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Assessment of Water Quality Based on Trophic Status and Nutrients-Chlorophyll Empirical Models of Different Elevation Reservoirs

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Abstract: Water quality degradation is one of the most pressing environmental challenges in reservoirs around the world and makes the trophic status assessment of reservoirs essential for their restoration and sustainable use. The main aims of this study were to determine the spatial variations in water quality and trophic state of 204 South Korean reservoirs at different altitude levels. The results demonstrated mean total phosphorus (TP), chlorophyll-a (CHL-a), total suspended solids (TSS), organic matter indicators (chemical oxygen demand: COD; total organic carbon: TOC), water temperature (WT), and electrical conductivity (EC) remain consistently higher in the very lowland reservoirs (VLLR) than those in other altitudes, due to sedimentary or alluvial watersheds. The average TP and CHL-a levels in VLLR crossed the limit of the eutrophic water, symptomizing a moderate risk of cyanobacterial blooms. Empirical models were developed to identify critical variables controlling algal biomass and water clarity in reservoirs. The empirical analyses of all reservoir categories illustrated TP as a better predictor of CHL-a (R^2 = 0.44, $p < 0.01$) than TN (R^2 = 0.02, $p < 0.05$) as well as showed strong P-limitation based on TN:TP ratios. The algal productivity of VLLR (R^2 = 0.61, $p < 0.01$) was limited by phosphorus, while highland reservoirs (HLR) were phosphorus (R^2 = 0.23, $p < 0.03$) and light-limited (R^2 = 0.31, $p < 0.01$). However, TSS showed a highly significant influence on water clarity compared to TP and algal CHL-a in all reservoirs. TP and TSS explained 47% and 34% of the variance in non-algal turbidity (NAT) in HLR. In contrast, the TP and TSS variances were 18% and 29% in midland reservoirs (MLR) and 32% and 20% in LLR. The trophic state index (TSI) of selected reservoirs varied between mesotrophic to eutrophic states as per TSI (TP), TSI (CHL-a), and TSI (SD). Mean TSI (CHL-a) indicated all reservoirs as eutrophic. Trophic state index deviation (TSID) assessment also complemented the phosphorus limitation characterized by the blue-green algae (BGA) domination in all reservoirs. Overall, reservoirs at varying altitudes reflect the multiplying impacts of anthropogenic factors on water quality, which can provide valuable insights into reservoir water quality management.

Keywords: chlorophyll-a; elevation; nutrients; trophic state index; water clarity

Citation: Mamun, M.; Atique, U.; An, K.-G. Assessment of Water Quality Based on Trophic Status and Nutrients-Chlorophyll Empirical Models of Different Elevation Reservoirs. *Water* **2021**, *13*, 3640. https://doi.org/10.3390/w13243640

Academic Editor: Shiming Ding

Received: 22 October 2021
Accepted: 14 December 2021
Published: 17 December 2021

1. Introduction

Over the last century, many reservoirs have been built worldwide, mainly for hydropower generation. They are further exploited for various reasons, including drinking water supply, fisheries, irrigation, flood mitigation, and tourism [1–3]. However, reservoir water quality is a significant concern across the world as it faces multiple problems linked to anthropogenic activities such as excessive input of nutrients and pollutants from household wastewater, agricultural and industrial runoff [1,4]. In addition, reservoir water quality degrades more quickly than that of natural lakes [5]. Moreover, reservoir characteristics and water quality patterns are regulated by local and regional climatic conditions, geological landscape, land use, and hydrology [6–9]. This calls for essential, detailed, and recurrent limnological as well as trophic status research on the typology of reservoirs.

Besides, reservoir physicochemical and biotic features differ depending on geological, morphological, climatic, biogeographical, and anthropogenic factors [6,10]. Therefore, the regional limnology of reservoirs is particularly complicated and susceptible to degradation due to climate change, deforestation, infrastructure development, and intensive farming activities [9–11].

Regional limnology has been studied in "lake districts" characterized by uniform catchment morphology, geology, climate, and vegetation conditions [6,11,12]. Altitudinal influences on lotic systems along with continuous gradients have received more attention than lentic ecosystems [13–15]. On the other hand, comparable investigations into lentic systems have been discontinuous. Some previous research claimed that altitude has a greater impact on water temperature, ionic strength, water residence time, nutrient concentrations, and phytoplankton biomass [6,7]. However, researchers studying high altitude reservoirs found low ions and nutrient concentrations with modest algal biomass compared to low altitude waterbodies [6,8].

The case of South Korea is interesting as most of the reservoirs are located in midland (100–200 m) to very lowland (<50 m) altitudes. Consequently, there are fewer reservoirs in highland (>200 m) areas. Intensive agricultural farming, urbanization, and industrialization have been developed mostly in lowland (50–<100 m) to very lowland regions owing fewer slopes and profusely available water resources [10,16]. Most of the reservoir studies were based on land use patterns in Korea [9,10]. There are few comprehensive investigations on detailed limnology, water quality, and altitudinal gradient in the highland to lowland zones. Several researchers have repeatedly recommended that more comparative studies on reservoir limnology and water quality are essential, based on altitudinal gradient [10,17].

The most frequently used strategy for addressing water quality issues, particularly eutrophication in reservoirs, is to reduce external and internal nutrient loads (TP, TN) [4,18,19]. This technique presupposes that algal development in aquatic habitats is P-limited, N-limited, or co-limited by P and N. In freshwater systems, TP strongly regulates algal chlorophyll [17,20]. In contrast, TN has a strong influence on CHL-a in marine systems [21]. However, certain aquatic systems, particularly in high alpine locations, are co-limited. CHL-a: TP and TN:TP ratios have been recommended as valuable markers for eutrophication control in aquatic systems. If the TN:TP ratio is less than 6, aquatic habitats are termed N-limited; if the ratio is larger than 16, aquatic ecosystems are deemed P-limited [5,22]. However, when the ratio is between 6 and 16, co-limitation occurs. Additionally, Carlson (1977) created a quantitative score based on TP, CHL-a, and SD to evaluate the degree of eutrophication in lentic habitats [23]. Carlson and other limnologists have agreed that TP may be the best predictor of algal CHL-a [4,10,18,19,24]. Simultaneously, CHL-a is the most trustworthy indication of algal biomass, whereas SD is the most accurate indicator of water clarity in lentic systems [25,26]. This index is a very useful tool for water quality management in reservoirs.

Previous research has suggested that empirical analyses are important for identifying key variables controlling algal biomass and water clarity in lakes and reservoirs and for setting nutrient reduction targets [10,18]. The observed relationships between CHL-a and nutrients are among the most extensively investigated patterns in limnology [4,17,27]. TP regulates more freshwater algal growth than TN [10,28,29]. Moreover, algal biomass is influenced by seasonal climatic variations, morphometry, zooplankton grazing and fish composition in reservoirs [10,18,30]. These easily observed empirical analyses are very useful for eutrophication management and for ensuring high water quality in aquatic systems.

This study explores how trophic status and water quality of reservoirs vary with altitude. Further, we investigated the relationship between water clarity, nutrients, suspended solids, and algal CHL-a to determine potential limiting factors in different altitude reservoirs, including highland, midland, lowland, and very lowland reservoirs. This study may aid in determining the optimum management techniques for enhancing reservoir water quality on the altitudinal gradient.

