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Estimation of eutrophication in Paldang Reservoir using trophic state index deviation

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Abstract: Carlson's trophic state index (*TSI*) evaluates trophic status using transparency (expressed as Sechhi depth – *SD*), chlorophyll-a (Chl), and total phosphorus (TP), while the trophic state index deviation (*TSID*) plot graphically integrates their variations. This study applied *TSI* and *TSID* to assess eutrophication dynamics in South Korea's Paldang Reservoir using monthly data (2018–2022) from five sites influenced by the South Han River, the North Han River, and Gyeongan Stream. Values of *TSI* indicated mesotrophic to eutrophic conditions, with the shallow, Gyeongan Stream-affected site (P5) showing persistent eutrophy (*TSI*(Chl) = 54–67). Spatial patterns reflected tributary influence: P4 and P5 exhibited *TSI*(Chl) ≈ *TSI*(*SD*) > *TSI*(TP), suggesting algal-driven light attenuation under phosphorus limitation, while the South Han River sites (P1, P3) often had *TSI*(*SD*) > *TSI*(Chl) due to particulate inflows after rainfall. Plots of *TSID* confirmed phosphorus-limited conditions (TN:TP > 17) but revealed strong seasonal variability in Chl and *SD*. Summer monsoons increased TP and reduced N:P ratios, with riverine sites showing biomass suppression and lacustrine sites remaining stable. Prolonged rainfall in 2021 caused exceptional biomass fluctuations at riverine sites, including temporary oligotrophy at P1. Compared to TP alone, the TSID approach more effectively captured hydrological-biological interpretations, suggesting that controlling phosphorus load alone may not be sufficient to mitigate eutrophication. Although high-flow events temporarily reduced cyanobacterial abundance, winter cyanobacterial presence has risen, suggesting climate-driven shifts in bloom dynamics. Continuous, site-specific *TSID* monitoring can enhance understanding of eutrophication processes and support adaptive management of large multipurpose reservoirs under changing hydrological regimes.

Keywords: eutrophication, trophic state index (*TSI*), trophic state index deviation (*TSID*) plot, Paldang Reservoir, water source management

INTRODUCTION

The increase in greenhouse gas emissions caused by industrialisation has become a major driver of global warming, leading to abnormal temperatures and extreme weather events worldwide. According to the IPCC Sixth Assessment Report (IPCC, 2022), river and lake surface temperatures have been rising at a rate of 0.01 to 0.45°C per decade, contributing significantly to eutrophication – the enrichment of water bodies with nutrients, particularly nitrogen (N) and phosphorus (P). When nutrient loading exceeds the self-purification capacity of water, large-scale cyanobacterial (blue-green algae) blooms occur, raising the cost and complexity of managing freshwater resources sustainably (Cho *et al.*, 2023).

Numerous studies have emphasised that reducing phosphorus discharge is a key strategy in controlling eutrophication (Schindler *et al.* 2016; Nazari-Sharabian *et al.*, 2018; Capua *et al.* 2022). In response, the South Korean government implemented the Total Maximum Daily Load (TMDL) system in 2004 to manage total phosphorus (TP) and biological oxygen demand (BOD) by regulating watershed pollutant loads. Despite these measures, algal bloom alerts were issued in the Paldang Dam and the North Han River in 2012 and 2015, and in 2023, a cyanobacterial bloom was observed for the first time in the upstream Soyanggang Dam area, signalling that even upstream reservoirs may be vulnerable to eutrophication under climate change.

Carlson (1977) introduced the trophic state index (*TSI*) using total phosphorus, chlorophyll-a, and Secchi depth (*SD*) as a measure of eutrophication. These three *TSI* indices incorporate causal factors essential for evaluating eutrophic state of water system. Consequently, they serve as valuable metrics not only for analysing eutrophication of various water systems, but also for elucidating temporal and spatial patterns of changes and informing corresponding management strategies (Nędzarek and Budzyński, 2024). However, as demonstrated in the study by Kaphle *et al.* (2025), which analysed the water quality of Syarpu Lake, relying solely on simple index comparisons has limitations in understanding temporal differences across seasons.

The trophic sate index deviation (*TSID*) plot visually illustrates the relationship between transparency and nutrient pollution (total phosphorus), which impacts biomass in water bodies (Havens, 2000). The *TSID* aids in tracing changes in the limiting factor spatially from upstream to downstream and sequentially from one season to another. For instance, Carlson and Havens (2005) employed *TSID* plots to elucidate nutrient pollution and chlorophyll increase upstream of Rochwell Reservoir in Ohio, and Saluja and Garg (2017) used it to describe the rise in particulate matter and chlorophyll in Bhindawas Wetland in India. There are some studies utilising *TSID* plots to analyse spatio-temporal changes of water quality for long period of time (Mamun, Kim and An 2020; Li *et al.*, 2021), however, few studies have examined in depth the linkage between changes in these indices and variations in rainfall. Previous study by Kim and Kim (2021) have also applied *TSID* to evaluate seasonal and monsoon-driven variations in reservoir water quality. While those studies analysed hydrological responses across multiple reservoirs, this study focuses specifically on the Paldang Reservoir system and its surrounding tributaries to examine spatial and temporal eutrophication dynamics in greater detail.

