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SPATIOTEMPORAL VARIATIONS AND EMISSION CHARACTERISTICS OF CO₂ FLUXES IN DEEP LARGE RESERVOIRS

Abstract: Climate change driven by greenhouse gas emissions is a global priority. Deep large reservoirs represent significant potential emission sources, yet their greenhouse gas source-sink dynamics and driving mechanisms remain inadequately understood. This study targeted three representative deep reservoirs of the upper Yellow River (Longyangxia (LYX), Lijiaxia (LJX), and Liujiaxia (LJXX)). Comparative analysis of water column conditions during the stratification period (summer) and mixing period (winter) was conducted. We quantified the spatial distribution of dissolved partial pressure of CO₂ ($p\text{CO}_2$) and the water-air interface exchange flux (F_{CO_2}), elucidating their spatiotemporal patterns and carbon source-sink attributes. Key findings include: (1) Concentration and Flux Characteristics: Mean $p\text{CO}_2$ was 765.00 μatm in summer and 739.00 μatm in winter. Corresponding mean F_{CO_2} was 12.273 $\text{mmol}/(\text{m}^2 \cdot \text{d})$ and 9.111 $\text{mmol}/(\text{m}^2 \cdot \text{d})$. (2) Regulatory Mechanisms: Thermal stratification, climatic fluctuations, and reservoir-specific properties influenced $p\text{CO}_2$ by modulating carbon cycling pathways and carbonate equilibria. (3) Source-Sink Nature: All three reservoirs exhibited significant spatial gradients and seasonal variations in $p\text{CO}_2$ and F_{CO_2} , collectively functioning as sources of the CO₂. This study provides critical theoretical support for quantifying the carbon footprint of hydropower projects.

Keywords: reservoir, CO₂ exchange flux, thin boundary layer model, water-air interface, carbon source-sink

Introduction

Anthropogenic increases in greenhouse gas concentrations are a primary driver of recent rapid climate warming and extreme weather events [1]. In recent decades, a large number of large reservoirs have been built in China, and the CO₂ emitted by these reservoirs has become an important source of greenhouse gases (Source is defined as the process that releases CO₂ into the atmosphere. Sink is defined as the process that absorbs CO₂ from the atmosphere) [2], exacerbating the greenhouse effect. Emissions from reservoir ecosystems now constitute a non-negligible component of global carbon budgets [3] and are a crucial consideration for achieving carbon neutrality goals.

Deep large reservoirs, characterised by substantial storage capacity, depth, surface area, and regulation capability, exhibit markedly different water-air carbon cycling and associated biogeochemical processes compared to natural rivers and shallow lakes [2, 4]. For instance, studies on the Xinfengjiang Reservoir [5] revealed its role as a CO₂ source during wet and dry seasons. Similarly, both the mainstream and tributaries of the karstic

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Wanfeng Lake Reservoir showed CO₂ supersaturation during summer [6, 7]. While existing research has explored spatiotemporal CO₂ dynamics in deep reservoirs from various perspectives [7], systematic studies on the upper Yellow River system remain limited. This investigation focuses on three deep reservoirs (LYX, LJX, LJXX) exhibiting distinct thermal stratification in the Longyangxia-Liujiaxia reach. Utilising hydrochemical equilibrium and TBL models, we monitored longitudinal (tail-zone to dam-front) and vertical variations in dissolved CO₂ during stratification and mixing periods. Our objectives are to: (i) characterise CO₂ dissolution patterns, (ii) quantify water-air exchange fluxes, and (iii) elucidate source-sink dynamics, thereby providing robust data for assessing greenhouse gas emissions from reservoir ecosystems.

Materials and methods

The Longyangxia-Liujiaxia reach (420 km long) in the upper Yellow River is a key section for hydropower development, where more than 10 reservoirs have been built so far. Reservoir operations have profoundly altered local hydrology, resulting in pronounced seasonal runoff variations and spatial heterogeneity [8]. Dominated by mountains, hills, and grasslands with minimal agricultural/pastoral activity and no industrial pollution, the region has a cold climate: cool, rainy summers and cold, dry winters.

