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Climate-driven decline in water level causes earlier onset of hypoxia in a subtropical reservoir

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ABSTRACT

Hypoxia, especially in the bottom water, is occurring in deep and stratified reservoirs worldwide, threatening aquatic biodiversity, ecosystem functions and services. However, little is known about the timing of onset and ending of hypoxia, especially in subtropical reservoirs. Based on five-year (from April 2015 to January 2020) sampling of a subtropical monomictic deep reservoir (Tingxi Reservoir) in southeast China, we found the evidence of about 40 days earlier onset of hypolimnion hypoxia during low water level periods in dry years compared to wetter high water level years. We explored the effects of stratification and mixing conditions on hypoxia, cyanobacterial biomass, and nutrient dynamics; and revealed the physical and biochemical conditions that drove hypoxia. The results indicated that 1) The decline in water level increased the intensity of thermal stratification, resulting in 40 days earlier onset of hypolimnion hypoxia in dry years than in wet years; 2) The decline in water level expanded the extent of hypoxia by promoting nutrient accumulation and phytoplankton biomass growth; 3) Warmer climate and less precipitation (drought) significantly promoted the risk of hypoxic expansion and endogenous phosphorus release in subtropical reservoirs. We suggest that more attention needs to be paid to the early onset of hypoxia and its consequences on water quality in subtropical stratified reservoirs during low water level periods in a changing climate.

1. Introduction

Dissolved oxygen (DO) levels are declining in reservoirs and lakes worldwide with the increasing temperatures and climate extremes (Smucker et al., 2021; Jane et al., 2021). Hypoxia is defined as the DO concentrations less than 2 mg/L in waters, and typically occurs in the hypolimnion layer (Conley et al., 2007). Persistent oxygen depletion affects aquatic ecosystem functions and services, threatening biodiversity (Jenny et al., 2016; Hughes et al., 2020). For example, climate warming has significantly altered the stratification pattern and oxycline depth in Lake Qiandaohu, subtropical China, impacting DO levels and aquatic ecosystems (Zhang et al., 2015).

Subtropical reservoirs often exhibit different stratification and oxygen dynamics due to their geographical location and climate characteristics (Havens and Paerl, 2015). Thermal stratification may be longer and more stable in subtropical regions. Due to climate warming and water level fluctuations, deep hypoxia is increasing in subtropical reservoirs (Liu et al., 2019). In monomictic lakes or reservoirs, oxygen in the deep water is mainly replenished during the deep recirculation periods in winter, when during a long enough circulation period oxygen concentration is approaching equilibrium concentrations with the atmosphere (i.e. 100 % saturation, e.g. Boehrer et al. 2021). However, the prolonged stratification in summer and autumn can lead to the gradual depletion of oxygen in deep water and forming the seasonal hypoxia, especially in tropical and subtropical areas (North et al., 2014).

Stratification, characterized by a strong temperature gradient in deep reservoirs, is a crucial factor controlling DO dynamics (Boehrer and Schultze, 2008). Stratification dynamics affect DO and also control

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nutrient fluxes and biogeochemical cycling (North et al., 2014). Thermal stratification in reservoirs can be influenced by extreme events such as climate warming (Mullin et al., 2020), rainstorms (Huang et al., 2014), water management policies (Fletcher et al., 2019) and hydrological changes (Bhattacharjee et al., 2021). For example, hypolimnetic water withdrawal can discharge cooler and anoxic deep water, altering stratification and causing anoxic conditions in low-latitude reservoirs (Weber et al. 2017; Winton et al., 2019). Deepening the thermocline reallocates mineral resources and plankton communities, affecting primary production and ecosystem respiration (Giling et al., 2017; Donis et al., 2021).

Changes in water levels, driven by varying water input and output, are a primary hydrological factor influencing reservoir ecosystems (Bhattacharjee et al., 2021). Water level fluctuations determine the hydrological and biogeochemical processes in reservoirs by changing the water budget, such as the direct deposit of rainfall, the inflows and outflows, and nutrient cycles (Wang et al., 2019; Qin et al. 2020; Song et al., 2023). Seasonal and interannual water level variations significantly impact stratification, oxygenation patterns, and nutrient cycling in tropical reservoirs (Neto et al., 2022). Increased water levels can dilute cyanobacteria biomass and change aerobic respiration by modifying light conditions (Yang et al., 2016). Lower water levels typically result in a reduction in the overall thermal capacity of the water body, making it more susceptible to stable thermal stratification due to external temperature fluctuations (Li et al., 2016). During this period, the bottom waters are deprived of fresh oxygen supply which would contribute to the earlier onset of hypoxia in the hypolimnion during stratification (Mi et al., 2024).

It is necessary to improve our understanding of how changes in water level affect oxygen, nutrients, and phytoplankton by affecting the thermal stratification of subtropical deep reservoirs. In addition, the seasonal thermal stratification has a considerable influence on the phytoplankton biomass. Especially the DO increase in bottom waters could reduce the release of nutrients from sediments and lead to a rapid reduction in phytoplankton biomass in the reservoir when the stratification breaks down (Berger et al. 2006; Li et al., 2015).