This study utilised water quality data from the past five years (2018–2022) extracted from the Water Environmental Information system. Eutrophication indices and changes in the N:P ratio were computed, and variations in water bodies were visualised through a *TSID* plot. This study also plotted modified indices which are developed to better reflect Korean environmental condition and compared their robustness in explaining water quality changes in relation to environmental events. This analysis facilitates continuous monitoring of water bodies to furnish insights into eutrophic status across zones and seasons, serving as a foundation for ecologically and economically reliable management strategies.

MATERIALS AND METHODS

RESEARCH AREA

Paldang Dam, situated at the confluence of the South Han River, the North Han River, and Gyeongan Stream (37°31'35.0"N, 127°16'44.6"E), marks the boundary between eastern Seoul and central Gyeonggi Province, South Korea. The dam serves multiple functions, including hydroelectric power generation, flood regulation, and regional water resource management. Five monitoring sites (P1–P5) were selected within Paldang Reservoir as part of the National Water Quality Monitoring Network (NWQMN), which enables real-time assessment of water quality in major aquatic systems.

Each of the five selected study sites exhibits distinct hydrological characteristics determined by their respective location. Two sites (P1 and P3) were located at the confluence of the inflowing tributaries of the South Han River at an average depth of 8.8 m. One site (P4) represents the most downstream point of the North Han River Basin, with an average depth of 9.2 mwhile P5, with an average depth of 3.0 m, is located on the Gyeongan Stream and influenced by the Gyeongan Stream. The site P2, located at the confluence of the South Han, North Han, and Gyeongan stream basins with an average depth of 22.5 m, is considered a representative location for water quality in the Paldang Reservoir. The five research points are shown in Figure 1.

Fig. 1. Geographical location of Paldang Reservoir (PDR) and the five water quality monitoring sites (P1–P5): a) the location of the reservoir within the Korean Peninsula, b) the confluence of the South Han River, the North Han River, and Gyeongan Stream, c) details of hydrological features and the spatial distribution of the monitoring stations; source: own elaboration

DATA SOURCE

The water quality data used in this analysis were obtained from the Water Environment Information System operated by the Ministry of Environment of Korea (NIER, 2022), covering monthly measurements from 2018 to 2022. Each parameter was processed based on monthly average values, and seasonal classifications were defined as spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). Seasonal values were calculated by averaging the data from each corresponding month across the five-year period. However, in winter, some missing values occurred due to ice cover, and these months were excluded from the seasonal averages. Detailed location information for the five study sites and the site codes for accessing the database are presented in Table S1.

Water quality data were compared with rainfall data obtained from the meteorological database. The rainfall dataset for the monitoring basin was retrieved from the Yangpyeong Weather Station, maintained by the Korean Meteorological Administration (KMA, 2022), spanning January 2018 through December 2022.

TROPHIC STATE INDEX AND TROPHIC STATE INDEX DEVIATION'S PLOT

The *TSI* was calculated using monthly measurement data from January 2018 to December 2022. Method of the Carlson's *TSI* analysis was applied using three variables: transparency measured by the Secchi depth (*SD*) for physical water quality, chlorophyll *a* (Chl) for biological water quality, and total phosphorus (TP) concentration for chemical water quality. The formulae used for *TSI* calculation are as follows (Carlson, 1977):

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

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

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

where: TP = phosphorus level ($\mathrm{mg \cdot m^{-3}}$), Chl = concentrations of chlorophyll *a* ($\mathrm{mg \cdot m^{-3}}$), and *SD* = Secchi disc visibility, or Secchi depth (m).

The Korean trophic state index (TSI_{KO}) was calculated using the following equations (NIER, 2006; Kim and Kong, 2019).

$$TSI_{\mathrm{KO}}(\mathrm{TOC}) = 17.9 + 64.4 \cdot \log(\mathrm{TOC}) \tag{4}$$

$$TSI_{\mathrm{KO}}(\mathrm{Chl}) = 12.2 + 38.6 \cdot \log(\mathrm{Chl}) \tag{5}$$

$$TSI_{\mathrm{KO}}(\mathrm{TP}) = 114.6 + 43.3 \cdot \log(\mathrm{TP}) \tag{6}$$

where: TOC = total organic carbon compounds ($\mathrm{mg \cdot dm^{-3}}$).

The TSI_{KO} was developed to reflect the unique characteristics of lentic ecosystems in South Korea, which are typically subject to short water residence times and are heavily influenced by allochthonous organic matter. Unlike traditional trophic state indices, TSI_{KO} excludes *SD* and instead incorporates chemical oxygen demand (COD) as an indicator parameter (NIER, 2012); however, the *TSI*(COD) parameter has since been replaced with *TSI*(TOC), as TOC has been introduced as a standard parameter.

The eutrophication status of the water bodies was divided into four categories according to *TSI* values (Tab. S2). The variations between the three *TSI* values are summarised in Table S3, providing insights into the biological changes affecting the physiochemical variations in the watershed. Deviations in *TSI*(Chl)–*TSI*(TP) were plotted against *TSI*(Chl)–*TSI*(*SD*) to understand the changes in biological and physiochemical factors in these areas. Interpretation of the data points on the plot was based on the suggestion of Carlson and Havens (2005) and is described in Figure 2.