Sampling and analysis

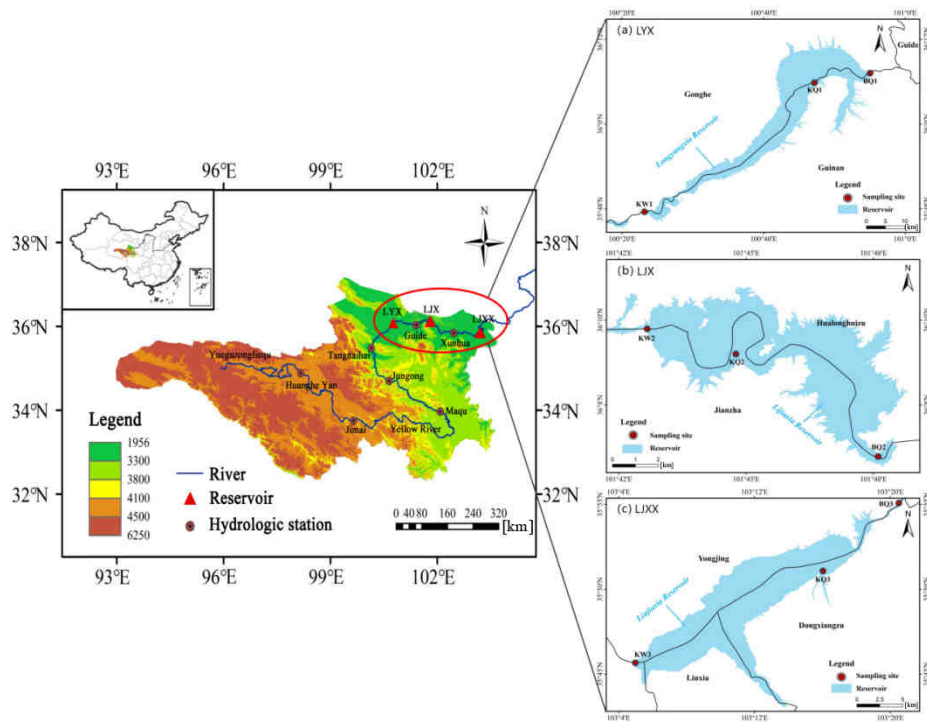


Fig. 1. Location of study reservoirs and sampling sites

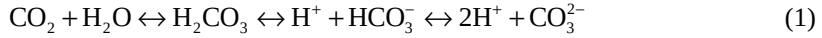
Samples were collected from LYX, LJX, and LJXX reservoirs during the stratification period (August 2023) and mixing period (January 2024). Sampling sites were established at the tail (KW), central zone (KQ), and dam front (BQ) of each reservoir (Fig. 1). The surface water samples were collected at a depth of 0.5 m via a plexiglass water collector, and water samples were simultaneously collected in layers along the depth of water on the vertical line of the cross-section via a Niskin stratified water collector (at intervals of 5 m - 10 m). And a YSIEXO₂ multiparameter water quality meter was used for onsite determination of hydrological parameters.

Data processing and calculations

(1) Dissolved partial pressure of CO₂ calculation:

The $p\text{CO}_2$ was estimated using the hydrochemical equilibrium method [9-11] implemented via CO₂SYS [12]. This approach calculates $p\text{CO}_2$ based on field-measured pH, water temperature (WT), and total alkalinity (Talk), utilising the aqueous carbonate equilibrium system:

The principle of the carbonic acid equilibrium of CO₂ in water:



$$K_H = [\text{H}_2\text{CO}_3] / p\text{CO}_2^{\text{water}} \quad (2)$$

$$K_1 = [\text{HCO}_3^-] \cdot [\text{H}^+] \quad (3)$$

$$K_2 = [\text{CO}_3^{2-}] \cdot [\text{H}^+] \quad (4)$$

$$pK_H = -7 \cdot 10^{-5} WT^2 + 0.06 WT + 1.11$$

$$pK_2 = 9 \cdot 10^{-5} WT^2 - 0.0137 WT + 10.62 \quad (5)$$

$$pH_1 = 1.1 \cdot 10^{-4} WT^2 - 0.012 WT + 6.58$$

where WT - water temperature [°C].

