Taiwan Environmental Protection Administration (EPA) for the financial support.

Availability of data and materials

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

Declaration

Competing interests

The authors declare they have no competing interests.

Author details

¹Department of Environmental Engineering, Chung Yuan Christian University, Chung-Li 320314, Taiwan. ²Center for Environmental Risk Management, College of Engineering, Chung Yuan Christian University, Chung-Li 320314, Taiwan. ³Department of Water Resources and Environmental Engineering, Tamkang University, New Taipei City 251301, Taiwan.

Received: 22 October 2021 Accepted: 16 March 2022

Published online: 29 April 2022

References

- O'Hare MT, Baattrup-Pedersen A, Baumgarte I, Freeman A, Gunn IDM, Lazar AN, et al. Responses of aquatic plants to eutrophication in rivers: a revised conceptual model. *Front Plant Sci.* 2018;9:451.
- Longley KR, Huang WR, Clark C, Johnson E. Effects of nutrient load from St. Jones River on water quality and eutrophication in Lake George, Florida. *Limnologia.* 2019;77:125687.
- Wilkinson GM. Eutrophication of freshwater and coastal ecosystems. In: Abraham MA. *Encyclopedia of sustainable technologies.* 4. Amsterdam: Elsevier; 2017. p. 145–52.
- El-Serehy HA, Abdallah HS, Al-Misned FA, Al-Farraj SA, Al-Rasheid KA. Assessing water quality and classifying trophic status for scientifically based managing the water resources of the Lake Timsah, the lake with salinity stratification along the Suez Canal. *Saudi J Biol Sci.* 2018;25:1247–56.
- Barinova SS, Nevo E. The Upper Jordan River algal communities are evidence of long-term climatic and anthropogenic impacts. *J Water Resour Prot.* 2010;2:507–26.
- Al Shehhi MR, Gherboudj I, Ghedira H. An overview of historical harmful algae blooms outbreaks in the Arabian Seas. *Mar Pollut Bull.* 2014;86:314–24.
- Londo AJ, LaBarge G, Watters H, Culman S, Rose MA, Hall P, et al. Water quality and nutrient management extension programs in Ohio. *J Contemp Water Res Educ.* 2015;156:48–55.
- Carlson RE. A trophic state index for lakes. *Limnol Oceanogr.* 1977;22:361–9.
- Osgood R. Who needs trophic state indices? *Lake Reserv Manag.* 1984;1: 431–4.
- Pomari J, Kane DD, Nogueira MG. Application of multiple-use indices to assess reservoirs water quality and the use of plankton community data for biomonitoring purposes. *Int J Hydrol.* 2018;2:173–84.
- Cunha DGF, Calijuri MD, Lamparelli MC. A trophic state index for tropical/subtropical reservoirs (TSI_{tr}). *Ecol Eng.* 2013;60:126–34.
- Gupta M. A new trophic state index for lagoons. *J Ecosyst.* 2014;2014: 152473.
- Kuo YM, Wu JT. Phytoplankton dynamics of a subtropical reservoir controlled by the complex interplay among hydrological, abiotic, and biotic variables. *Environ Monit Assess.* 2016;188:689.
- Liu WW, Zhao EM, Kuo YM, Jang CS. Identifying the relationships between trophic states and their driving factors in the Shihmen Reservoir, Taiwan. *Limnologia.* 2017;64:38–45.
- Putri MSA, Lin JL, Chiang Hsieh LH, Zafirah Y, Andhikaputra G, Wang YC. Influencing factors analysis of Taiwan eutrophicated reservoirs. *Water-Sui.* 2020;12:1325.
- Carlson, R.E. Expanding the trophic state concept to identify non-nutrient limited lakes and reservoirs. In *Proceedings of a National Conference on Enhancing the States' Lake Management Programs.* Chicago: North American Lake Management Society; 1991:59–71.
- Li X, Huang TL, Ma WX, Sun X, Zhang HH. Effects of rainfall patterns on water quality in a stratified reservoir subject to eutrophication: Implications for management. *Sci Total Environ.* 2015;521:27–36.