2. Materials and Methods

2.1. The Study Region

This study was conducted in 204 artificial reservoirs in South Korea. The majority of Korean reservoirs (about 90%) are shallow (<5 m), have a small water storage capacity (1,000,000 m^3), have high watershed reservoir area ratios, and exhibit variable hydrodynamics [12]. The principal source of nutrients is allochthonous, and the ecosystem is eutrophic [5]. The elevation ranges of the selected reservoirs extended from 0 m to 648 m in the Republic of Korea. The sampled reservoirs were categorized into four distinct groups based on their elevations, namely high land reservoirs (HLR: >200 m), midland reservoirs (MLR: 100–200 m), lowland reservoirs (LLR: 50–<100 m), and very lowland reservoirs (VLLR: <50 m; Figure 1). The investigated study sites are impacted by a variety of altitudinal regions that differed significantly in terms of general land use (Figure 1). The HLR and MLR are primarily located in protected areas rather than forest-dominated areas. In contrast, LLR may receive water from agricultural drainage. However, VLLR in the watersheds are affected by intensive agriculture farming, industrialization, and urbanization. Such varying land-use patterns could reflect the heterogeneity among nutrient loading and algal biomass, thereby supporting the hypothesis that "decreased nutrient loading is evident with increasing elevation" [6].

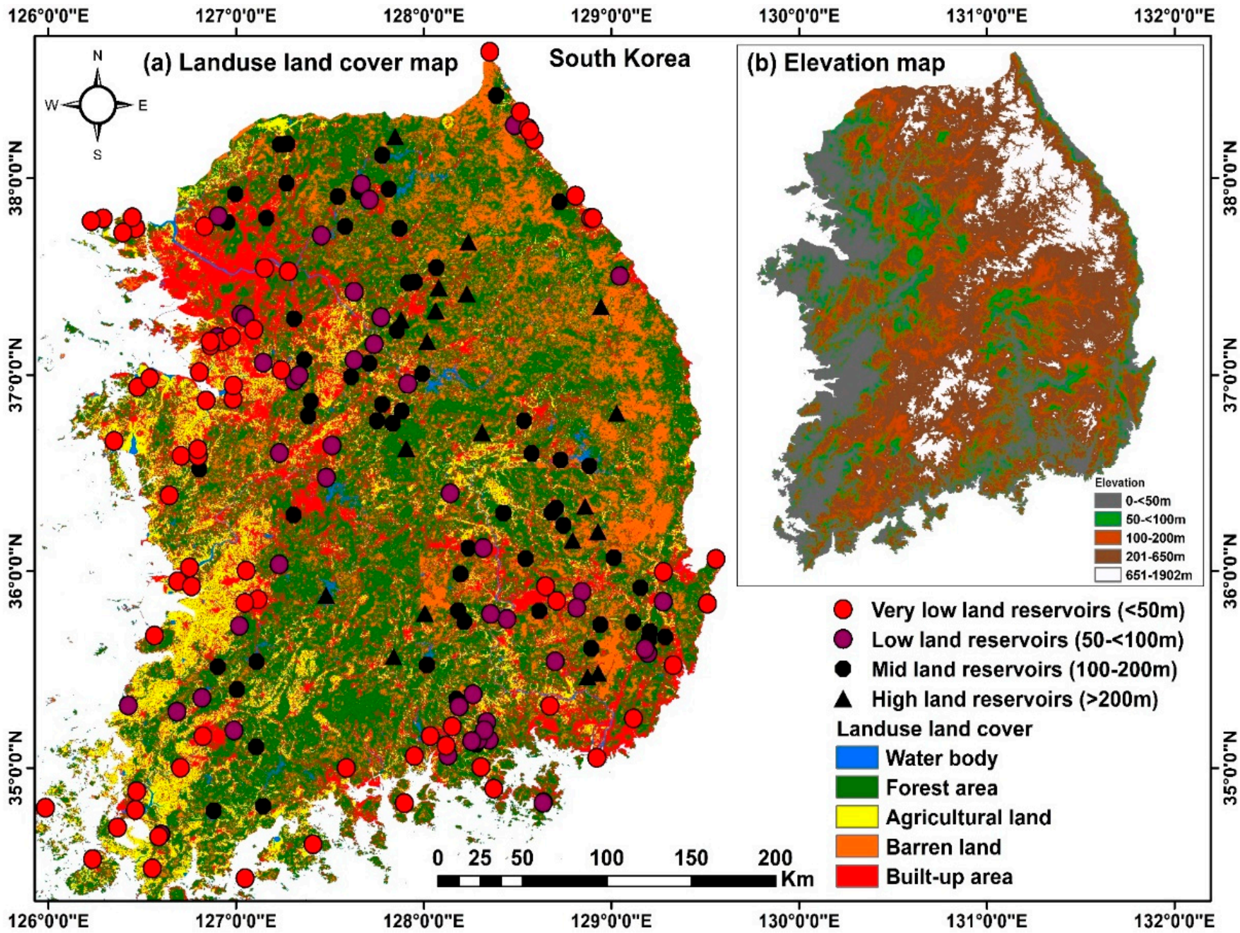

Figure 1. The study area map shows the different elevation reservoirs in South Korea with land use and land cover.

2.2. Data Source and Analysis of Water Quality

Monthly water quality data were obtained from the Korean Ministry of Environment (MOE) Water Information Network (available online: http://water.nier.go.kr (accessed on 15 April 2021)). We studied ten water quality parameters in 204 selected Korean reservoirs in

2019. The water samples were taken from the reservoirs' surface layer (<0.5 m) at the chosen sampling location (Figure 1). One-liter high-density polyethylene (HDPE) bottles were used to collect the water from the surface layer (<0.5 m) of the selected reservoir sites. The sampling bottles containing water samples were immediately placed in an icebox to avoid sunlight exposure. The selected water quality parameters included WT, EC, dissolved oxygen (DO), TSS, COD, TOC, TN, TP, CHL-a, and SD. A portable multiparameter analyzer (YSI Sonde Model 6600, YSI Incorporated, Yellow Springs, OH, USA) was used onsite to measure WT, electrical conductivity (EC), and DO. A 30-cm metal disk was used to measure the SD at the time of sample collection. The sampling, preservation, and analytical procedures for TSS, COD, TOC, TN, TP, and CHL-a were performed according to the approved methods of the Korean Ministry of Environment [31].

2.3. Trophic Status Index Deviation

The conventional trophic state index (TSI) criteria based on TP, CHL-a, and SD were used to evaluate eutrophication in the selected reservoirs. The average range of TSI for oligotrophic conditions is 30–40; mesotrophic conditions are 40–50; eutrophic conditions are 50–70, and hypereutrophic conditions are greater than 70 [26,32]. The TSI in reservoirs was determined using the following formulae [23]:

I. TSI (CHL-a, μgL^{-1}) = $10 \times [6 - (2.04 - 0.68 \ln(\text{CHL-a}))/\ln 2]$

II. TSI (TP, μgL^{-1}) = $10 \times [6 - \ln(48/\text{TP})/\ln 2]$

III. TSI (SD, m) = $10 \times [6 - \ln(\text{SD})/\ln 2]$

Both the TSI (CHL-a)−TSI (SD) and TSI (CHL-a)−TSI (TP) approaches were used to infer the deviations of the TSI of the reservoirs. Using this method, eutrophication and limiting nutrient status in reservoirs and lakes can also be assessed [33].

2.4. Non-Algal Turbidity

Non-algal turbidity (NAT) is widely used to determine the light availability of reservoirs and measured using SD and CHL-a, following the method of Jones and Hubbart (2011) [34]. The following equation has been used to estimate each reservoir's maximum potential SD (SD_{max}) value.

IV. $\text{Log}_{10}\text{SD}_{max} = 0.90 - 0.29\text{Log}_{10}\,(\text{CHL-a}) - 0.138\text{Log}_{10}(\text{CHL-a})^2$

The back-transformed reciprocal of SD_{max} was then subtracted from the reciprocal of the observed SD value at each reservoir to determine NAT using the following equation:

V. NAT = $(1/\text{SD}) - (1/\text{SD}_{max})$

This technique yielded a quantitative estimation of NAT as expected by Walker's (1986) equation [35].