(2) F_{CO_2} calculation:

The gas exchange flux can be calculated via the following equation [11]:

$$F_{\text{CO}_2} = K_{\text{CO}_2} \cdot (p\text{CO}_2^{\text{water}} - p\text{CO}_2^{\text{air}}) pH_1 \quad (6)$$

where F_{CO_2} - CO₂ gas diffusion flux [mmol], K_{CO_2} - water-gas interface gas exchange rate [cm/h], $p\text{CO}_2^{\text{water}}$ - dissolved concentration of CO₂ in water [μmol/L], $p\text{CO}_2^{\text{air}}$ - dissolved concentration of CO₂ in air [μmol/L],

For the estimation of the exchange coefficient K_{CO_2} , the formula established by Jahne et al. [13] in 1998 has been adopted in most current studies:

$$K_{\text{CO}_2} = k_{600} \left(\frac{600}{S_c} \right)^x \quad (7)$$

where k_{600} - exchange coefficient of sulphur hexafluoride [cm/h]; S_c - Schmidt number, the Schmidt constant for CO₂ at °C; x - wind speed correlation coefficient, x is 0.67 when the wind speed is less than 3 m/s and 0.5 when the wind speed is greater than 3 m/s.

(3) Other data:

The meteorological data used in this research were obtained from the China Meteorological Data Service Center, and the reservoir operation data were sourced from the reservoir management authorities.