Therefore, obtaining the vertical profile data of environmental variables is crucial for investigating the effects of thermal stratification on nutrient fluxes, oxygenation, and biogeochemical cycling in deep lakes or reservoirs, and contributes to enhancing our understanding of the consequences of thermal stratification in reservoir ecosystems (Becker et al., 2010; North et al., 2014; Donis et al., 2021). Recent research indicates that warming water temperatures lengthen deep-water hypoxia durations in both temperate reservoirs (Smucker et al., 2021) and temperate lakes (Stow et al., 2023). Despite this, subtropical reservoirs receive less attention compared to tropical reservoirs; from 1900 to 2024, only 1345 publications on the topic of "subtropical reservoir" were found on the Web of Science (Core Collection), versus 3878 for the topic of "tropical reservoir" (accessed on 11 September 2024). Additionally, only 113 publications related to DO (the topic of "subtropical reservoir" and "dissolved oxygen") in subtropical reservoirs were found, with 20 publications on the topic of "subtropical reservoir" and "dissolve oxygen" and "water level" (accessed on 11 September 2024). However, none of them reported the impact of low water levels on early hypoxia onset.

Here, we explored how water level and meteorological changes (especially temperature) affect hypolimnion hypoxia in a monomictic subtropical deep reservoir in China. The aims of this study were to: 1) reveal the annual and seasonal variation of thermal stratification and oxygen dynamics in the Tingxi Reservoir from 2015 to 2020; 2) explore the temperature-thermocline-environment relationships to explain the reason for the early onset of hypoxia during low water level periods; 3) assess the future water quality risk of Tingxi Reservoir under climate-driven hydrological change. We hypothesize that water level reduction will lead to earlier onset of hypolimnion hypoxia and increased cyanobacteria by intensifying thermal stratification in the subtropical reservoir.

2. Materials and methods

2.1. Sampling and the environmental variables

In this study, we conducted a five-year (2015–2020) field investigation (sampling time interval was every 10 days) at a station closed to the dam at Tingxi Reservoir (24°48′ N, 118°08′ E) in Xiamen City, southeast China (Fig. 1a). There were occasional delays (more than 10 days) due to typhoons affecting sampling dates. Tingxi Reservoir is a typical subtropical reservoir with annual mean temperature of 20.7 °C and precipitation of 1336 mm (Yang et al., 2012, 2016). The basin area of Tingxi Reservoir is about 100 km^2 and the total storage is 0.485×10^8 m^3 (Yang et al., 2012).

The depth profiles of water temperature and dissolved oxygen were measured using a multiparameter water quality analyzer (Hydrolab DS5, HACH Company, Loveland, CO, USA) with a vertical resolution of 0.5 m from the surface to bottom waters. Besides, water samples were collected at three layers from surface (0.5 m), anoxic boundary water layer (middle waters) and bottom waters (2 m above the sediment). The water samples were immediately sent back to the laboratory for the chemical quantification, including total nitrogen (TN), total phosphorus (TP), total carbon (TC), total organic carbon (TOC), ammonium-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), nitrite-nitrogen (NO_2-N), phosphate-phosphorus (PO_4-P). Both TC and TOC were measured by TOC-VCPH (Total Organic Carbon Analyzer, Shimadzu Corporation, Japan). Both TN and TP were determined by TU-1810 UV/VIS spectrophotometer (Beijing Purkinje General Instrument Company Co., Ltd, Beijing, China) after digestion. While NH_4-N, NO_3-N, NO_2-N and PO_4-P were measured following standard methods (Clesceri et al., 1998).

The phytoplankton data include the chlorophyll-*a* of cyanobacteria, chlorophyta, bacillariophyta/dinophyta were specifically measured using a PHYTO-PAM Phytoplankton Analyzer (Heinz Walz GmbH, Effeltrich, Germany) in the laboratory immediately after sampling (Luo et al., 2022). The meteorological data including the daily mean air temperature, daily total precipitation, daily sunshine hours, and daily mean wind speed were downloaded from China Meteorological Data Service Center (http://data.cma.cn) (Station ID 59134; coordinates 24° 29′ N, 118°04′ E).

2.2. Thermocline and oxycline analysis

The thermocline thickness and hypoxic thickness are the depth range along water column between the upper and lower thermocline or hypoxic boundaries, respectively (North et al., 2014; Liu et al., 2019). In this study, we used the thermocline depth and thermocline thickness as thermal stratification indicators, and the hypoxic thickness as the oxycline stratification indicator. In addition, we defined minor thermocline change (0–0.2 °C/m) as no stratification period, moderate thermocline (0.2–0.5 °C/m) as weak stratification period, and major thermocline changing (>0.5 °C/m) as strong stratification period.

The hypoxic thickness of the oxycline were grouped from DO concentration values based on the relative thickness. In this study, we defined three groups: DO concentration >2 mg/L as "no hypoxia", DO concentration between 0.2–2 mg/L as "hypoxia" and DO concentration <0.2 mg/L as "strong hypoxia" (Conley et al., 2007; Diaz, 2001; Alvisi and Cozzi, 2016).