2.5. Statistical Analysis

Each reservoir's TP, TN, and CHL-a values were used to compute the CHL-a: TP and TN:TP ratios. It was necessary to $\log_{10}$-transform water quality parameters concentrations in order to increase the normality of the data before regression analysis. The TP, CHL-a, and SD datasets were utilized to determine each reservoir's trophic status. Finally, regression analysis investigated the link between water quality parameters and constructed an empirical model. Sigma Plot (Ver. 14; Systat Software Inc., San Jose, CA, USA) was used to conduct this analysis.

3. Results

3.1. Physicochemical Characteristics of Korean Reservoirs

The physicochemical water quality attributes of selected reservoirs at different elevations showed varying patterns of heterogeneity (Table 1). The surface WT fluctuated with altitude, with the mean WT nearly 13.44 °C at VLLR. However, the WT decreased to 9.06 °C in the HLR. The mean DO level was similar in the HLR, MLR, LLR, and VLLR sites. Nevertheless, the average EC of the VLLR was significantly higher (2913.95 μScm^{-1}) than the other reservoir types based on altitude (HLR: 103.85 μScm^{-1}, MLR: 112.84 μScm^{-1}, and

LLR: 128.65 μScm^{-1}. Mean TP, TSS, and organic matter indicators (COD, TOC) displayed consistently higher loads in the VLLR (TP: 39.10 μgL^{-1}, TSS: 7.98 mgL^{-1}, COD: 7.05 mgL^{-1}, TOC: 4.12 mgL^{-1}) than in LLR (TP: 20.32 μgL^{-1}, TSS: 4.26 mgL^{-1}, COD: 4.90 mgL^{-1}, TOC: 2.96 mgL^{-1}), MLR (TP: 16.84 μgL^{-1}, TSS: 3.49 mgL^{-1}, COD: 4.57 mgL^{-1}, TOC: 2.89 mgL^{-1}), and HLR (TP: 14.41 μgL^{-1}, TSS: 2.73 mgL^{-1}, COD: 3.86 mgL^{-1}, TOC: 2.40 mgL^{-1}). Lower average TN:TP ratios were observed in the VLLR (57.21), followed by LLR (68.55), MLR (97.51), and HLR (119.44). The mean values of CHL-a and CHL-a:TP ratios were found higher in VLLR (CHL-a: 19.26 μgL^{-1}, CHL-a:TP: 0.51) than LLR (CHL-a: 8.24 μgL^{-1}, CHL-a:TP: 0.47), MLR (CHL-a: 6.71 μgL^{-1}, CHL-a:TP: 0.47) and HLR (CHL-a: 5.81 μgL^{-1}, CHL-a:TP: 0.44). The water transparency (SD) was lower in VLLR (SD: 1.61 m) compared to LLR (SD: 1.91 m), MLR (SD: 2.55 m), and HLR (SD: 2.48 m).

Table 1. Summary of selected water quality parameters of high land (HLR), midland (MLR), lowland (LLR), and very low land (VLLR) reservoirs (units mgL^{-1}, except WT (°C), EC (μScm^{-1}), TP (μgL^{-1}), CHL-a (μgL^{-1}), SD (m), and NAT (2/m).

Reservoir Types	Summary Attributes	WT	EC	DO	TSS	COD	TOC	TN	TP	TN:TP	CHL-a	CHL-a:TP	SD	NAT
HLR (n = 19)	Min	4.70	40.00	6.70	0.80	1.80	1.20	0.52	6.58	39.62	1.37	0.14	0.90	−0.01
	Max	17.50	312.88	14.30	9.86	8.20	5.90	2.55	25.06	229.43	12.10	0.89	4.50	1.18
	Mean	9.06	103.85	10.02	2.73	3.86	2.40	1.45	14.41	119.44	5.81	0.44	2.48	0.31
	SE	0.82	15.25	0.50	0.55	0.39	0.29	0.13	1.23	12.73	0.68	0.04	0.25	0.07
MLR (n = 64)	Min	5.00	26.50	6.15	0.60	1.98	1.30	0.33	5.00	11.26	0.65	0.03	0.70	−0.32
	Max	18.80	333.00	13.10	17.50	12.53	9.23	2.51	39.33	362.40	23.00	1.89	10.00	1.06
	Mean	10.43	112.84	9.54	3.49	4.57	2.89	1.25	16.84	97.51	6.71	0.47	2.55	0.31
	SE	0.41	7.76	0.21	0.39	0.26	0.18	0.07	1.09	7.75	0.50	0.04	0.18	0.03
LLR (n = 49)	Min	2.50	27.75	4.63	1.00	1.94	1.18	0.49	8.00	15.40	1.24	0.05	0.30	0.04
	Max	18.63	414.20	13.45	20.57	9.13	6.37	2.29	44.33	200.75	22.67	1.27	3.50	3.13
	Mean	11.22	128.65	9.70	4.26	4.90	2.96	1.12	20.32	68.55	8.24	0.47	1.91	0.47
	SE	0.56	12.68	0.25	0.49	0.23	0.16	0.07	1.21	5.56	0.73	0.04	0.11	0.09
VLLR (n = 72)	Min	5.70	36.00	4.83	1.03	1.60	1.10	0.31	5.00	5.93	2.38	0.06	0.50	−0.91
	Max	24.30	54,320.08	15.02	34.68	20.00	9.61	5.64	126.20	334.96	167.48	1.88	5.11	1.43
	Mean	13.44	2913.95	10.14	7.98	7.05	4.12	1.33	39.10	57.21	19.26	0.51	1.61	0.43
	SE	0.51	1126.26	0.23	0.78	0.44	0.23	0.13	3.65	6.81	3.04	0.04	0.11	0.05

WT: water temperature, EC: electrical conductivity, DO: dissolved oxygen, TSS: total suspended solids, COD: chemical oxygen demand, TOC: total organic carbon, TN: total nitrogen, TP: total phosphorus, CHL-a: chlorophyll-a, SD: Secchi depth, NAT: non-algal turbidity, Min: minimum, Max: maximum, SE: standard error).

3.2. *Assessment of Nutrients, NAT and Algal CHL-a*

Regression analysis on all samples (n = 204) in study reservoirs (supplementary file; Figure S1) demonstrated TP as a better predictor of CHL-a (R^2 = 0.44, p < 0.01) than TN (R^2 = 0.02, p < 0.05). In HLR, algal CHL-a exhibited similar response to TP (R^2 = 0.23, p < 0.03) and NAT (R^2 = 0.31, p < 0.01; Figures 2 and 3). A highly significant positive association was observed between TP and CHL-a in VLLR (R^2 = 0.61, p < 0.01) than in LLR (R^2 = 0.03, p < 0.17), MLR (R^2 = 0.16, p < 0.01) and HLR (R^2 = 0.23, p < 0.03; Figure 2). On the other hand, a significantly negative relationship was found between TN:TP and CHL-a, with TN:TP explaining 26% and 17% of the variance in the MLR and VLLR, respectively. The TN:TP ratio was used as the predictor variable in regression analysis to explain the nutrient limitation for algal CHL-a (Figure 4). It is well established that a larger TN:TP ratio points out a greater likelihood of P-limitation. We observed a significant decline in CHL-a concentration with increasing TN:TP ratios (R^2 = 0.24, p < 0.01), with 95.59% of the observations presenting a P-limitation scenario.

