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Influencing Factors Analysis of Taiwan Eutrophicated Reservoirs

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Abstract: Treatment cost and quality of domestic water are highly correlated with raw water quality in reservoirs. This study aims to identify the key factors that influence the trophic state levels and correlations among Carlson trophic state index (CTSI) levels, water quality parameters and weather factors in four major reservoirs in Taiwan from 2000 to 2017. Weather (e.g., air temperature, relative humidity, total precipitation, sunlight percentage and cloud cover) and water quality parameters (e.g., pH, chemical oxygen demand, suspended solids (SS), ammonia, total hardness, nitrate, nitrite and water temperature) were included in the principal component analysis and absolute principal component score models to evaluate the main governing factors of the trophic state levels (e.g., CTSI). SS were washed out by precipitation, thereby influencing the reservoir transparency tremendously and contributing over 50% to the CTSI level in eutrophicated reservoirs (e.g., the Shihmen and Chengchinghu Reservoirs). CTSI levels in the mesotrophic reservoir (e.g., Liyutan Reservoir) had strong correlation with chlorophyll-a and total phosphorus. Results show that rainfall/weather factors were the key driving factors that affected the CTSI levels in Taiwan eutrophicated reservoirs, indicating the need to consider basin management and the impacts of extreme precipitation in reservoir management and future policymaking.

Keywords: reservoir; eutrophication; source apportionment; Carlson trophic state index

1. Introduction

The quality of water bodies has deteriorated. This phenomenon has been observed for several decades because humans prioritize their short-term economic goals over the long-term environmental sustainability of reservoir. Thus, monitoring and assessing water quality are highly recommended [1]. Specifically, reservoir eutrophication has been investigated globally because it causes serious damage to reservoir ecosystem resilience. Increased nutrient loading generated from industrial wastewater, municipal sewage and irrigation water causes the eutrophication of freshwater lakes, thereby increasing the growth of algae and high plants [2,3]. Correlation of chlorophyll-a (Chl-a) abundance with eutrophication has frequently been investigated using the integration approach of multivariate statistical analysis [4,5]. According to several studies, increased temperature, total precipitation and nutrient runoff are the main factors that enhances the eutrophication process in nature [5–8]. The nutrient factor is an important factor for predicting the eutrophic level. Eutrophication is caused by the enrichment of macronutrients that enhances vegetation growth and the exclusion of less competitive species [9]. Harmful alga bloom is a negative effect of eutrophication [10]. Nutrient runoff dominantly affects the Carlson trophic state index (CTSI) level [11].

Both natural and anthropogenic factors affect the water quality in surface water, lake or reservoir [12]. Taiwan's reservoir has the highest sedimentation rate in the world because of the geographical condition of the country. Taiwan has tectonically shattered subduction trench lithologies, rapid uplift, intense monsoon and typhoon rains that result in rapid erosion rates. The steep slopes, regular earthquakes, and intense rainfall cause regular landslides and debris flows across the island [13,14]. Taiwan also has many residential and industrial areas around the reservoir that can cause anthropogenic pollution in Taiwan's major reservoir. This study aims to identify the key water quality parameters and evaluate the main governing factors of the significant factors that affect the trophic state levels in four Taiwan reservoirs from 2000 to 2017 using principal component analysis (PCA) and absolute principal component scores (APCS) models. The key parameters in this study include chemical oxygen demand (COD), suspended solid (SS), ammonia, total hardness, nitrate, nitrite, water temperature and weather factors. This study provides scientific consideration for authorities using CTSI as a water quality indicator for reservoirs.

2. Materials and Methods

2.1. Characteristics of Reservoirs

The Shihmen Reservoir works as the main supply of drinking water, irrigation, power, flood control and recreation in Taipei and Taoyuan cities in Northern Taiwan. It is also the third largest reservoir in Taiwan [15,16]. The Dahan River is the main stream in this area, which is the upper stream of the Tamsui River. Shihmen Reservoir has an approximate volume of 203,150,000 m^3 and flow rate of 800,000 m^3/day. The annual average rainfall is 2350 mm [17], of which 80% occurs between May and October, due to typhoon precipitation.

The Liyutan Reservoir is the largest off-site reservoir in Taiwan, it is used for power, drinking water, irrigation and recreation. Originally, this reservoir was built to fulfill the irrigation water needs for cropping lands in Central Taiwan and some water for public use. Due to population growth and increased public water demand, the government has expanded the water supply capacity of this reservoir and built a delivery pipe to introduce water from other upstream basins into the reservoir [18]. The Liyutan Reservoir has a volume of 117,900,000 m^3 and supplies 700,000 m^3/day. Almost one-third of the land-use in Miaoli County is agricultural (Figure 1), which constitutes an important non-point sources in the form of water run-off with high nutrient content. Fruits, especially strawberries, are the main crops grown in this area [18].

The Wushantou Reservoir is located in Tainan City. This reservoir is surrounded by residential and agriculture areas (Figure 1). The Wushantou Reservoir has a volume of 78,280,000 m^3 and supplies 350,000 m^3/day. 59% of the catchment area is forest, 19% accounts for orchards, while the reservoir and water systems account for approximately 17% and the remaining 5% are wasteland, buildings and grassland.

The Chengchinghu Reservoir is located in Kaohsiung, Southern Taiwan. It is surrounded by agricultural, industrial and residential area (Figure 1). This reservoir is used for irrigation and drinking water and recreation. The Chengchinghu Reservoir has a volume of 3,937,300 m^3 and supplies 450,000 m^3/day [16,19].