2.3. Data analysis

We used the partial least squares path models (PLS-PM) to explore the relationship between meteorological factors (air temperature and sunshine hours), stratification (thermocline thickness and hypoxia layer), phytoplankton (cyanobacterial biomass) and nutrients (TN and TP) during low and water level periods, respectively. The PLS-PM model

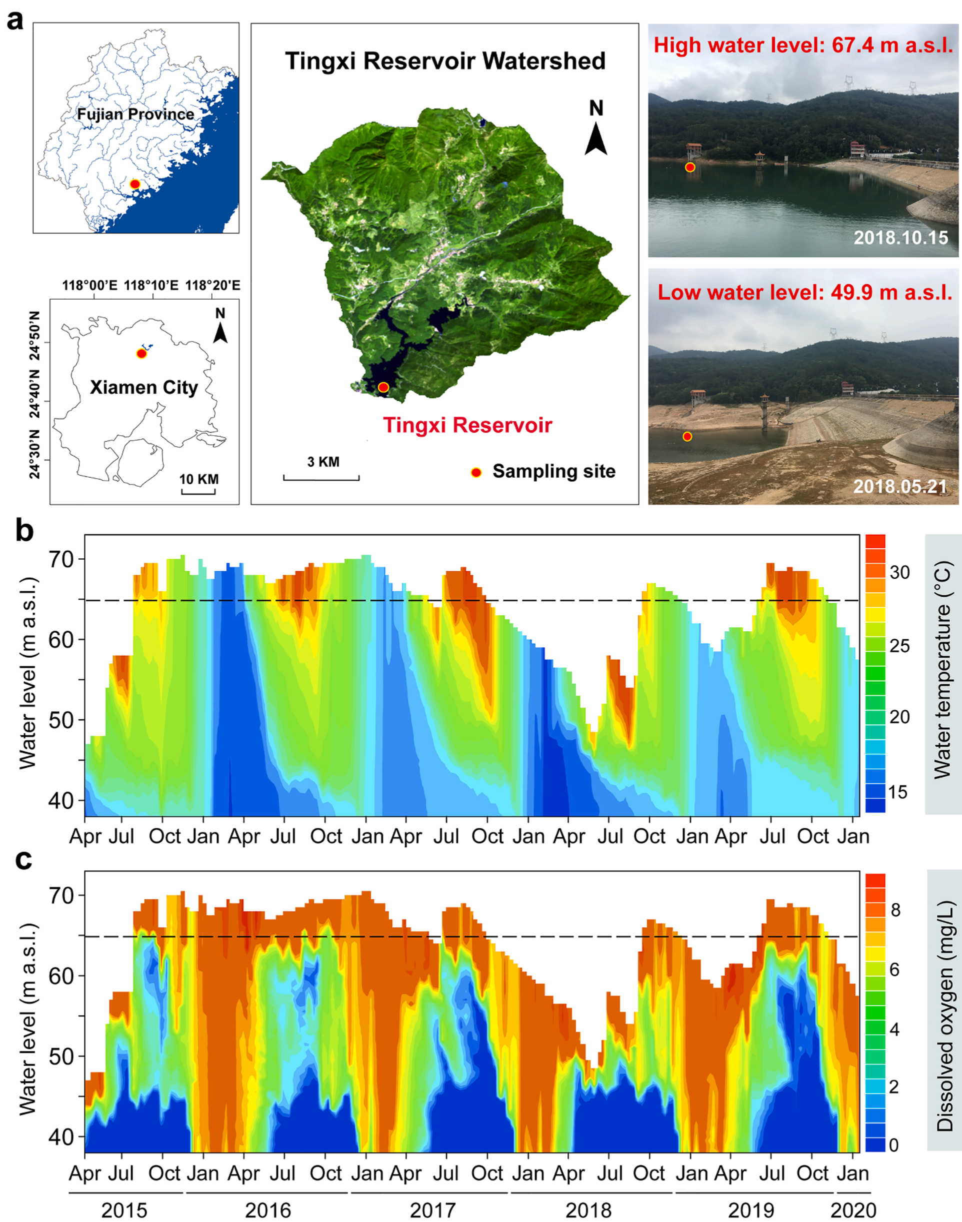

Fig. 1. Location of Tingxi Reservoir in Xiamen City, southeast China and its profiles of water temperature and dissolved oxygen. (**a**) The red dot is the sampling site for time-series monitoring. Depth-time profiles of (**b**) water temperature and (**c**) dissolved oxygen from 10 April 2015 to 15 January 2020 in Tingxi Reservoir. The a.s.l. is above sea level. The dashed line is the mean water level line.

is a framework that can show structural relationship between variables (Tenenhaus et al., 2005). The generalized additive model (GAM) was used to explore the variation of meteorological factors, stratification, phytoplankton and nutrients during low and high water-level periods, respectively. Further, the relationship between relative hypoxia thickness and thermocline in weak stratification, moderate stratification and strong stratification periods were analyzed, respectively. In addition, time series of the stratification intensity, the nutrient and the phytoplankton biomass were constructed to observe seasonal changes of environmental factors at sampling sites. All analyses were conducted in R environment (R Core Team, 2023).