3.3. Water Clarity, NAT, and Other Variables

Water clarity measured as SD and NAT is widely used to determine the light availability in freshwater reservoirs worldwide (Table 2, Figure 5). The SD illustrated a stronger influence of TP, TN, TSS, and CHL-a concentrations in the varying elevation reservoirs. In HLR, TSS ($R^2 = 0.60$, $p < 0.01$) was the better predictor of SD than TP ($R^2 = 0.53$, $p < 0.01$) and CHL-a ($R^2 = 0.48$, $p < 0.01$). A similar pattern was observed in MLR (TSS: $R^2 = 0.52$, $p < 0.01$; TP: $R^2 = 0.31$, $p < 0.01$; CHL-a: $R^2 = 0.36$, $p < 0.01$), LLR (TSS: $R^2 = 0.28$, $p < 0.01$; TP: $R^2 = 0.24$, $p < 0.01$; CHL-a: $R^2 = 0.03$; $p < 0.22$) and VLLR (TSS: $R^2 = 0.38$, $p < 0.01$; TP: $R^2 = 0.23$, $p < 0.01$; CHL-a: $R^2 = 0.24$; $p < 0.01$). A significant positive relationship was observed among NAT with TP, and TSS in HLR, MLR, and LLR, but it showed an insignificant negative relationship in VLLR (Figure 5). TP and TSS explained 47% and 34% of the variance in NAT in HLR, respectively. In contrast, it was 18% and 29% in MLR and 32% and 20% in LLR of the variance in NAT.

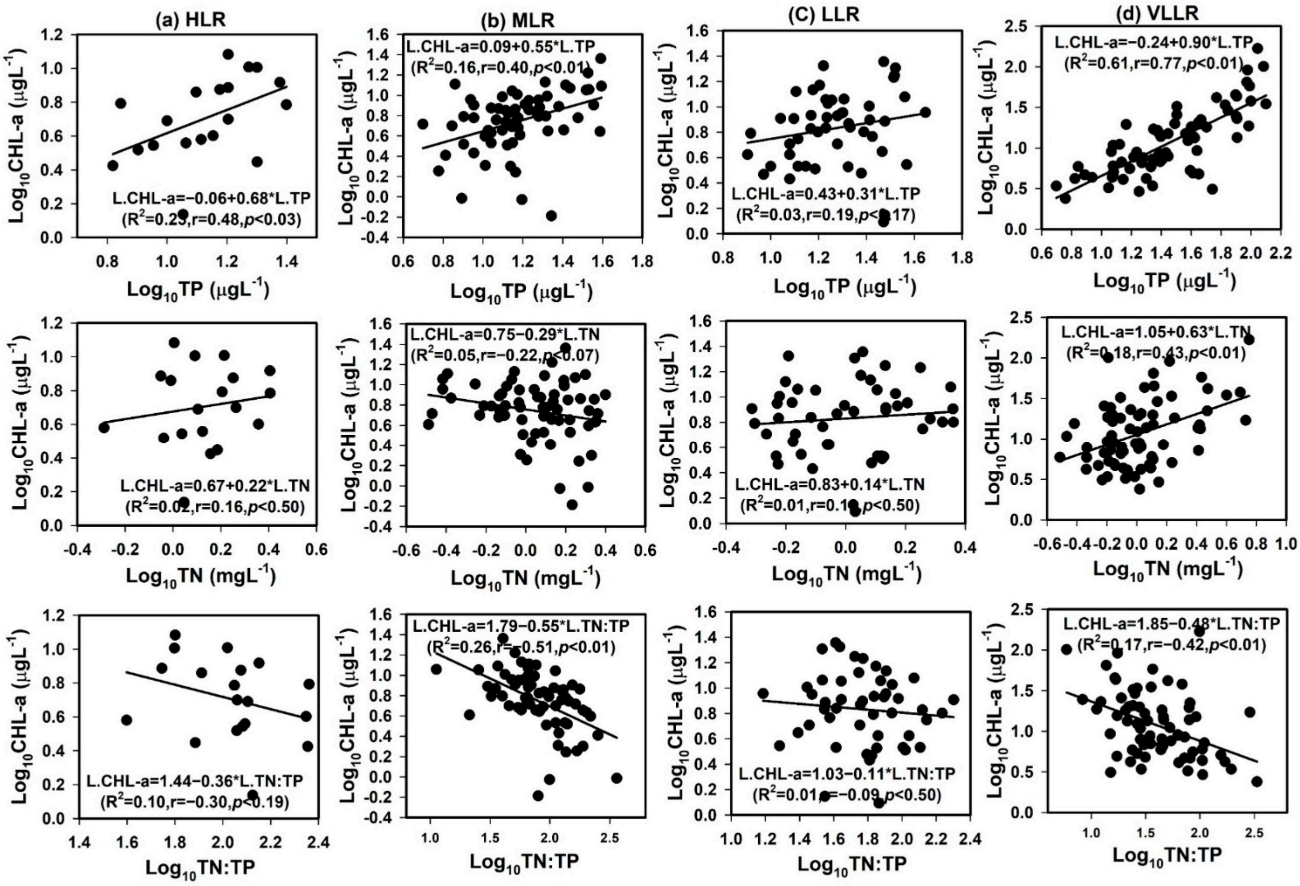

Figure 2. Regression analysis of log-transformed chlorophyll-a (CHL-a) with total phosphorus (TP), total nitrogen (TN), and TN:TP ratios in high land (HLR), midland (MLR), lowland (LLR), and very low land (VLLR) reservoirs.

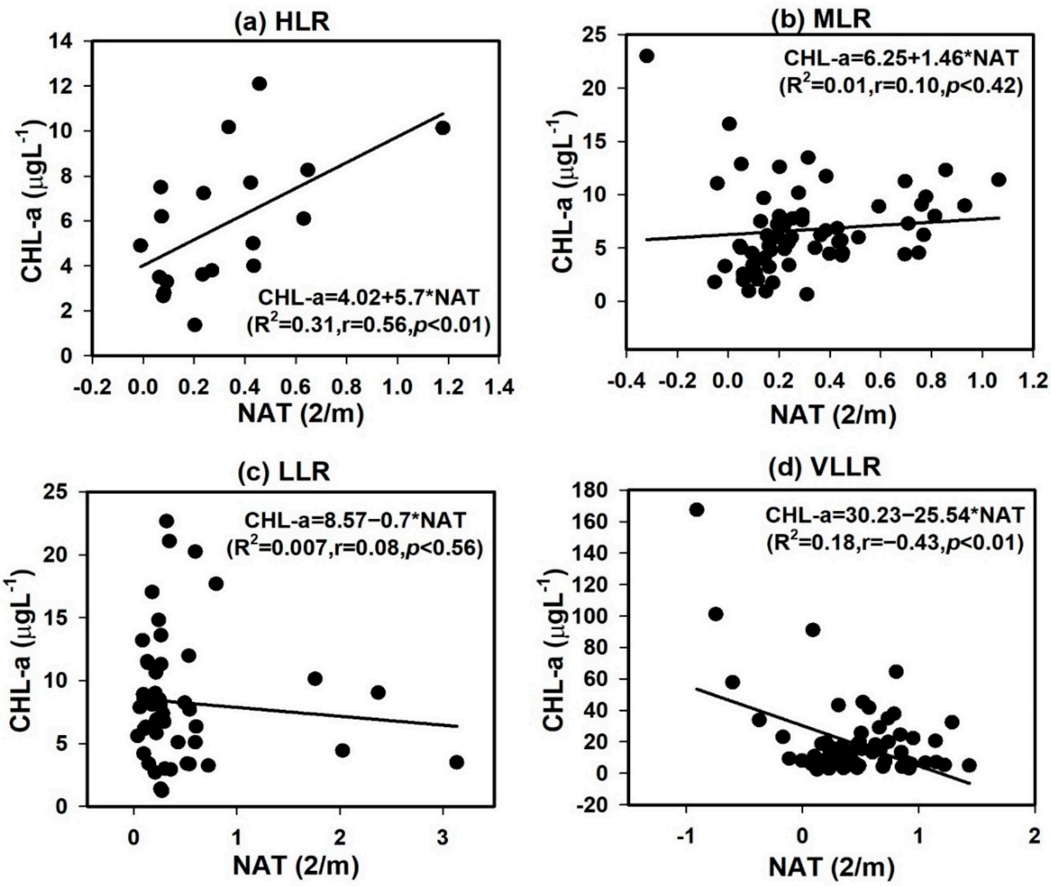

Figure 3. Regression analysis of chlorophyll-a (CHL-a) with non-algal turbidity (NAT) in high land (HLR), midland (MLR), lowland (LLR), and very low land (VLLR) reservoirs.