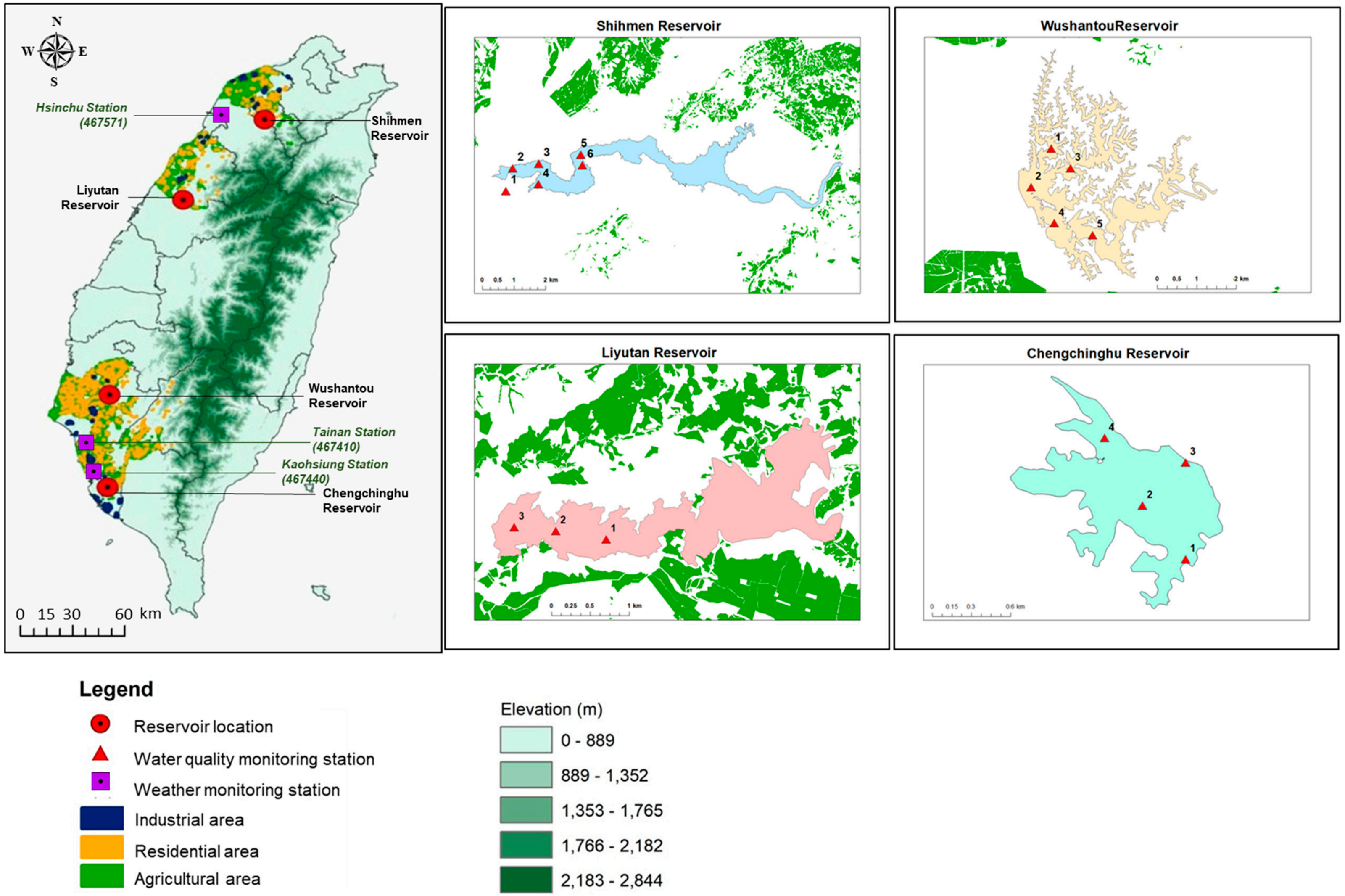

Figure 1. Four studied reservoirs and monitoring stations.

The water quality monitoring stations are displayed in Figure 1 along with the residential, agricultural and industrial areas near the reservoirs in the cities of Taoyuan, Miaoli County, Tainan and Kaohsiung. The characteristics of the four reservoirs are shown in Supplementary Table S1. As determined by the Organization for Economic Cooperation and Development, the trophic categories (e.g., oligotrophic, mesotrophic, eutrophic and hypereutrophic) of P and Chl-a correspond to <10, 10–25, 35–100, >100 µg/L and <2.5, 2.5–8, 8–25, >25 µg/L, respectively [20]. Reservoir water quality is assessed by calculating CTSI using the concentrations of three water quality parameters, namely, surface water Chl-a, transparency and total P (TP) (https://wq.epa.gov.tw).

In 2006 the CTSIs in the reservoirs of Shihmen (50.9–52.9), Liyutan (45.1–59.4) and Chengchinghu (55.8) were generally high. In 2015, the Shihmen Reservoir continued to be eutrophic (47.0–63.0). In 2010, the Liyutan (37.4–46.2) and Wushantou Reservoirs (37.4–50.2) fluctuated between mesotrophic and eutrophic. In 2007 and 2011, the Chengchinghu Reservoir was eutrophic (48.7–62.2, 46.0–58.0, respectively) and seriously eutrophic in 2015 (53.0–63.0) [21]. Reservoir quality is strongly affected by climate conditions, especially precipitation and typhoons [22]. For example, landslides can elevate levels of SS and thereby turbidity during typhoon and contribute to changes in eutrophication levels [23,24].