3. Results

3.1. Early onset of hypoxia in reservoir bottom water during low water level period

We found the onset of hypoxia about 40 days earlier in the bottom water during the spring period of low water level in both 2015 and 2018 (Figs. 1, 2 and Table 1). Meanwhile, the mean duration of hypoxia in 2015 and 2018 was 246 days, which was 36–56 days longer compared to years 2016, 2017 and 2019 (Table 1). There were significant differences between the surface water temperature and the mean DO between low water level periods and high water level periods in the warming or cooling months, with surface water temperatures particularly higher in March and lower in December (Fig. S1). Specifically, the difference in mean DO in spring between low and high water level periods was mainly observed at the bottom, while surface DO levels were more stable (Fig. S1). During low water level period, the thermocline thickness (>

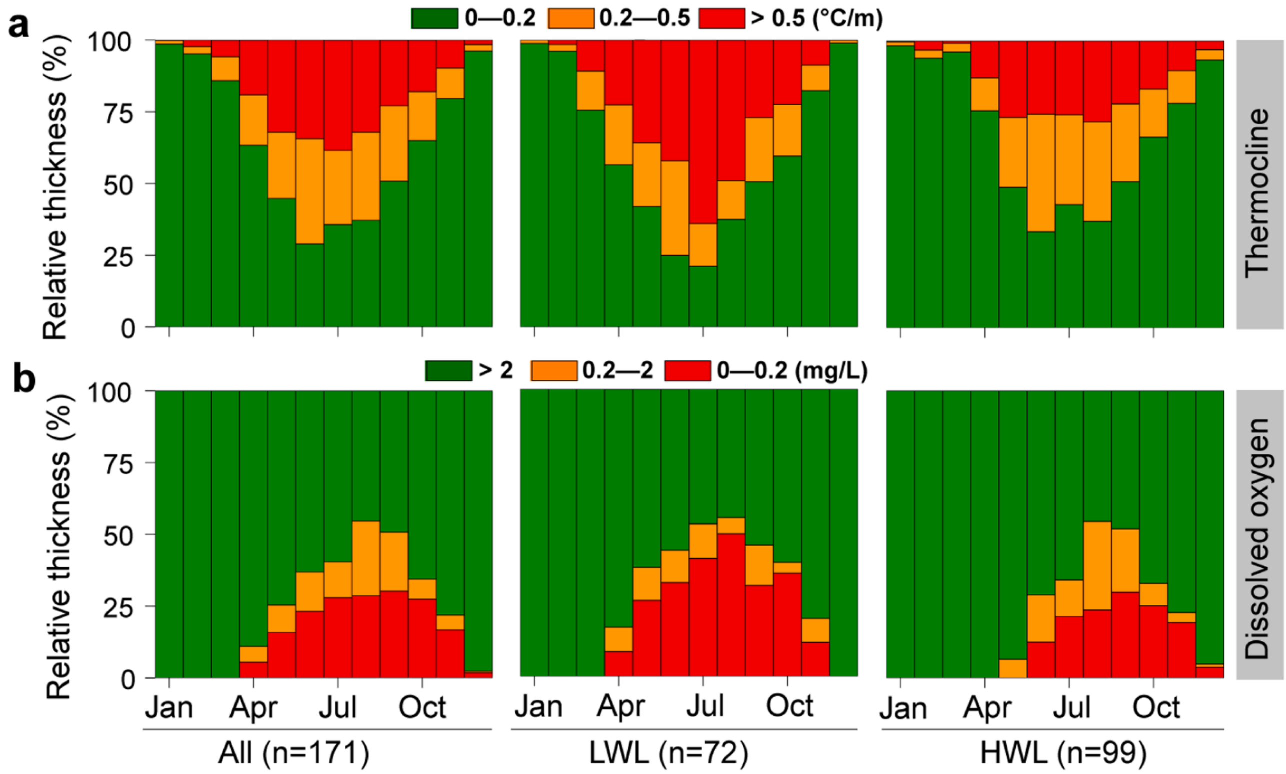

Fig. 2. Relative thickness of thermocline and hypoxic layer in Tingxi Reservoir from 2015 to 2020. (**a**) Monthly variation in thermocline thickness. The value of the criterion for the vertical gradient of water temperature thermocline between 0 and 0.2 °C/m, between 0.2 and 0.5 °C/m and above 0.5 °C/m is showed, respectively. (**b**) Monthly variation of hypoxic layer thickness. The value of the criterion for the dissolved oxygen concentration gradient is greater than 2 mg/L, between 0.2 and 2 mg/L, and below 0.2 mg/L, respectively. LWL: low water level period, HWL: high water level period.

Table 1
The onset time, ending time, duration and relative thickness of hypoxic layer in Tingxi Reservoir.

Year	N	Water depth (m a.s.l)		Onset time	Ending time	Duration (days)	Relative thickness (%)	
		Mean	Range	Julian day			Mean	Max
2015	27	62.9	47.8—70.6	99	344	245	31	63
2016	35	69.2	67.7—70.3	147	356	209	17	62
2017	36	65.8	59.3—70.1	131	341	210	25	73
2018	35	59.6	48.9—67.7	98	346	248	29	75
2019	36	65.2	58.1—70.4	149	339	190	23	76

Relative thickness: relative hypoxic thickness with dissolved oxygen from 0 to 2 mg/L.
N: sample size.