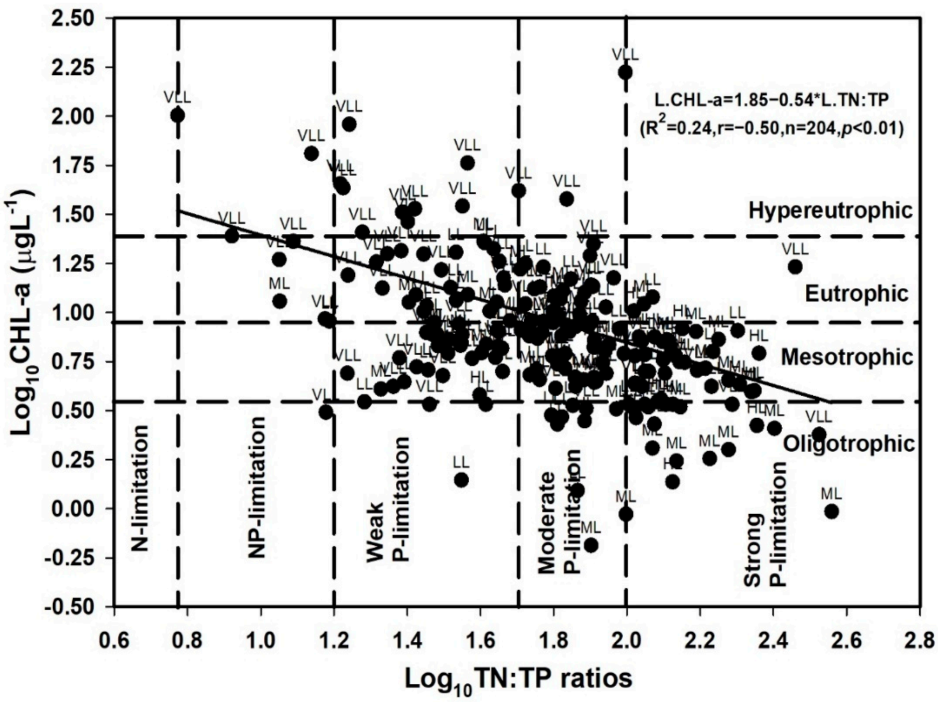

Figure 4. Determination of nutrient limitation status based on empirical modeling of CHL-a with TN:TP ratios (high land (HLR), midland (MLR), lowland (LLR), and very low land (VLLR) reservoirs.

Table 2. Regression analysis of log-transformed Secchi depth (SD) with total phosphorus (TP), total nitrogen (TN), total suspended solids (TSS), and chlorophyll-a (CHL-a) in high land (HLR), midland (MLR), lowland (LLR), and very low land (VLLR) reservoirs.

Reservoir Types	Models	R-Value	R^2	*p*-Value
HLR	Log_{10} (SD) = 1.35 − 0.89 × Log_{10} (TP)	−0.72	0.53	<0.01
	Log_{10} (SD) = 0.37 − 0.20 × Log_{10} (TN)	−0.17	0.02	<0.48
	Log_{10} (SD) = 0.51 − 0.51 × Log_{10} (TSS)	−0.77	0.60	<0.01
	Log_{10} (SD) = 0.78 − 0.6 × Log_{10} (CHL-a)	−0.70	0.48	<0.01
MLR	Log_{10} (SD) = 1.02 − 0.57 × Log_{10} (TP)	−0.56	0.31	<0.01
	Log_{10} (SD) = 0.56 − 0.49 × Log_{10} (TSS)	−0.72	0.52	<0.01
	Log_{10} (SD) = 0.67 − 0.43 × Log_{10} (CHL-a)	−0.60	0.36	<0.01
LLR	Log_{10} (SD) = 0.94 − 0.54 × Log_{10} (TP)	−0.49	0.24	<0.01
	Log_{10} (SD) = 0.44 − 0.37 × Log_{10} (TSS)	−0.52	0.28	<0.01
	Log_{10} (SD) = 0.34 − 0.12 × Log_{10} (CHL-a)	−0.17	0.03	<0.22
VLLR	Log_{10} (SD) = 0.62 − 0.33 × Log_{10} (TP)	−0.48	0.23	<0.01
	Log_{10} (SD) = 0.14 − 0.12 × Log_{10} (TN)	−0.14	0.02	<0.23
	Log_{10} (SD) = 0.45 − 0.41 × Log_{10} (TSS)	−0.62	0.38	<0.01
	Log_{10} (SD) = 0.45 − 0.29 × Log_{10} (CHL-a)	−0.48	0.24	<0.01

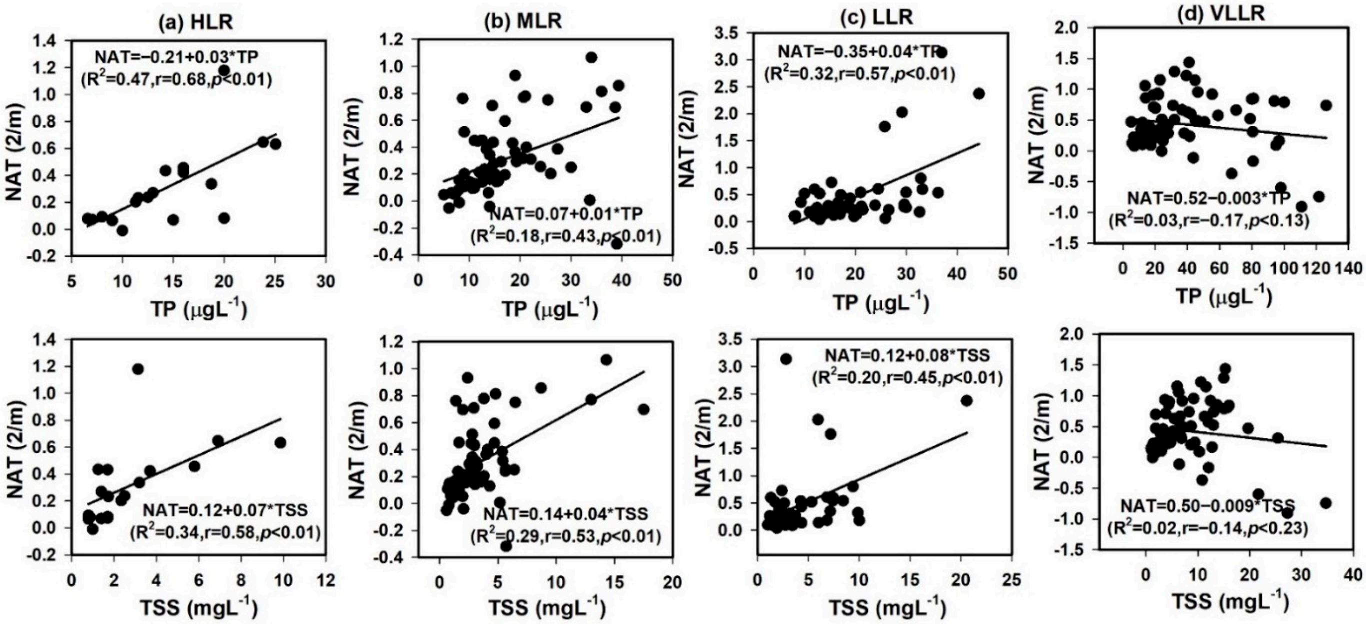

Figure 5. Regression analysis of non-algal turbidity (NAT) with total phosphorus (TP) and total suspended solids (TSS) in high land (HLR), midland (MLR), lowland (LLR), and very low land (VLLR) reservoirs.