2.2. Dataset

2.2.1. Water Quality Parameters

The water quality dataset for Chl-a, TP, transparency (SD), pH, COD, SS, ammonia, total hardness, nitrate, nitrite and water temperature (WT) from 2000 to 2017 were obtained from the Taiwan Environmental Protection Administration (Taiwan EPA). Water quality monitoring data were collected once per season: March to May (spring), June to August (summer), September to November (autumn) and December to February (winter). The total number of water quality monitoring stations in the Shihmen, Liyutan, Wushantou and Chengchinghu Reservoirs are 6, 3, 5 and 4, respectively (Figure 1). The measurement methods for water quality parameters are listed in Supplementary Table S2.

2.2.2. Weather Parameters

The weather parameter data from 2000 to 2017, including air temperature (°C), relative humidity (%), total precipitation (mm), sunshine percentage (%) and cloud amount (okta), were collected from the Taiwan Central Weather Bureau (data obtaining from Hsinchu station for Shihmen and Liyutan Reservoirs, Tainan station for Wushantou Reservoir and Kaohsiung station for Chengchinghu Reservoir). This study used the weather data measured on the water quality sampling dates.

2.3. Statistical Methods

2.3.1. Carlson's Trophic State Index

The CTSI is defined as the total weight of living biologic material (biomass) in a waterbody at a specific location and time. The CTSI uses algal biomass as the basis of trophic state classification [14]. Three variables, including Chl-a, SD and TP level, are used to estimate the algal biomass. The CTSI can be determined by calculating the average of trophic state index (TSI) of each indicator from three interrelated factors in accordance to Taiwan EPA regulations [25]:

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

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

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

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

where:

CTSI: Carlson Trophic State Index.

TSI: Carlson trophic state index calculated from each variable, such as:

SD (m); Chl-a (μg/L); and TP (μg/L).

Previous study reported the limitation of Carlson's model which overestimated the trophic levels, partly due to that it only considers the highest productive seasons (e.g., spring and summer) in temperate lakes and Carlson index. Therefore, multiple studies have adopted different approaches derived from Carlson index to assess water quality. The modified indices for reservoirs are suitable for tropical and subtropical conditions, specifically for tropical/subtropical reservoirs that are sensitive to data variability [26]. The United States, Iran, Europe and Africa have adopted water quality index (WQI) as monitoring programs because it is a strong and reliable index composed of physical, chemical and biologic (i.e., dissolved oxygen (DO), COD, BOD, N-NH_4^+, CL^-, Fe-Total, etc.) variables to determine quality of water [27–29]. In addition, New Zealand has developed a modification for the trophic state index into trophic level index that is more suitable for their environment [30]. However, Vietnam, Indonesia and India still use CTSI as their water quality indicator to classify trophic status [31–34]. Henny and Nomosatryo studying the eutrophication status of Lake Maninjau in Indonesia stated that the trophic status of their study area did not portray the actual condition of the lake itself [31].

2.3.2. Pearson's Correlation Analysis

Pearson's correlation analysis was conducted to identify the key factors that influence the phytoplankton biomass. This approach was performed using the CTSI indicators (e.g., Chl-a, SD and TP) and the water quality and weather factors with logarithmically transformed data to achieve a significant correlation ($r > 0.3$ with $p < 0.01$) for further PCA analysis [35]. $r > 0.3$ indicates a correlation among parameters and $p < 0.01$ indicates a significance of the result.

2.3.3. PCA–APCS

PCA and APCS models were applied to determine the main governing factors of the significant factors that affect the trophic state levels in reservoirs [36]. The Kaiser–Meyer–Olkin (KMO) test (>0.7) and Bartlett's Sphericity test ($p < 0.01$) were determined first [37]. If these two tests fulfill the requirement, then the total variance with a value >60% should be considered. Rotated variables with factor loading >0.7 are considered relevant and indicate a possible emission source [38]. The regression of APCS and standardization of selected key parameters were applied to determine the contribution (%) of each pollution source [39,40]. Our study generated a good significance of regression output with $R^2 > 0.8$ [41]. In linear regression, the sum of each parameter standardization is defined as a dependent variable, and the APCS is defined as an independent variable.

2.4. Data Display and Analysis Tools

This study used Microsoft Excel 2016 for data plotting, sorting and organizing; R program version 3.3.2 was used to conduct the Pearson's correlation analysis for reservoir water quality factors and weather factor data; ESRI ArcGIS 10.2 was utilized to display the geographic information of the reservoir water quality monitoring stations, digital elevation model and land use map; and IBM Statistic 22 was used to conduct the PCA–APCS analysis.

3. Results

3.1. Correlations among Influencing Factors and CTSI

Table 1 lists the statistics of water quality and weather parameters in the four reservoirs from 2000 to 2017. The highest TP and Chl-a were found in the reservoirs of Chengchinghu and Liyutan, respectively. The Chengchinghu Reservoir had the highest average, water temperature, total precipitation, total hardness, SS, nitrate and nitrite. At the Shihmen Reservoir, the pH was the highest, while the Liyutan

Reservoir had the highest COD, ammonia and SD. Figure 2 shows the seasonal average CTSI of the four reservoirs from 2000 to 2017. The TSI(SD) level was the major contributor to the CTSI level in the reservoirs of Shihmen, Wushantou and Chengchinghu; whereas the TSI(Chl-a) level was the key factor in the Liyutan Reservoir. The highest CTSI occurred in spring for Shihmen, summer for the Liyutan and winter for Wushantou and Chengchinghu Reservoirs.