0.5 °C/m) increased strongly from March to July with a high point in July (Fig. 2a). Meanwhile, a thickening of the hypoxia layer at the bottom of Tingxi Reservoir was observed from April to November with its greatest extent in August during low water level periods (Fig. 2b).

However, it is important to note that the DO stratification began to appear gradually only after April, which was delayed 40 days during high water level period, especially in 2016, 2017 and 2019 (Fig. 2 and Table 1). In addition, bottom hypoxia ended earlier in November during low water level periods (dry years) compared to high water level periods or all (wet years) water level periods (Fig. 2). Another interesting observation was that the DO stratification period during high water level periods lasted until December, which did not occur during low water level periods (Fig. 2).

3.2. Variation of the climate, water level and DO stratification

From 1980 to 2020, the average temperature in Xiamen rose by more than 2 °C, and there were distinct dry and wet years due to the large variations in precipitation and sunshine hours (Fig. S2; Fig. S3). Meanwhile, wind speeds declined sharply from 1990 to 2000 and stabilized with minor fluctuations from 2000 to 2020 (Fig. S2). The high temperatures in summer have pushed the surface water temperature of Tingxi Reservoir to over 30 °C (Fig. 1). In general, the dry years for Tingxi Reservoir were 2015 and 2018, marked by a significant drop in water level, while the wet years were 2016 and 2017, characterized by higher water level (Fig. 1b). Notably, since the first half of 2019, the water level of Tingxi Reservoir remained consistently below the average until May, after which it rose above the average (Fig. 1b).

From 2015 to 2020, hypolimnion hypoxia was found in Tingxi Reservoir with seasonal thermal stratification occurring throughout the water column, especially from June to November (Fig. 1). Particularly low water levels were recorded between April and July 2015, and between late 2017 and October 2018, with hypoxia at the bottom being detected from Julian day 99 or 98 in 2015 or 2018, respectively (Fig. 1c). Additionally, thermal stratification generally occurred earlier than bottom hypoxia of Tingxi Reservoir from 2015 to 2020 (Fig. 1).

In general, the thermal stratification intensity of Tingxi Reservoir was generally stronger in the hotter months (especially from April to

October) with an obvious stratification in DO from May to October (Fig. 2). No DO stratification was observed from January to March, while the thermal stratification was very weak during this period (Fig. 2).

3.3. Variation of the meteorological factors and hypoxic layer thickness at different thermocline layers

The thermocline responded strongly to air temperature and sunshine hours (Fig. S4). Specifically, the variation in the thermocline was greater during the low water level period than the high water level period, especially when the air temperature exceeded 15 °C (Fig. S4a). The accumulation of sunshine hours between two sampling dates also had the influence ($r = 0.406$, $P < 0.001$) on the temperature difference of the thermocline during the low water level period (Fig. S4c). However, Tingxi Reservoir tended to have a weak temperature difference when sunshine hours exceeded 100 h between two sampling dates during the high water level periods (Fig. S4c).

The state of stratification significantly influenced the thickness of hypoxia in the hypolimnion (Fig. S5). During periods without thermal stratification (thermocline=0–0.2 °C/m), the GAM indicated a reduced presence of hypoxia (Fig. S5b). Conversely, during periods of strong stratification (thermocline>0.5 °C/m), the hypoxic zone notably expands as the relative thickness of the thermocline increases (Fig. S5d). This trend is particularly pronounced under strong stratification conditions, demonstrating a close correlation between the thickness of the thermocline and the expansion of hypoxia. Moreover, during moderate stratification periods (thermocline=0.2–0.5 °C/m), there is also an increase in hypoxia thickness, although to a lesser extent (Fig. S5c).

3.4. Relationships between cyanobacterial biomass, temperature and nutrient during low or high water level periods

During low water level periods, cyanobacterial biomass significantly increased with thermocline thickness, which was not significant during high water level periods (Fig. 3). However, the relationship between surface water temperature and cyanobacterial biomass was positive during all periods (Fig. 3). During low water level, the total phytoplankton biomass was significantly higher in the middle and bottom layers in summer, while cyanobacterial biomass increased in the surface waters during these periods (Fig. S6).

At the beginning of the thermocline period (after February), surface TN was significantly higher during the low water level period compared to the high water level period, but was lower in the end of the thermocline formation period (October and November) (Fig. S7). Generally, the nutrients (TC, TOC, TN and TP) increased in the low water level period, especially in TN (July to August) and TP (May, October and November) in the bottom waters (Fig. S7). During low water levels, enhanced mixing due to a higher mixing depth ratio increased nutrient availability (Fig. S8).