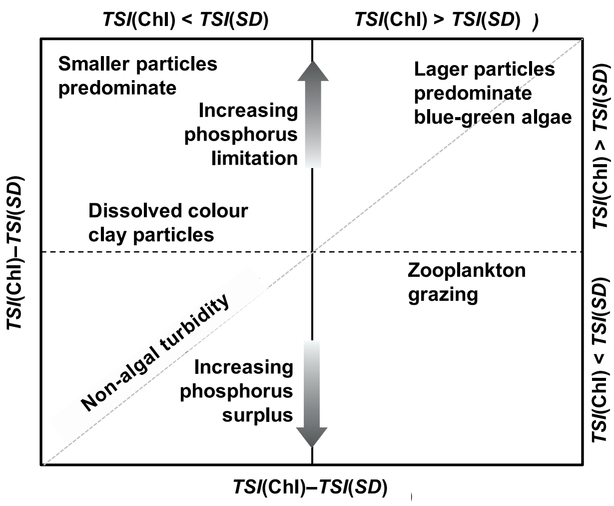

Fig. 2. Interpretation of deviations of trophic state index (*TSI*) values; source: Carlson and Havens (2005), modified

RESULTS AND DISCUSSION

EUTROPHIC STATUS OF PALDANG RESERVOIR BASED ON TROPHIC STATE INDEX

The monthly average of *TSI* values over the past five years of the five research sites around Paldang Reservoir are summarised in Table S2.

The *TSI*(*SD*) ranged from 43 to 60, from 45 to 59 at P1 and P3, respectively, influenced by the South Han River, and from 43 to 55 at P4, influenced by the North Han River. At confluence point P2, where the North Han River, the South Han River, and Gyeongan Stream merge, it ranged from 46 to 58, indicating a mesotrophic to eutrophic state. However, at P5, influenced by the Gyeongan Stream, it showed a range of 54–67, indicating a monthly eutrophic state. The deviation in *TSI*(*SD*) across the surveyed points showed that P1, which was most influenced by the South Han River, had a larger deviation than P4, which was influenced by the North Han River. This suggests that the South Han River might have influenced transparency owing to external inputs and algal blooms.

The *TSI*(Chl) indicated a eutrophic state throughout the year at P2, which was located in front of the dam, and at P5, where the water depth was the lowest. The months with the highest values were September and August at P5 and P4, April at P2, and February and March at P3 and P1, indicating different periods of high biological eutrophication according to locations.

The *TSI*(TP) showed a mesotrophic state at all locations, mainly increasing during summer, along with an increase in *TSI*(*SD*). At the shallow P5 point, the deviation was 1.1, indicating no significant change in the eutrophication index of the TP throughout the year. However, at deeper points influenced by the North Han River, the South Han River, and in front of the dam, the *TSI*(TP) increased in July and August. Due to its strong flow dependence, TP is presumed to increase during the summer monsoon as external material inflow rises, and further elevated after the monsoon due to nutrient release from the sediment (Park *et al*., 2011; Kim *et al*., 2016; Jargal *et al*., 2023).

The N:P ratio showed seasonal variations, being low in summer and high in winter (Fig. 3). Such changes in the N:P ratio