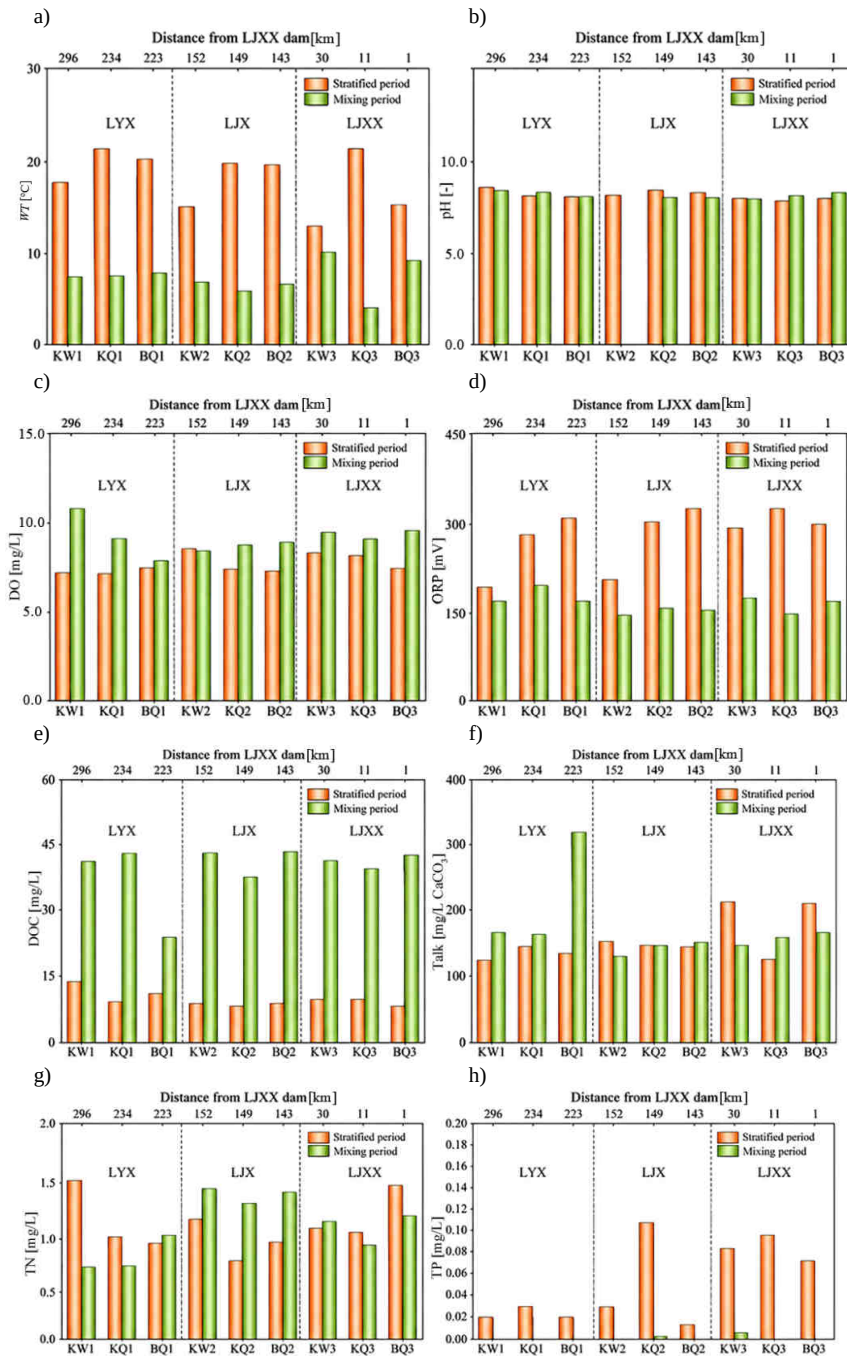


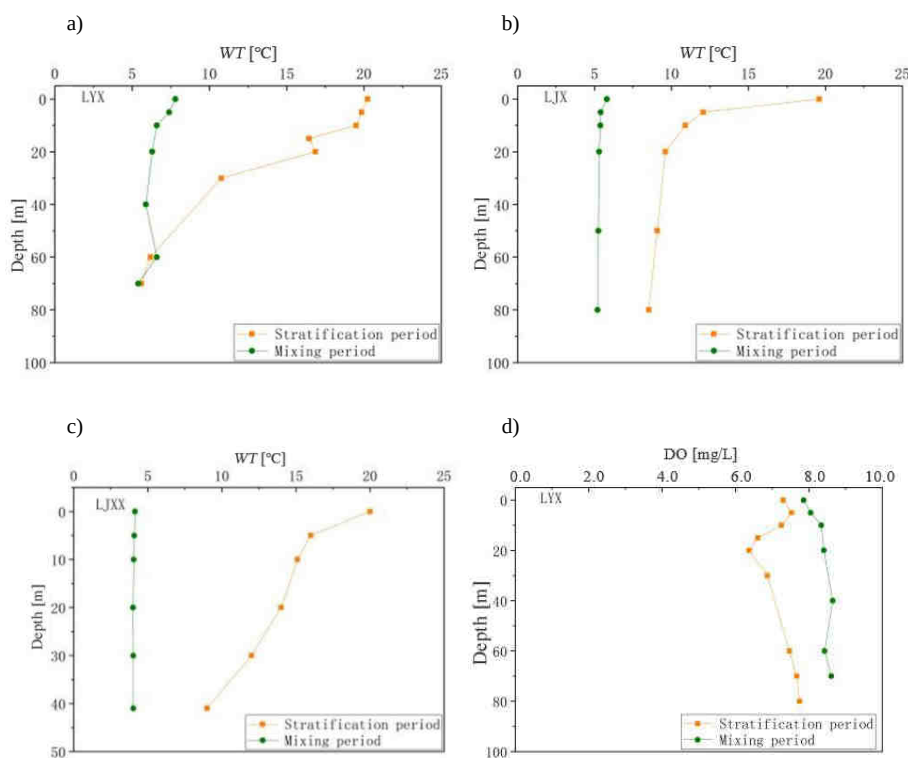
Fig. 2. Longitudinal spatiotemporal variations in water quality parameters: a) WT, b) pH, c) DO, d) ORP, e) DOC, f) Talk, g) TN, h) TP