Table 1. Descriptive statistic of water quality and weather parameters in Taiwan major reservoirs.

Parameters	Descriptive Statistic	Shihmen Reservoir	Liyutan Reservoir	Wushantou Reservoir	Chengchinghu Reservoir
Water quality					
Total phosphorus (mg/L)	Min	0.004	0.00	0.00	0.01
	Mean	0.03	0.02	0.02	0.05
	Max	0.38	0.10	0.03	0.25
	Standard Deviation	0.02	0.00	0.01	0.01
Chlorophyll-a (μg/L)	Min	0.10	0.10	0.10	0.25
	Mean	4.70	6.17	0.44	10.67
	Max	56.80	58.80	3.30	46.33
	Standard Deviation	4.70	3.60	1.34	2.72
Water temperature (°C)	Min	8.80	12.20	5.82	18.26
	Mean	21.70	22.38	20.08	27.28
	Max	30.80	32.70	29.80	32.30
	Standard Deviation	4.71	1.05	0.34	0.23
Total hardness (mg/L as $CaCO_3$)	Min	19.40	104.00	82.70	101.16
	Mean	93.13	157.73	120.68	221.01
	Max	143.00	384.00	4.47	541.80
	Standard Deviation	16.52	6.51	13.80	30.87
SS (mg/L)	Min	0.40	0.70	1.48	4.10
	Mean	10.10	4.32	0.77	12.25
	Max	1650.00	50.25	53.20	32.08
	Standard Deviation	60.40	1.27	8.64	0.86
pH	Min	6.82	6.50	0.28	7.33
	Mean	8.21	8.16	8.11	8.07
	Max	9.54	9.60	8.88	8.62
	Standard Deviation	0.50	0.15	0.09	0.06
Nitrate (mg/L)	Min	0.01	0.01	0.01	0.13
	Mean	0.31	0.54	0.50	0.68
	Max	1.91	5.30	0.35	1.44
	Standard Deviation	0.17	0.19	0.15	0.05
Nitrite (mg/L)	Min	0.0003	0.00	0.00	0.01
	Mean	0.0059	0.01	0.00	0.04
	Max	0.1170	0.23	0.02	0.20
	Standard Deviation	0.0070	0.01	0.01	0.01
COD (mg/L)	Min	1.39	4.00	0.53	4.00
	Mean	4.99	9.46	6.24	7.61
	Max	56.59	48.82	35.02	29.75
	Standard Deviation	5.57	1.63	1.67	1.65

Table 1. *Cont.*

Parameters	Descriptive Statistic	Shihmen Reservoir	Liyutan Reservoir	Wushantou Reservoir	Chengchinghu Reservoir
Ammonia (mg/L)	Min	0.01	0.00	0.01	0.01
	Mean	0.04	0.33	0.07	0.08
	Max	0.35	1.30	0.49	0.58
	Standard Deviation	0.05	0.06	0.03	0.03
SD (meter)	Min	0.10	0.40	0.43	0.35
	Mean	1.73	2.14	0.25	0.98
	Max	3.80	5.50	2.90	1.78
	Standard Deviation	0.84	0.12	0.61	0.03
Weather					
Air temperature (°C)	Min	11.40	11.40	11.40	17.90
	Mean	22.94	23.12	24.89	25.75
	Max	31.80	30.80	30.60	31.20
	Standard Deviation	5.51	5.33	4.68	3.71
Relative humidity (%)	Min	57.00	55.00	59.00	59.00
	Mean	77.15	75.90	74.78	74.86
	Max	93.00	98.00	90.00	93.00
	Standard Deviation	8.06	8.55	7.03	6.00
Total precipitation (mm)	Min	0.00	0.00	0.00	0.00
	Mean	2.08	2.08	2.21	3.44
	Max	66.80	36.00	62.00	52.66
	Standard Deviation	9.01	9.92	8.77	5.62
Sunshine percentage (%)	Min	0.00	0.00	0.00	0.00
	Mean	39.21	41.32	56.53	60.21
	Max	91.90	91.10	91.70	92.70
	Standard Deviation	31.34	30.05	25.54	27.08
Cloud amount (okta)	Min	1.00	0.30	0.00	0.00
	Mean	6.50	6.49	4.65	4.64
	Max	10.00	10.00	9.60	10.00
	Standard Deviation	2.81	2.85	2.41	2.51

Supplementary Figure S1 shows the Pearson's correlations among trophic states, water quality and weather factors. TP, Chl-a, water temperature, SS, air temperature and total precipitation were positively correlated with CTSI in the four study reservoirs; whereas SD was negatively associated with CTSI. In addition, the levels of nitrate, nitrite, COD and ammonia were positively correlated with CTSI in the Chengchinghu Reservoir. Supplementary Figure S2 presents weather parameters in each reservoir in 2000–2017.