4. Discussion

This study reveals the phenomenon of enhanced thermal stratification and earlier onset of hypoxia caused by climate-driven water level decline in a subtropical monomictic reservoir in dry years. These findings exhibit both unique and universal characteristics when compared to studies from other regions. In comparison to the temperate regions, subtropical reservoirs generally show a stronger response to the dual impacts of climate change and water level fluctuations (Null et al., 2013). Temperate reservoirs typically have longer winter mixing periods, which could help redistribute oxygen throughout the water column (Schladow and Fisher, 1995). For example, Smucker et al. (2021) has studied the hypoxia in northern U.S. reservoirs and indicated that the seasonal mixing period effectively mitigates summer hypoxia issues. However, our study finds that subtropical reservoirs, due to higher annual temperatures and shorter mixing periods, exhibited more severe hypoxia, particularly during low water level periods in dry years. As for tropical regions, studies usually focus on more extreme climatic conditions and the potential for year-round hypoxia. In African tropical reservoirs, year-round high temperatures and strong seasonal rainfall variations lead to persistent stratification and hypoxia (Jane et al.,

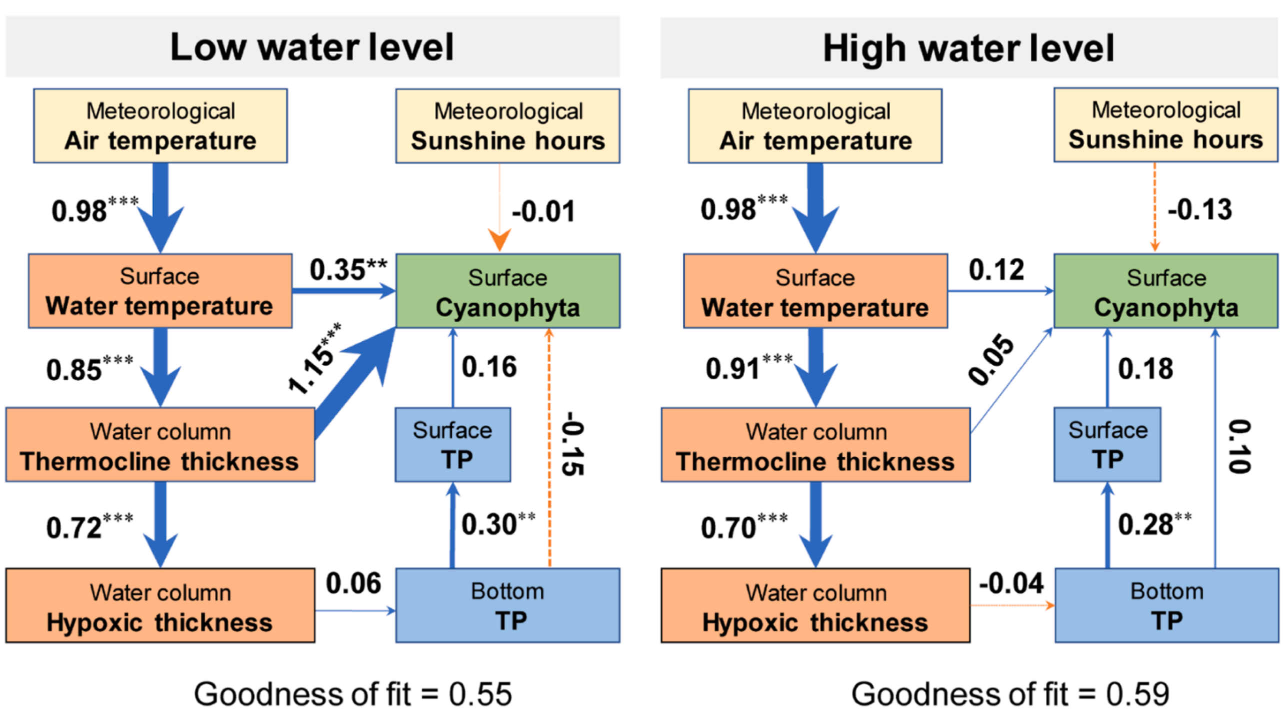

Fig. 3. The partial least squares path models (PLS-PM) showing the direct effects of meteorological factors on water temperature, thermal stratification, hypoxia, bottom water TP, surface water TP, and surface cyanobacteria during low water level and high water level periods, respectively, from 2015 to 2020. The solid blue line represents a positive relationship and the dotted orange line represents a negative relationship. $^*P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.

2021). Although the subtropical reservoir (Tingxi Reservoir) in this study did not exhibit year-round hypoxia in bottom waters, water level declines and seasonal variations significantly influenced the timing and duration of hypoxia. Compared to tropical reservoirs, subtropical reservoirs exhibited transitional characteristics in seasonal changes but still showed high environmental sensitivity.

Among the existing studies on hypoxia and stratification in inland waters in the subtropical regions, there is no literature that directly analyzes the impact of water level changes on the advance of hypoxia in a changing climate. The results of this study add to the research on hypoxia in subtropical reservoirs, but also highlight the unique response mechanisms of subtropical reservoirs under the context of climate and hydrological dynamics. Future research should further explore the ecological responses of reservoirs under different geographical and climatic conditions to comprehensively understand the impact of global changes on reservoir ecosystems.