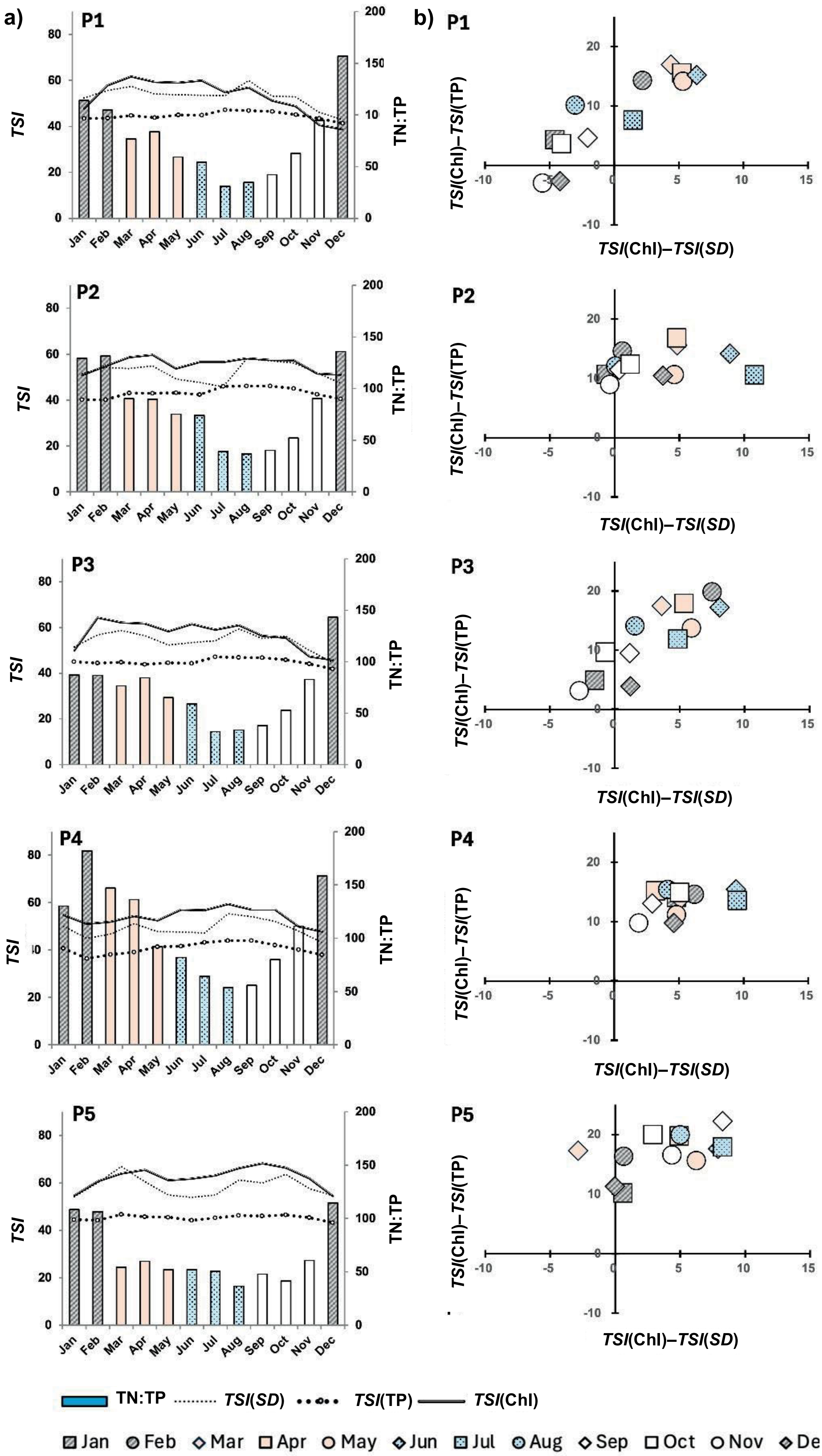

Fig. 3. Temporal and seasonal variations in trophic state indices (*TSI*) and total nitrogen and total phosphorus ratio (TN:TP) across five research sites over five years (a) and monthly variation of trophic state indices (b); Chl = chlorophyll *a*, *SD* = Secchi depth; source: own study

are considered to be an increase in the absorption of nitrogen by phytoplankton which align with rising summer temperatures (Lee *et al*., 2010).

The spatial and temporal eutrophication indices for Paldang Reservoir were mostly *TSI*(Chl) > *TSI*(*SD*). According to index interpretation in Table S3, this indicates a stage where blue-green algae with high chlorophyll content dominates and cannot be controlled through the food chain of the ecosystem. However, in this case, *TSI*(Chl) = *TSI*(TP) >> *TSI*(SD), which is different from Paldang Reservoir. In Paldang's case, especially P4 and P5, *TSI*(Chl) was 43–67, *TSI*(*SD*) was 39–68, and *TSI*(TP) was 36–47, showing small difference between *TSI*(Chl) and *TSI*(*SD*). Therefore, P4 and P5 can be judged as *TSI* (Chl) = *TSI*(*SD*) ≥ *TSI*(TP), and this water system can be interpreted as a water system where dominance of algae attenuate light penetration, while algal biomass is limited by P (Tab. S3).

Unlike P4 and P5, at P1 and P3, influenced by the South Han River, and P2 at the front of the dam, *TSI*(*SD*) was higher than *TSI*(Chl), which might be due to the influx of fine particulate matter, which was increased by rainfall.

In conclusion, the Paldang Reservoir has *TSI* relationships of *TSI*(Chl) = *TSI*(*SD*) ≥ *TSI*(TP), where P acts as a limiting factor in algal growth in some areas (P4 and P5).In contrast, in some areas (P1 and P3), *TSI*(*SD*) becomes greater than *TSI*(Chl) and *TSI*(TP) (i.e., *TSI*(*SD*) > *TSI*(Chl) ≥ *TSI*(TP)) when heavy rainfall causes an increase in particulate matters (Tab. S3). These characteristics were notably observed at P4 and P5, and P1 and P3, respectively, showing significant influence from tributaries at each location.

SPATIOTEMPORAL VARIATION OF EUTROPHICATION IN PALDANG RESERVOIR OBSERVED THROUGH TROPHIC STATE INDEX DEVIATIONS

Although *TSI* remains a practical index for trophic evaluation, its interpretation under changing climatic and anthropogenic pressures has limitations (Zhang *et al*., 2023). The *TSID* plot provides an integrated representation of trophic conditions by combining nutrient concentrations (TP), phytoplankton biomass (Chl), and water transparency (*SD*) into a two-dimensional coordinate system. This approach enables a more comprehensive understanding of ecological responses and environmental drivers in aquatic ecosystems. In this study, *TSID* was applied to five years of monthly mean *TSI* data to investigate the spatiotemporal dynamics of eutrophication in the Paldang Reservoir, based on the interpretive framework proposed by Carlson and Havens (2005).