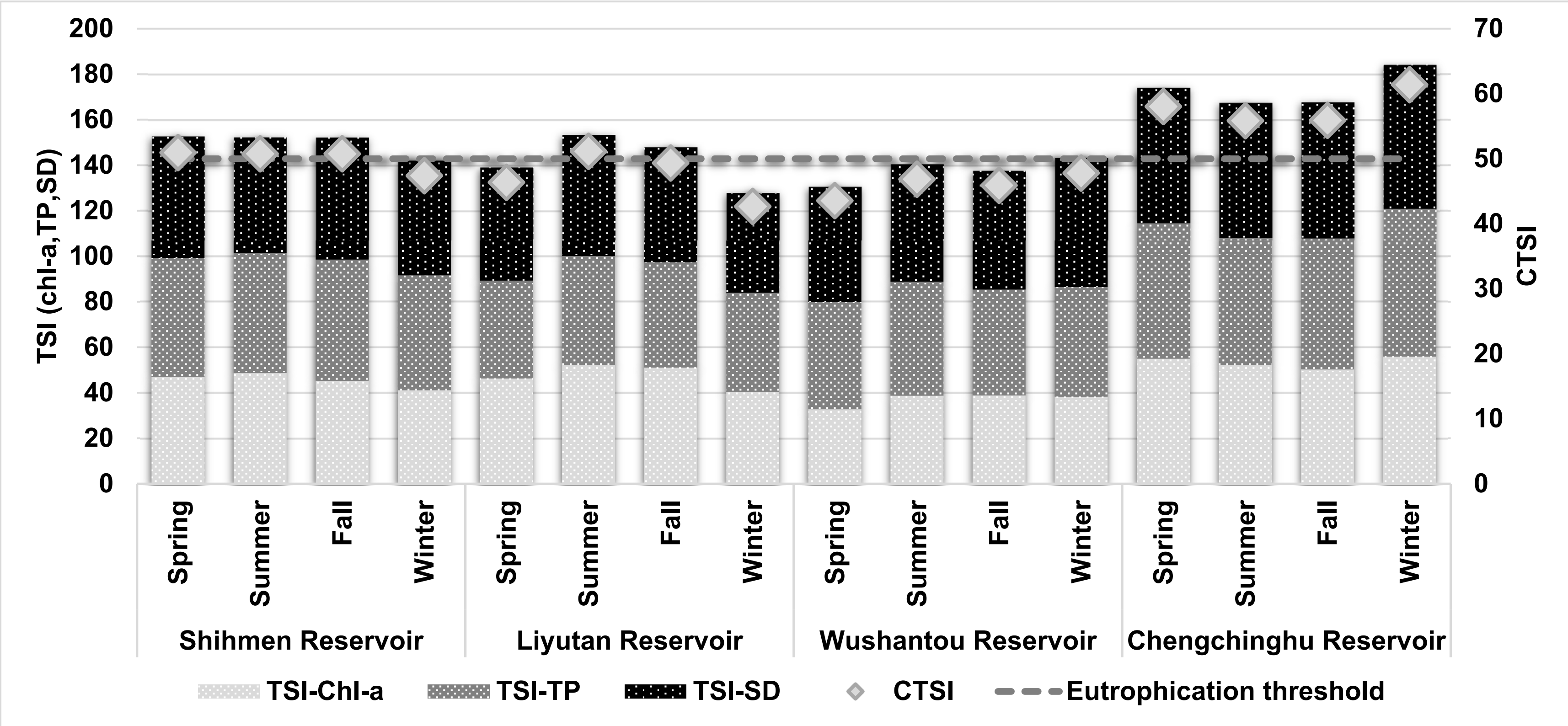

Figure 2. Carlson's trophic state index variation by seasons in four Taiwan major reservoirs.

3.2. Contribution of Influencing Factors to CTSI

The KMO–Bartlett's test and total cumulative percentage of variance of the four reservoirs are shown in Table 2. The overall KMO–Bartlett's test is greater than 0.70, indicating the good performance to predict each factor. The cumulative percentage of the reservoirs Shihmen, Liyutan, Wushantou and Chengchinghu accounted for 63.18%, 61.50%, 62.65% and 70.52%, respectively. This value indicates that the variability in water quality data has been reasonably well modeled by the extracted factor and the model is properly accepted to continue to the next step (Table 2).

Table 2. Kaiser–Meyer–Olkin (KMO)–Bartlett's test and total variance explained of all reservoirs.

Reservoir Name	Component/Factor	Initial Eigenvalue			KMO & Bartlett's Test	*p*-Value
		Total	% of Variance	% Cumulative		
Shihmen Reservoir	1 2 3	2.70 2.32 1.30	27.01 23.21 12.96	63.18	0.77	0.000086
Liyutan Reservoir	1 2 3	4.55 2.62 1.30	32.49 18.68 10.35	61.50	0.71	0.000012
Wushantou Reservoir	1 2 3	2.45 1.90 1.29	27.22 21.05 14.37	62.65	0.74	0.000046
Chengchinghu Reservoir	1 2 3	3.05 1.79 1.01	38.07 22.43 11.02	71.52	0.73	0.000031

Table 3 lists the varimax rotated factor for the four reservoirs in PCA. In the Shihmen Reservoir, Chl-a had a strong loading along the first principal component that represents a nutrient factor. The second principal component had strong loadings of total precipitation, SD, TP and SS. This component therefore represent the rainfall intensity factor or runoff discharge from rivers as explanatory factor. Air temperature and WT in the third component indicates loading from weather factors (Table 3). Figure 3 displays the factor contribution percentages that affects the trophic state levels of the four major reservoirs in Taiwan. The contribution of rainfall intensity was the most dominant factor in the reservoirs of Shihmen, Wushantou and Chengchinghu, accounting to 51%, 41% and 58%, respectively. Nutrient factors in the Liyutan Reservoir accounted for 38% (Figure 3).