3.4. Trophic Status Index and Its Deviation

Analysis of TSI and trophic status index deviation (TSID) in reservoirs presented valuable insights into algal growth, nutrient, and other factors. A TSI value between 40 to 50 is usually associated with the mesotrophic condition (Figure 6). TSI (TP) indicated mesotrophic conditions in HLR, MLR, and LLR, while it showed eutrophic tendency in the VLLR. TSI (CHL-a) alluded to the eutrophic trend in all elevation reservoirs. The HLR and MLR presented mesotrophic status based on TSI (SD), while LLR and VLLR were in a eutrophic condition.

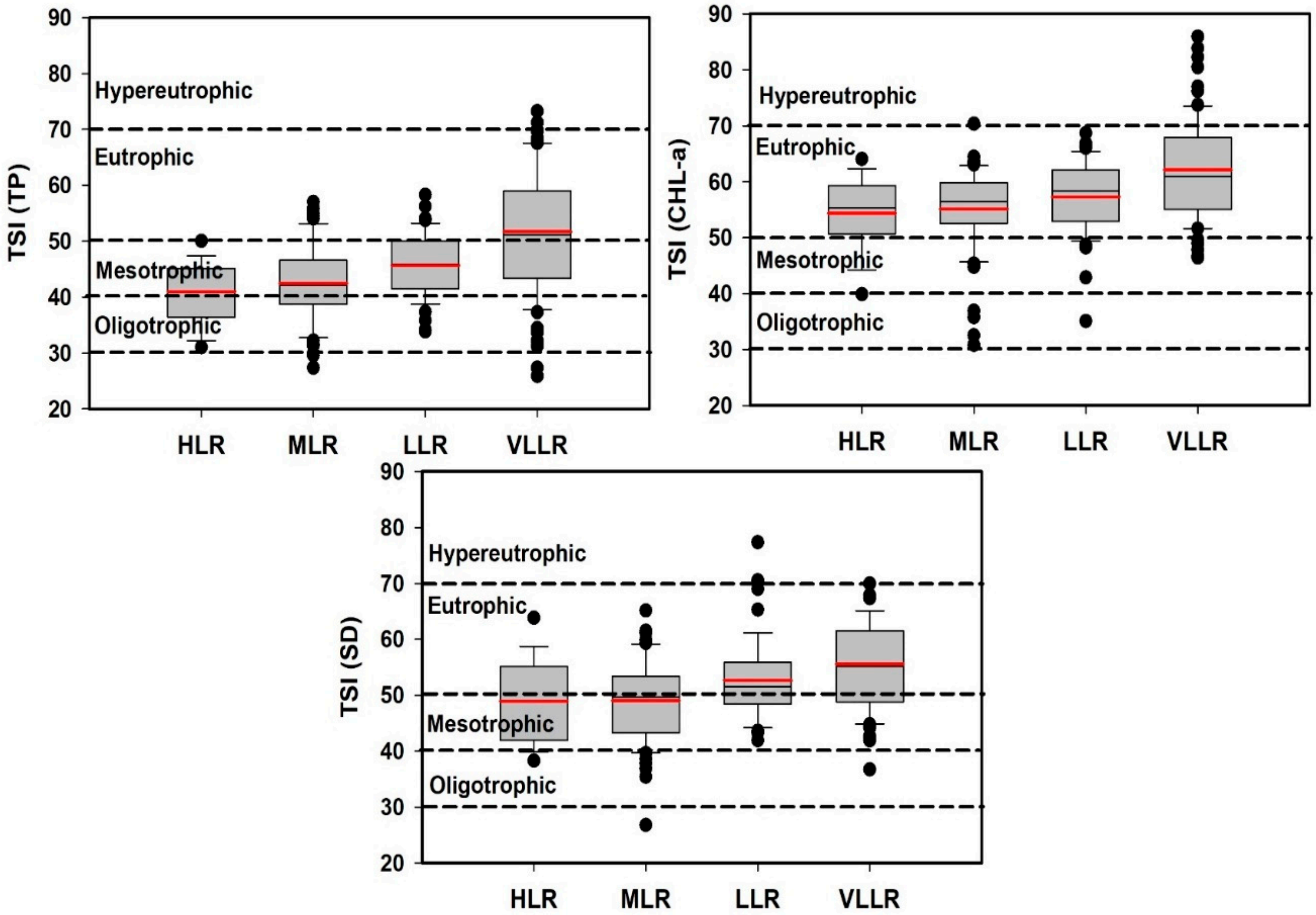

Figure 6. Trophic status of high land (HLR), midland (MLR), lowland (LLR), and very low land (VLLR) reservoirs based on total phosphorus (TP), chlorophyll-a (CHL-a), and Secchi depth (SD). The red line indicates the mean value.

The visual TSID assessment showed that phosphorus-limited BGA predominated in all reservoirs during the study period (Figure 7). For instance, in HLR, 26.31% of observations accounted for P-II, which indicated phosphorus limited smaller particles. Conversely, only 4.68% and 14.06% of observations pointed to NAT and phosphorus limitation as deciphered from the smaller particles in MLR. Correspondingly, only 20.40% and 8.16% of observations revealed phosphorus limited smaller particles and NAT in LLR. It was significant that a lower zooplankton grazing (4.16%) occurred in VLLR, while this was 15.27% and 5.55% for phosphorus limited smaller particles and NAT.