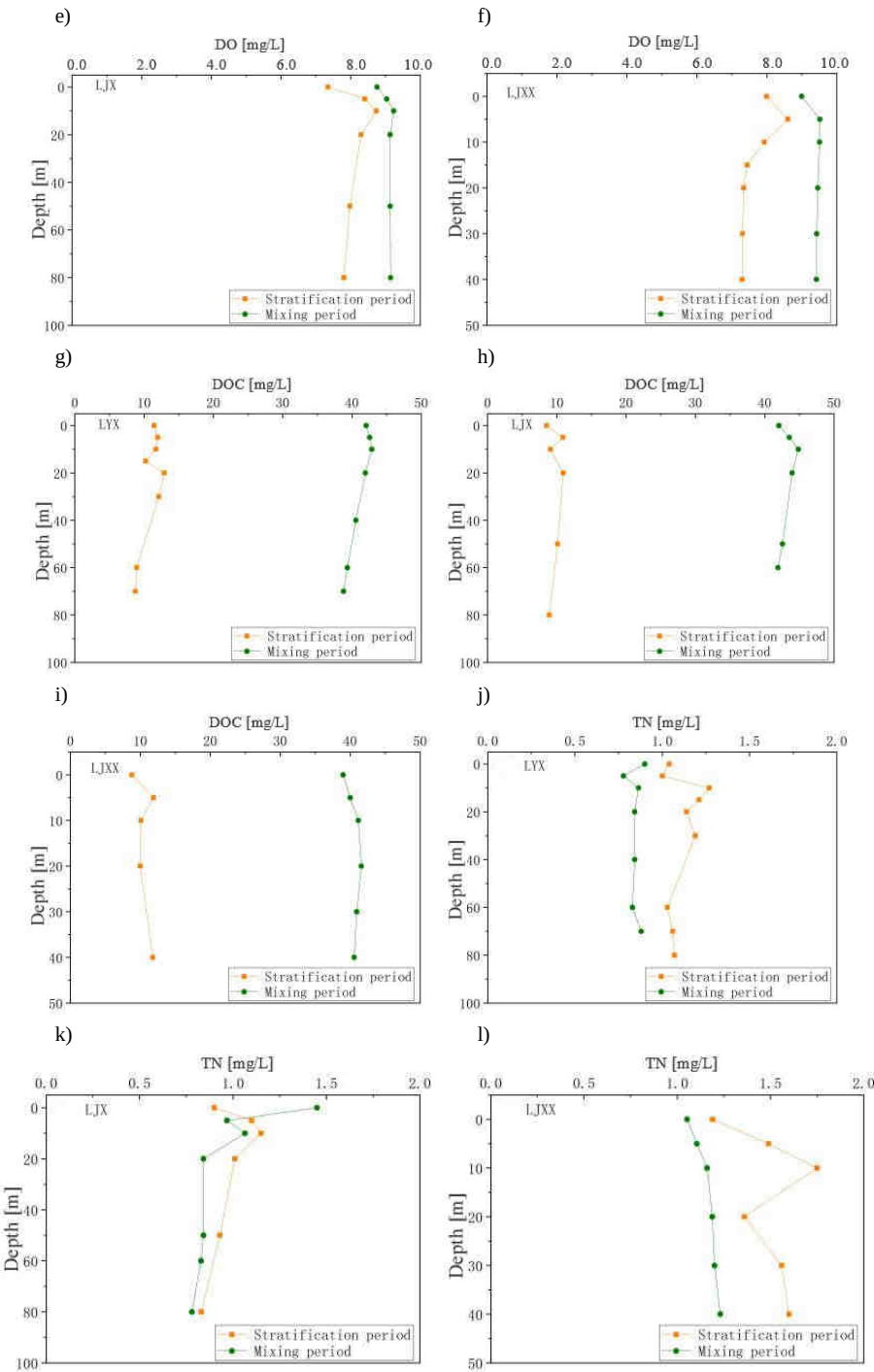
Results

Water quality parameters

In surface water of the Long-Liu reach, the water quality parameters exhibit certain spatiotemporal variation characteristics in their longitudinal distribution across different periods (stratification period, mixing period) (Fig. 2).