In the Liyutan Reservoir, the first components was mainly governed by pH and total precipitation, which suggests that it describes the precipitation or rainfall intensity as a governing factor. The second components is mainly loaded by SD, Chl-a, TP, COD and ammonia, which are mainly governed by irrigation and other agricultural activities. The air and water temperature also influenced the water quality in the Liyutan Reservoir, as shown in the third component. In the Wushantou Reservoir, nutrients and temperature were the main factors governing the first and second components, respectively; and the third factor was driven by rainfall intensity. Rainfall intensity was the major explanatory parameter for the variation in this reservoir (Table 4). In the Chengchinghu Reservoir, the first factor was mainly governed by rainfall, the second factor represents the nutrient factor, and the third factor was governed by temperature. The first factor was the highest contributor in the Chengchinghu Reservoir (Table 4).

Table 3. Varimax rotated factor of principal component analysis (PCA) of all reservoirs.

Parameters	Factor 1	Factor 2	Factor 3
Shihmen Reservoir			
Air temperature	0.03	0.35	0.79
Water temperature	0.04	0.13	0.88
Total precipitation	0.10	0.86	0.09
SD	−0.06	−0.76	−0.29
Chl-a	0.80	0.15	0.12
TP	0.25	0.75	0.17
SS	0.13	0.97	0.02
Liyutan Reservoir			
Water temperature	0.23	0.06	0.81
Air temperature	0.11	0.04	0.92
pH	0.70	0.10	0.11
Total precipitation	0.72	0.07	0.30
SD	−0.18	−0.75	−0.18
Chl-a	0.17	0.75	0.21
TP	0.09	0.71	0.13
COD	0.13	0.77	0.17
Ammonia	0.25	0.77	0.02
Wushantou Reservoir			
Chl-a	0.75	0.05	0.25
SD	−0.14	−0.11	−0.73
TP	0.79	−0.08	−0.14
Total precipitation	0.13	0.09	0.71
Air temperature	0.06	0.95	0.01
Water temperature	0.08	0.94	0.02
SS	0.05	0.03	0.93
Chengchinghu Reservoir			
Water temperature	0.03	0.04	0.95
SD	−0.72	−0.15	−0.12
Chl-a	0.09	0.71	0.13
TP	0.13	0.76	0.03
COD	0.74	0.01	0.13
Ammonia	0.88	0.83	0.11
Nitrate	0.11	0.76	0.02
Nitrite	0.13	0.81	0.08
SS	0.91	0.08	0.001
Total precipitation	0.82	0.12	0.09
Air temperature	0.003	0.20	0.85

Note: Grey background color indicates the value ≥ 0.7.

Table 4. Contribution percentage of each factor from linear regression.

Model	B	Sig.	% Contribution	R^2
Shihmen Reservoir				
Constant	1.14×10^{-14}	0.00	-	0.89
Factor 1	1.17	0.00	16%	
Factor 2	3.75	0.00	51%	
Factor 3	2.40	0.00	33%	
Liyutan Reservoir				
Constant	-1.286×10^{-14}	0.00	-	0.82
Factor 1	2.17	0.00	35%	
Factor 2	2.38	0.00	38%	
Factor 3	1.65	0.00	27%	

Table 4. *Cont.*

Model	B	Sig.	% Contribution	R^2
Wushantou Reservoir				
Constant	-2.329×10^{-14}	0.00	-	0.84
Factor 1	0.62	0.00	19%	
Factor 2	1.25	0.00	40%	
Factor 3	1.29	0.00	41%	
Chengchinghu Reservoir				
Constant	1.872×10^{-14}	0.00	-	0.81
Factor 1	3.24	0.00	58%	
Factor 2	1.43	0.00	25%	
Factor 3	0.93	0.00	17%	