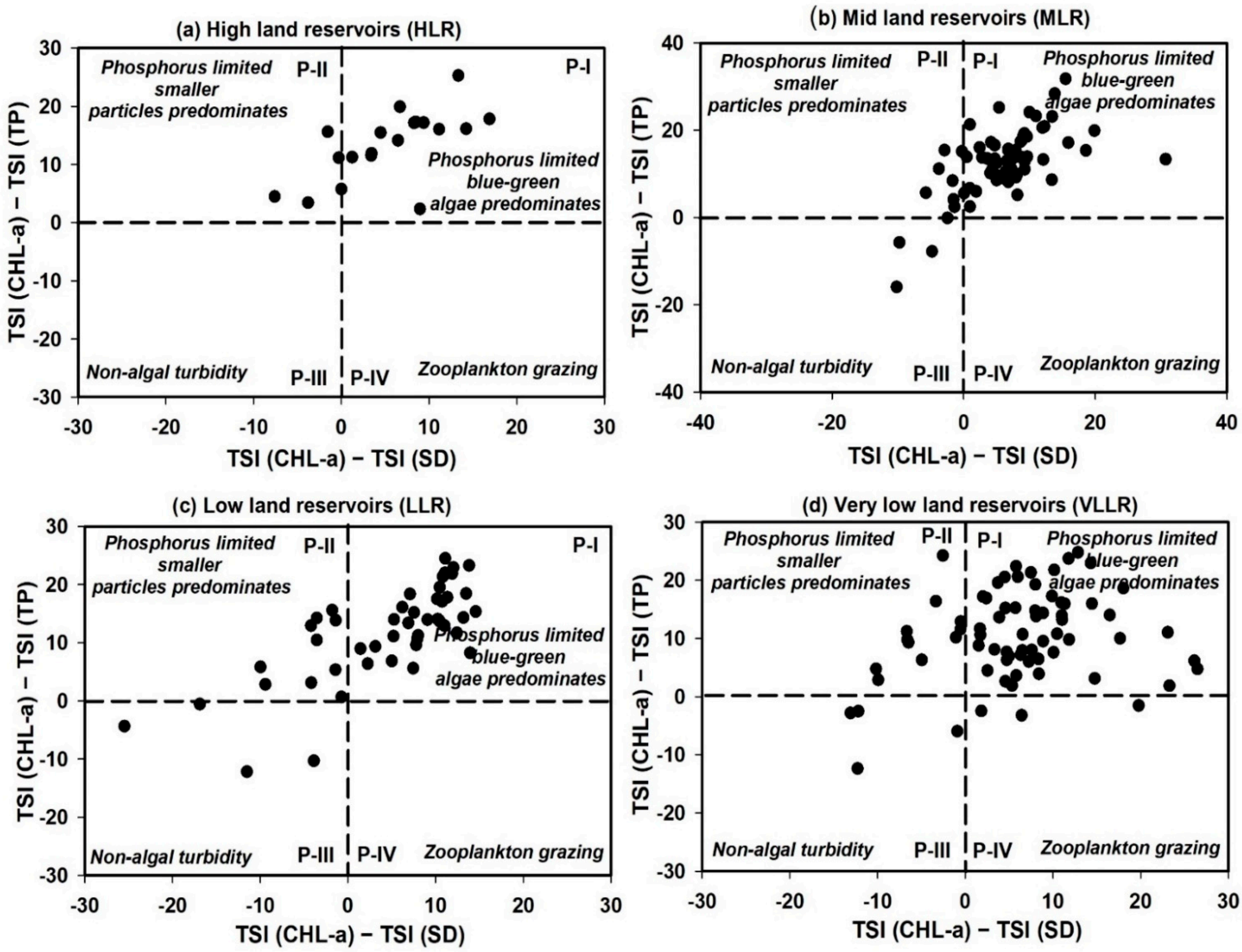

Figure 7. Trophic state index deviation (TSID) for high land (HLR), midland (MLR), lowland (LLR), and very low land (VLLR) reservoirs.

4. Discussion

4.1. Reservoirs Physicochemical Water Quality Attributes

Reservoir features are primarily regulated by local and regional weather patterns, the geological landscape, land use, hydrology, and altitude [4,5,12]. Most of the reservoirs occur from midland (ML) to very lowland (VLL) altitudinal regions in Korea. Consequently, there are fewer lakes and reservoirs in the highland (HL) areas. In Korea, surface water temperature differences were observed with altitude level and were affected by land use, wind action, watershed morphometry, and radiant heat [8]. The present study clearly observed water temperature response to altitude (Table 1; VLLR: WT 13.44 °C; HLR: WT 9.06 °C).

The reservoir's biochemical cycles are dependent on wide-ranging factors such as watershed area, atmosphere, outflow, inflow, evaporation, and sedimentation [6,8,36]. EC is a function of total dissolved ions in reservoirs and increased significantly from highland to lowland regions. HLR are usually small in extent and have shallow soil with steep slopes that allow percolating water to pass quickly, resulting in short water residence time (WRT) and less ionic strength [37,38]. On the contrary, lowland reservoirs are relatively large with deep soil and gentle slopes, allowing more significant mixing of minerals and percolating water, resulting in a longer WRT and increased ionic concentration [37]. Our findings on EC in reservoirs suggest that it was more diluted in HLR than LLR.

Suspended solids (TSS), COD, TOC, and TP in the reservoirs increased with decreasing altitude. On the other hand, TN concentration was higher in the HLR than LLR, owing to the insufficient water retention capacity of atmospherically deposited nitrogen in the high altitude catchments [37]. Mean TP concentration in VLLR was 2.7 times higher than HLR. As should be expected, given these nutrient concentration disparities, the average CHL-a concentration was 3.3 times higher in the VLLR compared to HLR. The water clarity based on SD of the reservoirs displayed an increasing tendency with altitude. These findings are consistent with the assumptions that VLLR have relatively higher nutrient import rates due to sedimentary or alluvial watersheds than highland water bodies [4,6,10]. Industrialization, urbanization, and agriculture farming are relatively intense in the alluvial plains and it can be hypothesized that VLLR are prone to a higher inflow of pollutants than the HLR. Researchers studying the highlands have claimed that the reservoirs have extremely low EC and nutrient concentrations with modest phytoplankton biomass [6,37,39,40].

4.2. Limiting Factors for Algal Growth

It is widely established that TP and TN are the key regulators of algal growth in aquatic systems [10,29,41]. We investigated whether TP, TN, or co-limited limit algal CHL-a along with NAT in Korean freshwater waterbodies. Empirical models based on TP, TN, and CHL-a suggested that TP played a dominant role in CHL-a growth regulation in the Korean reservoirs (supplementary file; Figure S1). This is frequent in temperate lakes worldwide [10,42,43]. This finding is consistent with prior research on reservoirs, which indicated that TP was the most critical component influencing algal growth, followed by TN, light regime, turbidity, and WRT [6,44,45]. However, TP and NAT are essential for algal development (Figures 2 and 3). NAT can enormously reduce the light penetration in the highland waterbodies, providing light limited conditions for algal growth. Several studies have reported that NAT can also lessen the algal biomass [46,47]. Our results suggest that light is also a limiting factor for algal development in HLR. In comparison, the primary productivity of the VLLR and MLR is more limited by the availability of TP than TN and NAT, indicating a robust P-limitation. However, additional research is required to elucidate the mechanisms between NAT and CHL-a in Korean reservoirs.

The TN:TP ratios are widely used indicators to determine nutrient limitations status of algae in aquatic habitats (Figure 4). It is widely accepted that a higher TN:TP ratio suggests a greater likelihood of P-limitation [22,48]. The present study showed a significantly decreasing CHL-a concentration trend with increasing TN:TP ratios that indicated strong P-limitation. To put it another way, the TN:TP ratios drop as CHL-a levels rise. In addition, a decreasing TN:TP ratio trend with increasing CHL-a level has been seen on a global scale. Yan et al. [49] observed a similar negative connection between the TN:TP ratio and CHL-a utilizing worldwide data from 157 publications. Abell et al. [7] concluded that TN:TP ratios were lower in lakes with a higher trophic status across a more comprehensive latitudinal range.

4.3. Light Availability with Nutrients, Solids, and Algal Chlorophyll

SD and NAT values for water clarity can significantly affect the underwater light availability in lentic environments [11,41]. In addition, light is required for algal growth to be viable [11]. Therefore, light availability significantly affects water column depth, nutrients (TP, TN), suspended solids (TSS), and algal growth [6,11].