4.1. The physical reasons of early hypoxia

First, water level fluctuations play an important role in temperature dynamics and evolution of reservoirs, which indicates an imbalance in water inflows and outflows of a reservoir, thereby they can cause interannual differences in thermal stratification characteristics (Owens, 1998). The significance of summer outflow is expected to remove the cooler water in the hypolimnion, reducing the temperature differences. This also implies the early onset of mixing in the same year's winter because of the warmer temperature in the epilimnion (Yang et al., 2021). Meanwhile, the oxygen concentration in the hypolimnion increased because the complete mixing of the water column (Schwefel et al., 2016). Subsequently, warm surface water in winter heats quickly in the following spring, leading to early thermal stratification, which determines the oxygen stratification and will intensify the formation of the lake hypolimnion anaerobic environment (Zhang et al., 2015).

On the other hand, the stability of the water column could also reduce because of the water volume decreasing, which could have different implications for biogeochemical processing. This can allow winds to decrease the surface water temperature in fall more easily, as the decreased water depth inherently reduces the amount of energy required to mix the full water column (Lewis et al., 2024). Therefore, it would expect to occur earlier due to the surface cooling and wind mixing (Owen, 1998). Similarly, surface water temperatures increase quickly due to the less storage capacity, which leads to the early onset of thermal stratification in subtropical reservoirs in early spring.

4.2. The biochemical conditions increase the extent of hypoxia

The expansion of bottom hypoxia in subtropical reservoirs could be influenced by the increase in phytoplankton biomass through oxygen consumption during decomposition, increased biological oxygen demand, altered nutrient dynamics, inhibited vertical mixing, and feedback loops involving cyanobacteria. Excessive loading of nitrogen and phosphorus from agricultural runoff or wastewater discharge could also stimulate the growth of phytoplankton (Ambler et al., 2001). The water level decline in summer through inflow reduction can increase water retention times and nutrients (Vollenweider, 1968). Longer water retention times allow cyanobacteria to take full advantage of the conditions, increasing their biomass and biological oxygen demand (Hilton et al., 2006). High biomass accumulations of phytoplankton result in significant removal of available inorganic nutrients such as nitrate and phosphate (Lemley et al., 2021). When the phytoplankton die, the organic carbon in the form of plant debris, dead phytoplankton, and other organic materials settle to the bottom of the reservoir. The organic matter decomposition by bacteria and other microorganisms consumes oxygen. High levels of organic carbon deposition can significantly increase oxygen demand in the bottom water layers, then contributing to hypoxia (Manzoni et al., 2010). Under hypoxic conditions, iron and manganese oxides in the sediment are normally reduced to soluble Fe^{2+} and Mn^{2+}, which can be released into the water (Xu et al., 2024). Shallower mixing depth might inhibit vertical mixing and enhancing stratification, which could also contribute to the hypoxia (Donis et al., 2021). This further promotes phosphorus release and cycling from sediment, increasing its availability in the water column, and reinforcing the feedback loops that exacerbate hypoxia. Those oxides can influence phosphorus cycling by enhancing its availability in the water column, promoting further phytoplankton growth and exacerbating hypoxia (Wang et al., 2024). The re-oxidation of metals can consume amounts of DO, perpetuating a feedback loop and led to the hypoxia (Guan et al., 2023).

Increased phytoplankton biomass can also affect vertical stratification and inhibit oxygen mixing in subtropical reservoirs in summer and autumn. Water transparency decreases due to increased phytoplankton biomass in the surface water, which can concentrate sunlight energy and strengthen stratification (Mesman et al., 2021). In eastern China, successive algal blooms have created a low DO pool, setting the stage for hypoxia zone development that the stratification caused by different water masses inhibited vertical mixing of oxygen from surface layers, accelerating the onset and duration of hypoxia in reservoirs (Zhang et al., 2022). Low water levels could also lead to higher concentrations of sulfides because reduced water volume leads to less dilution and increased interaction between water and sediment (Jing et al., 2019). Therefore, sulfate present in the bottom sediments can be reduced to sulfides by sulfate-reducing bacteria under hypoxic conditions. These sulfides are toxic and can further deplete oxygen levels in the water column, creating a feedback loop where hypoxia promotes sulfide formation, which in turn exacerbates hypoxia (Kim et al., 2016).

4.3. Adaptive strategies for subtropical reservoirs under climate-driven water level fluctuations

An increase in extreme events such as extreme high-temperatures (heat waves) and extreme rainfall events could lead to more frequent switching between wet and dry seasons (Gebremariam et al., 2021), which would shift the Tingxi Reservoir to a generally anoxic, phytoplankton-dominated system after a prolonged period of bottom anoxia in the future. The Tingxi Reservoir has experienced unprecedented and rapid climatic changes, with sustained warming (especially in the last decade) and sustained low wind speeds (especially in the last 20 years), which might lead to serious consequences for aquatic ecosystems as they affect the incidence and severity of hypoxia (Bocaniov et al., 2020). The water temperature is expected to continue to rise in the future (O'Reilly et al., 2015), and the deep lakes are more likely to experience greater thermal stratification changes over time (Kraemer et al., 2015).