Across all monitoring sites, the total nitrogen to total phosphorus (TN:TP) ratio exceeded 17, indicating phosphorus-limited conditions throughout the Han River watershed. While *TSI*(TP) values remained relatively consistent among sites – suggesting a limited role for phosphorus in differentiating trophic status – substantial seasonal variability was observed in *TSI*(Chl) and *TSI*(*SD*). Another previous study has demonstrated that TP serves as a more reliable predictor of water quality variations than TN (Mamun *et al*., 2021). Mamun, Kim and An (2020) also observed the same phenomenon through an analysis of Paldang Reservoir water quality data from 1996 to 2019, concluded that the reservoir is P-limited area, and algal growth was better explained by TP than by TN. Notably, the summer monsoon (July–August) led to increased phosphorus loading and a corresponding decrease in the TN:TP ratio, resulting in significant seasonal shifts in *TSID*. These patterns were particularly pronounced at site P2, located near the dam.

At the site P1, data from *TSID* exhibited a broad elliptical distribution, indicative of large seasonal and event-driven fluctuations in phytoplankton biomass, likely influenced by precipitation and inflow-derived particulate matter. During January–February, *TSI*(*SD*) and *TSI*(Chl) were nearly equivalent, suggesting increased biomass driven by non-cyanobacterial phytoplankton. From March to June, *TSID* coordinates shifted toward the upper left quadrant, reflecting biomass-driven eutrophication.

In July, despite rising TP concentrations, a decline in phytoplankton biomass – likely driven by rainfall-induced flushing and dilution – resulted in a shift of *TSID* points toward the origin and eventually to the lower left quadrant. Throughout this period, *TSI* values consistently indicated mesotrophic conditions, underscoring the utility of *TSID* in capturing rainfall-driven ecological responses.

Similar seasonal behaviour is observed at P1and P3, though distinct ecological signatures are noted. A sharp decline in the N:P ratio during January–February was accompanied by a *TSID* shift from the upper left to right quadrant. Values of *TSI*(Chl) exceeded *TSI*(*SD*), suggesting an increase in cyanobacterial biomass. Eutrophication was evident during early spring, followed by a decline in algal activity after July, likely due to increased turbidity and reduced light availability following heavy rainfall.

Among all sites, P4 exhibited the most stable trophic behaviour, with *TSID* points forming a compact circular distribution – indicative of consistent lentic (lake-like) characteristics. A brief increase in transparency during June–July corresponded with a temporary shift in cyanobacterial dominance. Overall, P4 maintained eutrophic conditions throughout the year, with minimal seasonal variability. These findings are consistent with Kim *et al.* (2016), who reported persistent cyanobacterial growth potential in Paldang Reservoir sediments.

The shallowest site and most directly influenced by Gyeongan Stream inflows (P5), exhibited a low N:P ratio in March and a clear cyanobacterial dominance in *TSID* plots from April through September. Anomalies in August, including a temporary rise in *TSI*(TP) and *TSI*(*SD*), were attributed to precipitation; however, compared to other sites, the impact of rainfall appeared minimal. From October to March, cyanobacterial dominance declined, and trophic conditions shifted toward mesotrophy.

Site P2, located near the dam and representing the central lentic region of the reservoir, displayed clear signs of eutrophication during the summer. Between May and July, *TSI*(Chl) values ranged from 54 to 57 (eutrophic), while *TSI*(*SD*) remained in the 46–49 range (mesotrophic). Values of *TSID* successfully integrated these parameters, confirming eutrophic conditions more definitively than *TSI* values alone.

Interestingly, *TSID* patterns at P2 during summer and winter aligned closely with those observed at P4, indicating influence from the North Han River. Conversely, during March–May, *TSID* behaviour at P2 resembled that of the South Han River sites (P1 and P3), suggesting that P2 is subject to seasonal hydrological and biological inputs from both tributaries. Monsoonal rainfall in July and August further suppressed biomass, shifting *TSID* coordinates toward the origin.

Distributions of *TSID* for the South Han River sites (P1 and P3) were dispersed across the first, second, and third quadrants, reflecting variable flow conditions and the influence of artificial reservoirs. These conditions promoted discontinuous hydrology and heterogeneous trophic responses. In contrast, P4 (the North Han River) *TSID* coordinates were concentrated in the first quadrant, highlighting stable lentic and consistently eutrophic conditions.

Site P2 demonstrated transitional characteristics, reflecting the complex interactions between the three major inflows: the South Han River, the North Han River, and Gyeongan Stream. In June, all sites converged toward similar trophic conditions; however, from July onward, the *TSID* plots revealed distinct site-specific divergences, corresponding to intensified monsoonal influence.