In summer (stratification period), in the surface water of Longyangxia Reservoir, Lijiaxia Reservoir, and Liujiaxia Reservoir, the following distribution characteristics were observed from the reservoir tail to the dam front: *WT* first increased and then decreased; electrical conductivity (*EC*) showed a fluctuating upward trend (Fig. 2e); dissolved oxygen (*DO*) and pH fluctuated within an extremely narrow range, with pH values all above 7.5 and little variation along the route (Figs. 2b, 2c); the concentrations of talk, total phosphorus (*TP*), and oxidation-reduction potential (*ORP*) generally exhibited a "rise-fall-rise" fluctuating trend (Figs. 2g, 2i, 2d); dissolved organic carbon (*DOC*) content showed an overall gradual decreasing trend (Fig. 2f); total nitrogen (*TN*) presented an overall fluctuating pattern, with *TN* content in all three reservoirs being lower in the reservoir area than at the the dam front and reservoir tail (Fig. 2h).





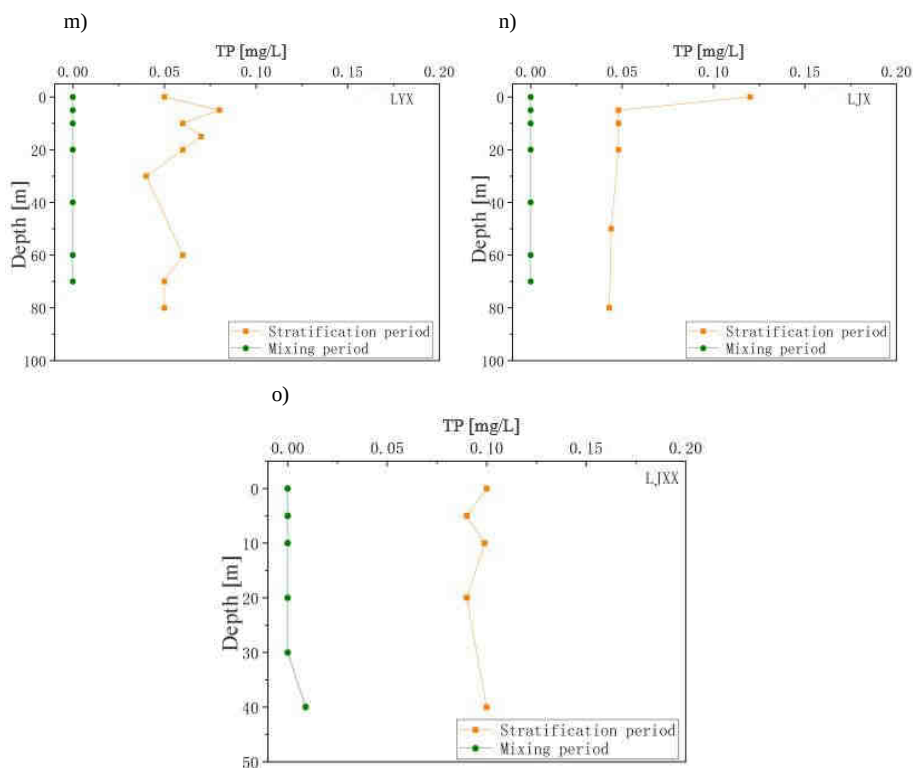


Fig. 3. Vertical distribution of key water quality parameters in the reservoir central zones: a-c) WT of LYX, LJX and LJXX, d-f) DO of LYX, LJX and LJXX, g-i) DOC of LYX, LJX and LJXX, k-l) TN of LYX, LJX and LJXX, n-o) TP of LYX, LJX and LJXX

Water environmental factors in the Long-Liu reach were measured and analysed vertically along water depth (Fig. 3).