Reservoir water transparency is affected by nutrients, phytoplankton, and turbidity associated with TSS (Table 2). SD is a simple and reliable method to determine reservoir water clarity. The reservoirs in the highland and midland are relatively transparent than those in the lowland and very lowland regions. The present study found that SD is highly influenced by TSS than TP and CHL-a in all reservoirs, irrespective of their elevation. TSS is strongly associated with silt and clay particles, organic colloids, and phytoplankton. The present results have coincided with previous studies [10,47,50]. SD values less than 1 m indicate poor water quality problems caused by organic turbidity and suspended particles in reservoirs [5]. The current study demonstrated a similar low water clarity in a few reservoirs based on the minimum SD value. NAT showed a significant positive relationship with TP and TSS in the HLR, MLR, and LLR (Figure 5). By contrast, it exhibited an insignificant and negative relationship in VLLR. The positive relationship between NAT with TP and TSS in Kansas and Missouri reservoirs support our findings [9,46]. However, the empirical connections of SD and NAT with TP, TSS, and CHL-a should be investigated further to ascertain other aspects of light availability in different elevation reservoirs.

4.4. Trophic Status Evaluation of Reservoirs with Its Deviation

The TSI of studied reservoirs based on TP, TN, CHL-a, and SD showed heterogenic responses of the varying altitude levels. All the reservoirs were categorized, from mesotrophic to eutrophic nutrient enrichment status, during this study (supplementary file; Table S1; Nürnberg, 1996 [51]). The VLLR displayed a eutrophic state, while HLR, MLR, and LLR showed a mesotrophic state based on mean TP and CHL-a concentrations. The higher TP concentrations supported a relatively higher concentration of algal biomass in VLLR. Thus, both point and non-point sources may contribute significantly to the anthropogenic nutrient loadings in the Korean and Asian lowland reservoirs [6,52,53]. The primary sources of nutrient loading are associated with agricultural fertilizer, animal manure, municipal sewage, and industrial effluents [10]. It is well known that a higher nutrient loading rate is linked with intensive agriculture farming, industrialization, and urbanized land-use (VLLR) than watersheds supporting the natural ecosystem (HLR) [6,54]. These differences in land-use indicate that the nutrient enrichment level of the reservoirs decreased with increasing elevation [6]. Notably, we found that all the reservoirs were in a mesotrophic state based on mean TN level. According to the proposed mean SD threshold values, LLR and VLLR exhibited eutrophic status, while HLR and MLR were mesotrophic.

Evaluating a water source's capacity and monitoring cyanobacterial blooms or BGA is critical to practical water resource management [55]. WT, TP, CHL-a, and SD all play a crucial role in influencing the cyanobacterial growth in aquatic systems [41,56]. The concentrations of TP and CHL-a in VLLR implied a moderate risk of cyanobacterial exposure (supplementary file; Table S2; WHO, 2015). In contrast, they indicate a low risk of exposure in HLR, MLR, and LLR. SD suggested a moderate risk of cyanobacterial presence in the VLLR and LLR, while it showed a lower risk in the HLR and MLR. These findings align with the assumptions that very lowland reservoirs are relatively vulnerable to cyanobacterial growth compared to highland reservoirs because of high nutrients [6,10].

The TSI and TSID analyses provided valuable information on the patterns of algal CHL-a development and the variability of nutrients and other significant factors in the aquatic ecosystems (Figures 6 and 7). TSI (TP) indicated the mesotrophic conditions in HLR, MLR, and LLR, while it showed eutrophic status in the VLLR. TSI (CHL-a) also revealed that all the reservoirs were in the eutrophic state. However, the HLR and MLR were in a mesotrophic state according to the TSI (SD), whereas LLR and VLLR were in eutrophic conditions.

The TSID showed that BGA were prevalent in all the reservoirs according to the relationships of TSI (CHL-a) with TSI (SD) and TSI (TP). It also indicated that BGA blooms are associated with reservoir eutrophication. The lower levels of NAT, zooplankton grazing, and P-limited small particles were observed in a few reservoirs. Furthermore, the TSID data showed that TSI (CHL-a) was significantly higher than TSI (TP) in all reservoirs, indicating algal productivity higher than expected and emphasizing the regulatory role of phosphorus [45,57]. Besides, Carlson's TSI (CHL-a) was consistently greater than 50, suggesting that all reservoirs were in the eutrophic state. The consistent eutrophic condition can lead to lower oxygen levels and disrupts sustainable ecological functioning [4,58]. If reservoirs remain eutrophic for an extended period, they may be dominated by macrophyte beds, resulting in the eventual loss of the reservoir [45]. These outcomes are consistent with earlier findings in Korean reservoirs [8–10].

5. Conclusions

In conclusion, this study supported the hypothesis that reservoir limnology varies with altitude and provides comparable insights into the physicochemical water quality characteristics of reservoirs. The average nutrients, algal CHL-a, TSS, organic matter (COD, TOC), WT and EC were consistently higher in the VLLR than other elevation reservoirs. This richly supported the assumption that VLLR has relatively higher nutrient, organic matter and ionic content import rates due to the watersheds' sedimentary or alluvial nature. The TP and CHL-a level in VLLR were relatively higher than the established eutrophic status limits and suggested a moderate risk of cyanobacterial exposure. The empirical relationship between nutrients and CHL-a indicated that TP was the most critical nutrient regulating algal growth. At the same time, TP and NAT are both essential for algal CHL-a in HLR. The TN:TP ratios revealed that TP was mainly responsible for the eutrophication in the studied reservoirs. TSI (CHL-a) was constantly greater than 50 in the HLR to VLLR, signifying that all reservoirs are in the eutrophic state. TSID suggested that BGA were predominant in all the reservoirs, and TP regulated the algal CHL-a. The results indicate that the external phosphorus loading may contribute to the rapid eutrophication events and increased primary productivity in all reservoirs, especially in VLLR. Therefore, it is essential to minimize the imminent nutrient enrichment in Korean reservoirs. The following steps can be taken: reducing industrial and domestic effluent disposal, minimizing fertilizer use, using low-impact and organic fertilizers, and controlling the inflow of livestock wastewater through the reservoir's catchment. Furthermore, it is essential to enforce stricter water quality regulations for reservoirs.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/w13243640/s1, Figure S1: Empirical relations among nutrients (TP: total phosphorus, TN: total nitrogen) with chlorophyll-a (CHL-a), Table S1: Trophic state criteria based on TP, TN, CHL-a, and SD from Nurnberg (1996) for high land (HLR), midland (MLR), lowland (LLR), and very low land (VLLR) reservoirs. (TN: total nitrogen, TP: total phosphorus, CHL-a: chlorophyll-a, SD: Secchi depth, O: oligotrophic, M: mesotrophic, E: eutrophic and H: Hypereutrophic), Table S2: Thresholds of risk associated with potential growth of cyanobacteria in high land (HLR), midland (MLR), lowland (LLR), and very low land (VLLR) reservoirs (adopted from WHO, 2015, LRG: lower risk of growth, MRG: moderate risk of growth and HRG: higher risk of growth, TP: total phosphorus, CHL-a: chlorophyll-a, SD: Secchi depth).

Author Contributions: Conceptualization, M.M. and K.-G.A.; methodology, M.M.; software, M.M.; validation, M.M. and U.A., formal analysis, M.M.; investigation, M.M.; resources, M.M. and U.A.; data curation, M.M.; writing—original draft preparation, M.M. and U.A.; writing—review and editing, M.M. and U.A.; visualization, M.M.; supervision, K.-G.A.; project administration, K.-G.A.; funding acquisition, K.-G.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by 'Korea Environment Industry & Technology Institute (KEITI)' through "Exotic Invasive Fish Species Management Project", funded by the Ministry of Environment, Korea (2018002270003, RE201807019).

Data Availability Statement: The data may be available upon request to the corresponding author, subject to the approval.

Acknowledgments: The authors are grateful to Korea Environment Industry & Technology Institute (KEITI) and also the Daejeon Green Environment Center under the Research Development Program (Yr 2018), so the authors would like to acknowledge for the assistance.

Conflicts of Interest: The authors declare no conflict of interest.

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