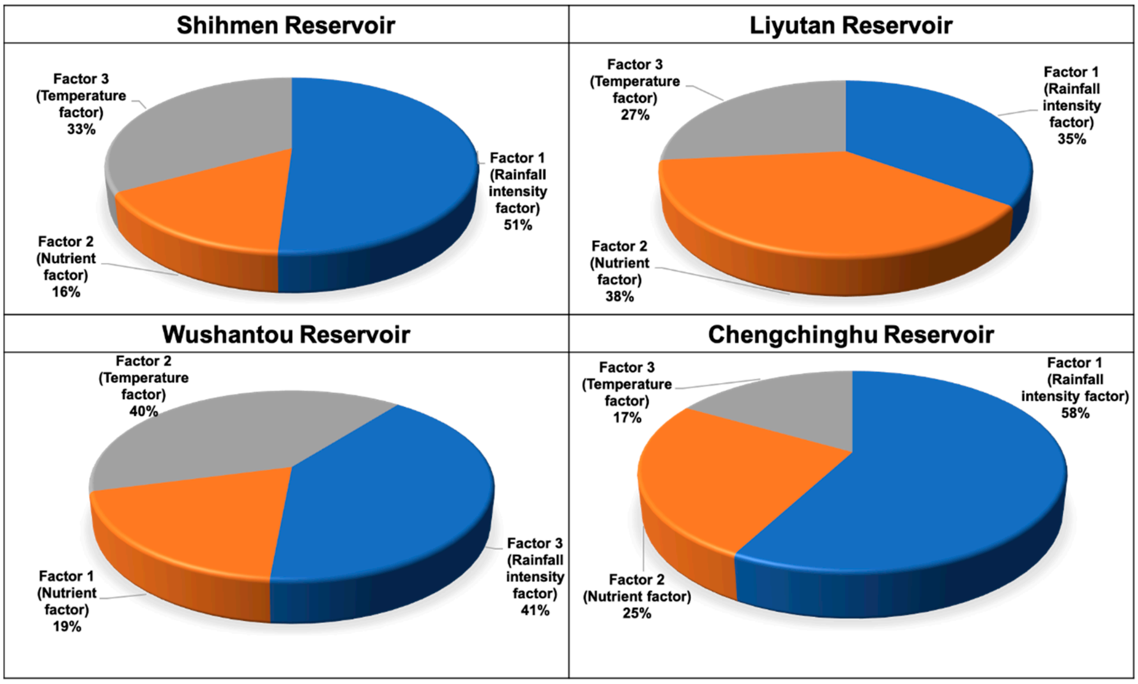

Figure 3. Factor contribution percentage affecting trophic states level for four Taiwan major reservoir.

4. Discussion

This study assessed the key factors that affect the trophic state levels of the four major reservoirs in Taiwan. CTSI levels were dominantly affected by the rainfall intensity/weather factor in three of the major reservoirs: Shihmen Reservoir (51%), Wushantou Reservoir (41%) and Chengchinghu Reservoir (58%). However, in the Liyutan reservoir, the CTSI level was mainly affected by the nutrient factor (38%). The CTSI level showed a strong correlation with SS in the Shihmen, Wusantou and Chengchinghu Reservoirs. In the Liyutan Reservoir, the CTSI level had a strong correlation with Chl-a and TP. Our findings differed from those of previous studies where the CTSI levels were mostly dominated by the algae/nutrient factor [11,42,43]. All regression models accounting from APCS (Table 4) showed remarkable performance ($R^2 > 0.7$), indicating good consistency between the modeled and observed values, verifying the reliability of the main governing factors for the results [44].

The concentrations of SS in the Shihmen, Wushantou and Chengchinghu Reservoirs were significantly higher in fall and summer (Supplementary Table S3). This finding is consistent with those of previous studies since the rainfall intensity is normally high during these seasons [45]. Previous studies conducted in the Shihmen Reservoir found that SS number in the water were higher in summer season [46]. The rainfall patterns along with frequency and intensity of extreme rainfall have significant effects on the physical and chemical characteristics of the reservoirs [47].

The Liyutan Reservoir showed the highest level of Chl-a, WT, nitrate, nitrite and ammonia in summer. The higher water temperature during this season favors the bloom of toxin-producing harmful phytoplankton. During summer, algae mass increases significantly, thereby accelerating the phosphorous cycle in water. Griffith and Gobler (2020) reported that temperature was a major factor that increases the growth of alga that lead to alga bloom [48]. Therefore, the higher temperature during summer in the Liyutan Reservoir may elevate the algae and nutrient loading [49,50].

The Pearson's correlation results supported our finding that algae are not the main contributors to CTSI in the major reservoirs in Taiwan. In the Liyutan Reservoir, CTSI level had a strong correlation with Chl-a. On the contrary, in the reservoirs of Shihmen, Wushantou and Chengchinghu, the association between CTSI level and SS were stronger than those of TP and Chl-a level. The high contribution of SD is associated with the high SS discharging from inflowing rivers. Particulate solids, N, P and soluble organic molecules are carried into the reservoir through inflow, thereby leading to increased concentrations of TN, TP and total organic carbon under storm runoff conditions [51]. The TSI(SD) provides the dominant contribution to CTSI levels due to the high rainfall intensity and heavy storm runoff which causes a high flow of particulates to this reservoir.

Rainfall intensity was the major contributor (51%) of eutrophication in the Shihmen Reservoir, and high levels of TSI(SD) was measured during fall (Figure 2). In addition to rainfall, temperature (33%) and nutrient factors (16%) also affect the quality of water body. Lin et al. (2011) reported that typhoon-triggered landslides delivered huge increases in sediment to the upstream channels of the Shihmen Reservoir. The high turbidity occurs during a typhoon event, that is, when the high water discharge flows into the reservoir scours the fine fraction sediment at the bottom of the reservoir and forms hyperpycnal flow with high turbidity, which then contaminate the surface water of the reservoir [23]. In addition, in Taoyuan, effluent from the wastewater treatment plant and a beverage factory may contribute to the increased amount of SS.

The eutrophication in the Liyutan Reservoir was dominantly affected by nutrients (38%), rainfall intensity (35%) and temperature (27%). Previous research has indicated that the nutrient concentration is the major factor that determines the variation in the level of measurement elements at this site.