18. Chang SP, Chuang SM. Eutrophication study of twenty reservoirs in Taiwan. *Water Sci Technol*. 2001;44:19–26.
19. Lee KT, Ho JY, Kao HM, Lin GF, Yang TH. Using ensemble precipitation forecasts and a rainfall-runoff model for hourly reservoir inflow forecasting during typhoon periods. *J Hydro-Environ Res*. 2019;22:29–37.
20. Tsai ZX, You GJY, Lee HY, Chiu YJ. Use of a total station to monitor post-failure sediment yields in landslide sites of the Shihmen reservoir watershed, Taiwan. *Geomorphology*. 2012;139–40:438–51.
21. Wang HW, Kondolf M, Tullio D, Kuo WC. Sediment management in Taiwan's reservoirs and barriers to implementation. *Water-Sui*. 2018;10:1034.
22. Chen YY, Huang W, Wang WH, Juang JY, Hong JS, Kato T, et al. Reconstructing Taiwan's land cover changes between 1904 and 2015 from historical maps and satellite images. *Sci Rep-UK*. 2019;9:3643.
23. Reijnders L. Phosphorus resources, their depletion and conservation, a review. *Resour Conserv Recy*. 2014;93:32–49.
24. Chrispim MC, Scholz M, Nolasco MA. Phosphorus recovery from municipal wastewater treatment: critical review of challenges and opportunities for developing countries. *J Environ Manage*. 2019;248:109268.
25. Taiwan Environmental Protection Administration. Water quality improvement projects. *Electron Environ Policy Mon*. 2020;23:1–12.
26. Carlson RE, Havens KE. Simple graphical methods for the interpretation of relationships between trophic state variables. *Lake Reserv Manage*. 2005;21:107–18.
27. Li S, Li ZL, Gong JY. Multivariate statistical analysis of measures for assessing the quality of image fusion. *Int J Image Data Fusion*. 2010;1:47–66.
28. Kuo JT, Lung WS, Yang CP, Liu WC, Yang MD, Tang TS. Eutrophication modelling of reservoirs in Taiwan. *Environ Modell Softw*. 2006;21:829–44.
29. Nyenje PM, Foppen JW, Uhlenbrook S, Kulabako R, Muwanga A. Eutrophication and nutrient release in urban areas of sub-Saharan Africa - a review. *Sci Total Environ*. 2010;408:447–55.
30. Oberholster PJ, Botha AM, Ashton PJ. The influence of a toxic cyanobacterial bloom and water hydrology on algal populations and macroinvertebrate abundance in the upper littoral zone of Lake Krugersdrift, South Africa. *Ecotoxicology*. 2009;18:34–46.
31. Mamun M, An KG. Major nutrients and chlorophyll dynamics in Korean agricultural reservoirs along with an analysis of trophic state index deviation. *J Asia-Pac Biodivers*. 2017;10:183–91.
32. Yan XC, Xu XG, Wang MY, Wang GX, Wu SJ, Li ZC, et al. Climate warming and cyanobacteria blooms: Looks at their relationships from a new perspective. *Water Res*. 2017;125:449–57.
33. Zhou J, Han XX, Qin BQ, Zhu GW. Responses of alkaline phosphatase activity to wind-driven waves in a large, shallow lake: implications for phosphorus availability and algal blooms. *J Environ Sci-China*. 2021;99:143–50.
34. Mukaka MM. Statistics corner: a guide to appropriate use of correlation coefficient in medical research. *Malawi Med J*. 2012;24:69–71.
35. Ferreira JG, Andersen JH, Borja A, Bricker SB, Camp J, da Silva MC, et al. Overview of eutrophication indicators to assess environmental status within the European Marine Strategy Framework Directive. *Estuar Coast Shelf S*. 2011;93:117–31.
36. Atique U, An KG. Landscape heterogeneity impacts water chemistry, nutrient regime, organic matter and chlorophyll dynamics in agricultural reservoirs. *Ecol Indic*. 2020;110:105813.
37. Lind OT. The effect of non-algal turbidity on the relationship of Secchi depth to chlorophyll *a*. *Hydrobiologia*. 1986;140:27–35.
38. Bilgin A. Trophic state and limiting nutrient evaluations using trophic state/level index methods: a case study of Borcka Dam Lake. *Environ Monit Assess*. 2020;192:794.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Ready to submit your research? Choose BMC and benefit from:

- fast, convenient online submission
- thorough peer review by experienced researchers in your field
- rapid publication on acceptance
- support for research data, including large and complex data types
- gold Open Access which fosters wider collaboration and increased citations
- maximum visibility for your research: over 100M website views per year

At BMC, research is always in progress.

Learn more biomedcentral.com/submissions