SEASONAL VARIATION OF EUTROPHICATION BASED ON TROPHIC STATE INDEX DEVIATION AND AMOUNT OF RAINFALL IN PALDANG RESERVOIR

Rainfall events result in an increase in phosphorus (P) due to the inflow of turbid water carrying particulate matter, leading to a decrease in water transparency. Saturday *et al.* (2023) demonstrated that deviations among *TSI*(Chl-a), *TSI*(*SD*), and *TSI*(TP) effectively reveal non-algal turbidity effects associated with fine suspended sediments. In a study of water reservoirs in Taiwan by Lin *et al.* (2022), small particulates were found to be responsible for non-algal turbidity after heavy rainfall; however, they showed no correlation with other *TSI*, and the primary factor influencing algal growth was TP. In contrast, the shifts of points on the *TSID* plot in this study demonstrate that not only rainfall but also water movement influenced by the location relative to the dam divides the aquatic environment, which can be easily identified using the *TSID* plot. Predictions indicated that rainfall could potentially shift points on the *TSID* plot away from the centre (0, 0) towards the upper left to lower left quadrant. Seasonal variations in *TSI* indices and the N:P ratio, along with corresponding changes on *TSID* plot, were examined from 2018 to 2022 in conjunction with the seasonal average rainfall (Figs. S1, S2). Deviation plots for sites influenced by the South Han River exhibited characteristics of a riverine system, whereas those influenced by the North Han River and Gyeongan Stream displayed characteristics closer to lacustrine systems (Fig. 4). The differentiation between riverine and lacustrine characteristics depends on their sensitivity to rainfall. Sites exhibiting riverine characteristics, such as P1 and P3, showed distinct shifts from upper right to left after rainfall, indicating a temporary decrease in algal biomass. The P1 point, influenced by external phosphorus (P) influx after rainfall, shifted from upper right to lower left in 2019 and 2021. Notably, in 2021, P1 showed a $TSI(\text{Chl}) < 30$, indicating a state of oligotrophy for the first time, with both points P1 and P3 located in lower left, indicating temporary absence of algal influences due to rainfall (Figs. S1, S2). In contrast, sites exhibiting lacustrine characteristics, such as P2, P4, and P5, showed relatively minor changes in algal biomass after rainfall, with no significant shifts of data points on the plot. However, after occasional heavy rainfall during the summer monsoon, these points moved slightly closer to the origin (0, 0) – Figure S2.

South Korea experiences frequent short-duration rainfall and floods, resulting in a pattern where the *TSID* for most points shifts align the middle after rainfall, which temporarily inhibits the increase in algal biomass during the summer. However, in cases of prolonged rainfall, such as in 2021, from spring to autumn, the response differed from that of short-duration rainfall. In this case of prolonged rainfall, the algal biomass in less rainfall-sensitive areas, such as the North Han River and Gyeongan Stream, did not show significant changes. In more rainfall-sensitive areas such as the South Han River, there was a temporary large variation in algal biomass, with data points initially positioned at lower left quadrant undergoing significant shifts to upper right after the rainy season. Moon *et al.* (2021) incorporated hydrochemical assessment data and precipitation records with 20 years of *TSI* data from the Okjeong Reservoir and found that monsoon intensity alone does not control the water quality dynamics of the study site. That study concluded that monsoon intensity was not a primary driver of water quality changes, attributing the weak correlation to the reservoir's low drainage ratio, which is different from the study sites in the Paldang Reservoir in this study. A more comprehensive dataset and long-term tracking of indices in the Paldang Reservoir will provide deeper insight into changes of water quality, enabling the development of effective water quality management strategies. In summary, points with lacustrine characteristics showed minor changes in algal biomass after prolonged rainfall, whereas points with riverine characteristics experienced unexpected significant biomass fluctuations. Therefore, continuous monitoring is necessary due to the unpredictable changes in algal biomass in riverine areas after prolonged rainfall.

ROBUST INTERPRETATION OF EUTROPHIC STATUS AND PERSPECTIVE APPLICATION TO WATER QUALITY MANAGEMENT

The *TSID* plot, introduced by Carlson and Havens (2005), aims to visualise spatial relationships among individual data points calculated from three *TSIs* related to algal biomass estimation: Chl, *SD*, and TP. Carlson and Havens (2005) emphasised that this graphical tool illustrates the simultaneous deviation of all three variables in a plot. This method facilitates an easy interpretation of the water system without requiring specialised statistical knowledge, enabling additional insights into lake dynamics.

Additional indices can be employed in the *TSID* plots. For example, TSI_{KO}, developed in South Korea, utilises total organic compounds (TOC) instead of transparency (Kim and Kong, 2019). When applied to the dataset in this study, the distribution of data points exhibited an overly right-shifted pattern, leading to an interpretation of the eutrophic status that did not align with actual changes in the water system (Fig. 5b). This rightward shift resulted in an underestimation of changes caused by an increase in blue-green algal cells. This underscores that *TSID* using Carlson's three indices offers a more robust interpretation of the eutrophic status, as the transparency index (*SD*) reflects changes caused by both inorganic particulate matter and organic matter.

The Ministry of the Environment manages the total phosphorus (P) load to ensure a stable water quality in the Four Major Rivers: the Han, Nakdong, Geum, and Yeongsan Rivers,