Rainfall intensity has the highest contribution to eutrophication in the Wushantou Reservoir (41%) followed by temperature (40%) (Figure 3). We found a strong correlation between transparency (SD) and SS. High TSI(SD) was observed in summer and winter. Our finding was supported by climate data (https://en.climate-data.org/asia/republic-of-china/tainan-city/tainan-city-983291/), showing that more rainfall in Tainan City occurred during summer, and the highest monthly average rainfall was in August (455 mm). In 2016, typhoon Megi landed in Southern Taiwan and carried 353 mm of precipitation to Tainan city within 24 h [52]. This phenomenon transported excessive amounts of nutrient that affects the aquatic ecosystem. The TSI(TP) in the Wushantou Reservoir showed a high level in summer (Figure 2), indicating the important role of nutrient factor for trophic states level in the Wushantou Reservoir. Therefore, seasonal factors dominantly affected the trophic state levels in the Wushantou Reservoir.

This study documents that the eutrophication in the Chengchinghu Reservoir was mainly dominated by rainfall intensity (58%). Figure 2 shows that the highest number of TSI(SD), which is governed by the increased rainfall intensity, during winter. The annual rainfall in Kaohsiung is 1885 mm in June–September. Chiu et al. stated that rainfall pattern at Kaohsiung Harbor was an influential factor in eutrophication; it can increase the volume of freshwater flow, which can cause the nutrient load to reach the coastal water [3]. Nevertheless, the nutrient factor only accounted for 25%. Other studies in Kaohsiung reported that nutrient levels have high contribution from farming activity running off to the Kaoping River as an inflow to the Chengchinghu Reservoir. The released N and P into water body through agricultural practice lead to severe eutrophication [3]. Summing up, the high trophic state level of the Chengchinghu Reservoir resulted from a combined contribution of population growth, industrial wastewater (Figure 1) and agriculture activities.

Due to the climate change, rapid industrialization and urbanization that affect eutrophication, the government needs to strengthen several regulations and implement abatement actions. Controlling anthropogenic loads of nutrients is currently a feasible and sensible strategy for alleviating eutrophication. Eutrophication could be reduced by controlling the discharges of industrial and agricultural effluents and improving recycling water [50,53]. Reducing the nutrient of surface runoff and improving the water quality before reaching the catchment area can be a management practice [54]. For instance, the adsorption of nutrients in the soil during the transport process can reduce N and P in the reservoir. Cui et al. suggested that implementing buffer strips along the side of streams and reservoir shorelines may be a good solution to reduce external nutrient loads [55]. A recent study conducted by Selbig [56] showed that major reduction (71%–84%) in the total and dissolved forms of nutrient could be achieved if we can prevent litter fall from reaching water body during the rainy season. Bu et al. also proved that buffer strips could reduce the sediments, TN and TP from surface runoff during rainfall [57].

Kuo et al. found that the rainfall pattern in Taiwan was complex because of the presence of the Central Mountain Range [45]. This study also shows that increased rainfall intensity occurred during different seasons in each reservoir. Therefore, the amount of SS in each reservoir varied in a different season. In addition, the climate change, resulting in more extreme events, was found to be a contributor in elevating surface runoff, rainfall intensity and flooding, which affect eutrophication. Therefore, with Global warming, sustaining our water resource is a great challenge for the policymakers that must be considered properly [58]. Climate change and extreme weather conditions should be considered in reservoir management. The future impacts of extreme weather may be minimized by implementing counteracts, such as using polymeric shading net in some reservoirs to avoid the increase in water body temperature during summer. Furthermore, providing an artificial circulation in water body that could increase the amount of dissolved oxygen that lead to biologic degradation activity on-site [59,60].

This study suggests that the water management sector should conduct routine evaluation and area-specific modification of indicators for trophic status of a water body to meet sustainable efficient management. Despite the contributions of this study, limitations are still observed. Our study only focused on weather and nutrient factors, without including the microbial, biodiversity and hydrodynamic factors. In addition, our prediction toward trophic state level did not involve the seasonal and hotspot area factors because of lack of seasonal water quality data and sampling location.

5. Conclusions

The PCA and APCS models were successfully used to identify the major factors that affect the eutrophication level in Taiwan reservoir. Rainfall/weather was the main predictor of eutrophication in the reservoirs of Shihmen, Wushantou and Chengchinghu. Typhoon events may affect the CTSI level in these reservoirs. The CTSI level in the Liyutan Reservoir is mainly affected by the nutrient factor derived from non-point agricultural activity. This study found a strong association between CTSI level and SS in the reservoirs of Shihmen, Wushantou and Chengchinghu. On the other hand, the CTSI level in the Liyutan Reservoir is strongly correlated with Chl-a and TP. Given the critical role of SS in the reservoirs of Shihmen, Wushantou and Chengchinghu, the Taiwan government should develop appropriate solutions to reduce nutrient loading to reservoirs by applying buffer strips alongside the reservoir shorelines; monitoring the CTSI level continuously; strengthening regulations regarding the use of N and phosphorous to minimize eutrophication; and consider the effects of climate change and extreme weather conditions.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/5/1325/s1. Figure S1: Pearson's correlation plot among water quality and weather factors in (a) Shihmen Reservoir, (b) Liyutan Reservoir, (c) Wushantou Reservoir and (d) Chengchinghu Reservoir, Figure S2: Boxplots of daily weather parameters in study area from 2000 to 2017 (a) temperature, relative humidity, sunshine percentage, cloud amount and (b) precipitation, Table S1: Reservoirs characteristic, Table S2: Water quality measurement methods, Table S3: Descriptive statistic of water quality in (a) Shihmen, (b) Liyutan, (c) Chengchinghu, and (d) Wushantou.

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