This earlier onset and stronger stratification pattern potentially impacted other ecological processes, such as nutrient migration and phytoplankton growth, in the Tingxi Reservoir. For example, higher water temperature directly benefits the survival of the overwintering cyanobacterial population (Paerl et al., 2016; Molot et al., 2021). Cyanobacteria can increase nutrients in the reservoir through nitrogen fixation, enhance nutrient uptake and recycling during blooms, or increase highly unstable carbon that eventually sinks and stimulates microbial respiration, reducing DO in the bottom waters (Smucker et al., 2021). After longer periods of internal phosphorus loading under anaerobic conditions at the bottom waters, measures to control external phosphorus yield to reservoirs might not be sufficient to control eutrophication (Neto et al., 2022). Additionally, the decomposition of organic material from the epilimnion uses DO during the summer stratification period (Zhang et al., 2015). As a consequence, extended stratification periods and lower ratios of hypolimnion volume to epilimnion volume exacerbate oxygen depletion (Zhang et al., 2015).

Although the man-made dam could control the water level of Tingxi Reservoir by storing and releasing water, this may significantly impact nutrient cycling and phytoplankton biomass and diversity (Wu et al., 2019). Sediment accumulation resulting from dam operations releases bioavailable phosphorus and/or increases dissolved inorganic nitrogen, causing deeper hypoxia (Chen et al., 2020; Cheng et al., 2020). We need to optimize transboundary dam policies and make water infrastructure planning more flexible to maintain natural DO concentrations during stratification (Fletcher et al., 2019). However, it is necessary to take management measures according to Tingxi Reservoir conditions across space and time due to differences in local climate and specific reservoir morphology.

4.4. Technological approaches to improve water quality in stratified reservoirs

Hypolimnetic water withdrawal is a widely used method that can avoid nutrient accumulation and anoxic conditions in reservoirs (Kerimoglu and Rinke, 2013). However, the stratification would be broken as withdrawing the cool hypolimnetic water, which could result in entrainment of nutrients to the epilimnion, thus might promote the increase of the harmful algae biomass (Barbiero et al., 1997). Therefore, for reservoirs prone to harmful algal blooms, it is more suitable to use new water withdrawal technologies. Artificial induction methods such as mechanical mixing or aeration, may be needed to promote water mixing or flushing in stratified reservoirs to reduce the risk of eutrophication and cyanobacterial blooms by dispersing and balancing water levels to create favorable oxygenated and mixing conditions (Paerl et al., 2016; Wen et al., 2022).

More studies are using models to develop optimized turbine withdrawal methods for stratified reservoirs to improve water quality. For example, temperature-control curtain technology for selective withdrawal to control outflow temperature has been confirmed in modeling a subtropical reservoir (He et al., 2017; Zheng et al., 2017). In the Itezhi-Tezhi Reservoir of Zambia, a one-dimensional model simulated biogeochemical processes within the reservoir and outflow water quality. The model estimated how the turbine water withdrawal could affect DO concentration, inorganic nitrogen and phosphorus loads in the stream (Kunz et al., 2013). The General Lake Model has also been extended to determine the optimal water extraction height based on the thermal structure or the oxygen concentration, which has been reported in the oligotrophic and monomictic Grosse Dhuenn Reservoir in Germany (Weber et al., 2017).

5. Conclusion

This study examined the impact of climate-driven water level fluctuations on hypoxia in Tingxi Reservoir, a monomictic subtropical reservoir in southeast China. Our five-year study focused on the interplay between water level declining, thermal stratification, nutrient dynamics, and dissolved oxygen levels. The results reveal that low water levels lead to earlier and more intense thermal stratification, precipitating hypoxia onset earlier in the reservoir's bottom layers than during high water level periods. This early stratification hinders oxygen replenishment to deeper waters, fostering conditions that enhance nutrient (phosphorus and nitrogen) release from bottom sediments. These nutrients feed into increased phytoplankton biomass that decays further depletes oxygen levels, reinforcing the hypoxic conditions. Moreover, the study documented a significant positive feedback loop wherein lower water levels intensify stratification, leading to prolonged hypoxia and nutrient accumulation, which then supports more phytoplankton growth, exacerbating DO depletion in dry years. The exacerbated hypoxia threatens aquatic life and disrupts ecosystem services, highlighting a critical need for adaptive management strategies in reservoir settings. Therefore, we recommend implementing optimized water withdrawal strategies and adopting advanced monitoring systems to better predict and mitigate the adverse impacts of hydrological changes. These strategies are crucial for managing the ecological health of subtropical reservoirs under the looming threats of climate change, aiming to safeguard water quality and preserve aquatic biodiversity. The insights from this study underscore the importance of a proactive approach to reservoir management in the face of climate change, ensuring the sustainability of water resources and ecosystem functions.

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CRediT authorship contribution statement

Huihuang Chen: Methodology, Investigation, Formal analysis, Data curation. **Anqi Luo:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Chenxi Mi:** Writing – review & editing, Methodology. **Yifan Lu:** Validation, Investigation. **Yuanyuan Xue:** Funding acquisition. **Lei Jin:** Investigation. **Hongteng Zhang:** Validation, Investigation. **Jun Yang:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2024.122445.

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