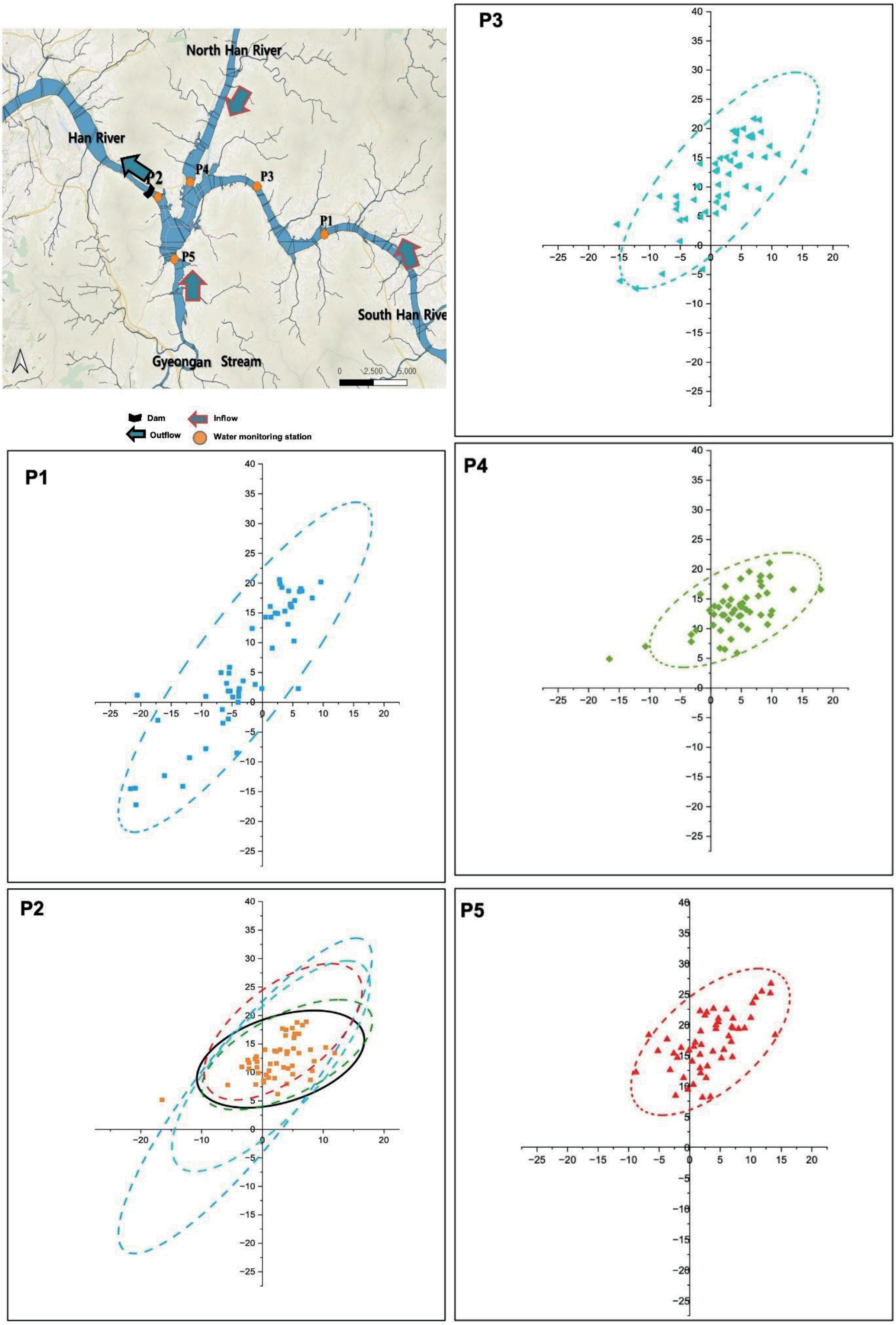

Fig. 4. Distribution of trophic state index deviation (*TSID*) at five study sites (P1–P5); the *TSID* distribution at each point is represented by different coloured outlines according to the river branches; source: own study

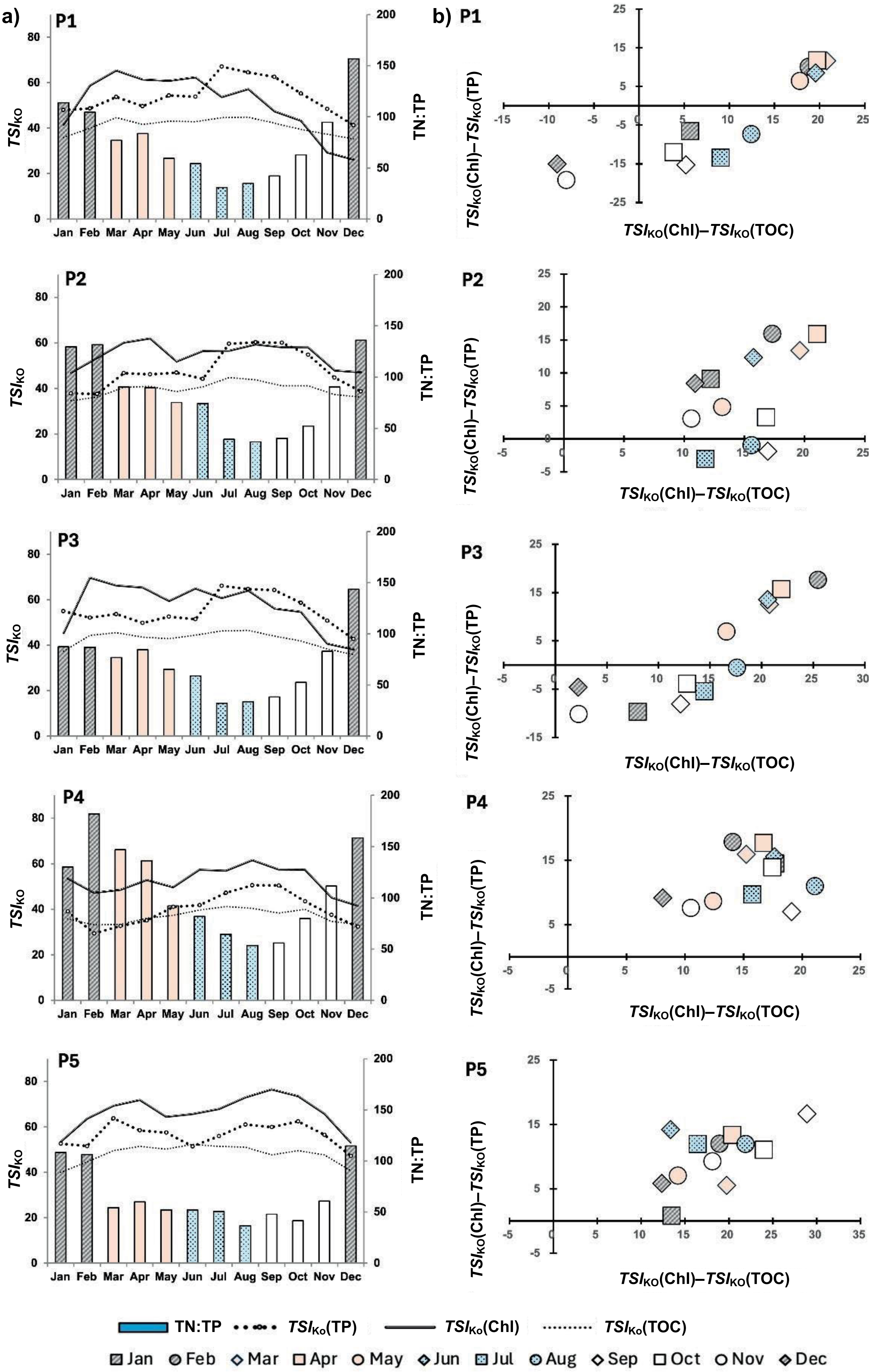

Fig. 5. The Korean trophic state index (TSI_{KO}) (a) and Korean trophic state index deviation ($TSID_{KO}$) plots (b) for the five study sites (P1–P5), based on the TSI_{KO} indices (refer to the materials and methods) are represented for each location; source: own study

which are the focus of Korea's national river restoration project. However, as observed in the *TSID* plots, the Paldang Reservoir is situated in a eutrophic zone (upper right quadrant), indicating the limitations in managing eutrophication solely through TP control. Carlson and Havens (2005) explained that water bodies with active zooplankton feeding were positioned at lower right quadrant in the plot. Unfortunately, this shift was not observed in the Paldang Reservoir, emphasising the need for ecological management and engineering strategies to improve water quality. A study of the water quality of Paldang Reservoir by Mamun, Kim and An (2020) also concluded that although a grazing effect by zooplankton exists, it is minimal. In their study, the reservoir was identified as a P-limited area, and TP was considered a reliable index for predicting algal biomass. This conclusion differs from that of the present study, which is based on tracking seasonal shifts of data points on the *TSID* plot according to their location within the reservoir, revealing different patterns in the trophic dynamics.

The eutrophication status and changes in the Paldang Reservoir were accurately assessed using the *TSID* plot. Although summer rainfall temporarily suppressed cyanobacterial occurrence, recent observations indicate an increase in cyanobacteria owing to eutrophication, even in winter. Continuous monitoring is essential for understanding biota changes resulting from climate change and altered rainfall patterns. As demonstrated by Hu *et al.* (2024), long-term monitoring reveals water quality trends that inform sustainable management and adaptive policy development. Consistent with this perspective, the present analysis contributes to continuous monitoring of eutrophic conditions across spatial and seasonal scales, supporting ecologically and economically viable management strategies.

CONCLUSIONS

Based on the analysis of the trophic state indices for the five years and *TSID* plots in Paldang Reservoir. This study confirms the reservoir's overall eutrophic condition driven by complex interactions among nutrient input, particulate matter, and hydrological factors. Phosphorus remains a key limiting nutrient in some areas, while in others, increased turbidity from rainfall-induced particulate inflows significantly affects water transparency and algal dynamics.

The *TSID* plot proved to be an effective and robust tool for capturing seasonal and spatial variations in eutrophication, distinguishing between riverine and lacustrine influences, and revealing responses to environmental events such as rainfall. Compared to alternative indices, the traditional *TSID* based on Carlson's indices provided a more accurate representation of the reservoir's trophic status.

Despite phosphorus management efforts, persistent eutrophication and minimal zooplankton grazing effects highlight the limitations of nutrient control alone. Therefore, integrated water quality management approaches that enhance ecosystem resilience and consider complex environmental interactions are essential for sustainable reservoir health. Continuous monitoring is critical to adapt to changing climate and hydrological conditions affecting algal dynamics.

CONTRIBUTION OF THE AUTHORS

Gueeda Kim: study design, data collection, statistical analysis, data interpretation, manuscript preparation, and literature search.
Seunghye Park: data interpretation and manuscript preparation.
EonSeon Jin: study design, data interpretation, and manuscript preparation.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at: https://www.jwld.pl/files/Supplementary_material_67_Kim.pdf.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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