The water environmental factors of LYX Reservoir exhibit significant vertical stratification characteristics in summer (the stratification period). WT gradually decreased from the surface to the bottom, with an obvious temperature jump, showing a "side-V" shaped variation. DO decreased in the (0-30) m water depth range, increased in the (30-90) m range.

The water environmental factors of Longyangxia Reservoir (LYX Reservoir) show no obvious vertical stratification characteristics in winter (the mixing period). DOC concentration in the reservoir area showed a slightly fluctuating decreasing trend. TN showed fluctuating changes with little overall variation, while TP concentration showed no obvious variation trend.

The spatiotemporal distribution characteristics of water environmental factors in LJX Reservoir and LJXX Reservoir are basically consistent with those of LYX Reservoir: both exhibit obvious vertical stratification characteristics in summer and no obvious vertical stratification characteristics in winter.

Spatial and temporal distributions of $p\text{CO}_2$

Along the course, during the stratification period, the $p\text{CO}_2$ ranged from 198 to 1333 μatm (Fig. 4). The maximum value was observed at the dam front of LJXX in the Long-Liu reach, and the minimum value was recorded at the tail of the LYX Reservoir. In winter (mixing period), the maximum value was observed at the dam front of LYX in the Long-Liu reach, and the minimum value was recorded at the tail of the LYX Reservoir.

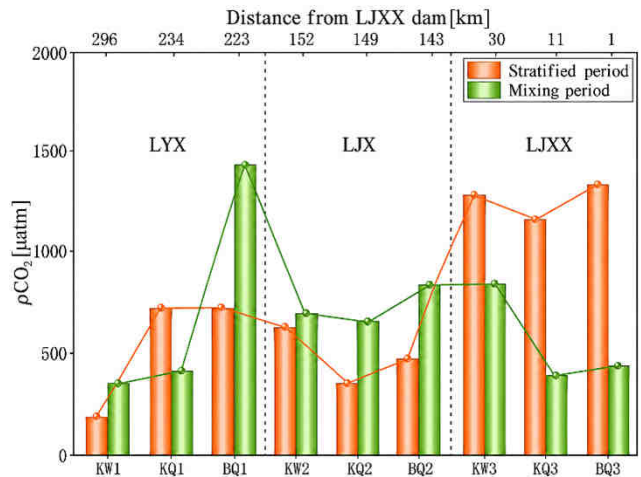


Fig. 4. Longitudinal distribution of $p\text{CO}_2$

Vertically, in summer (stratification period), the $p\text{CO}_2$ in the LYX Reservoir area showed a gradual decreasing trend along the water depth (0-40) m, with a slight recovery in the bottom layer (40-90) m, showing obvious stratification consistent with water temperature variations (Fig. 5a). In the LJX Reservoir area, the vertical variation of $p\text{CO}_2$ along the water depth was characterised by relatively higher $p\text{CO}_2$ in the Epilimnion and Hypolimnion, and relatively lower $p\text{CO}_2$ in the Thermocline. In the LJXX Reservoir area, $p\text{CO}_2$ showed an overall fluctuating decreasing trend along the water depth. The vertical variation was characterised by a gradual decrease in $p\text{CO}_2$ in the Epilimnion, followed by a slight recovery in the middle layer and bottom layer (Fig. 5c). The $p\text{CO}_2$ in the LYX and LJX Reservoir areas showed fluctuating variations with little overall change in winter (mixing period), while the $p\text{CO}_2$ varied slightly along the water depth, remaining essentially constant in LJXX Reservoir (Fig. 5).

Pearson correlation analysis was conducted between $p\text{CO}_2$ in reservoir water samples from the two periods (stratification period and mixing period) and various water environmental indicators.

Longitudinal correlation analysis indicated that during the stratification period, $p\text{CO}_2$ in this reach had a positive correlation with Talk (Fig. 6a). During the mixing period, the variation trend of $p\text{CO}_2$ is opposite to that of DO and DOC, while consistent with that of talk (Fig. 6b).

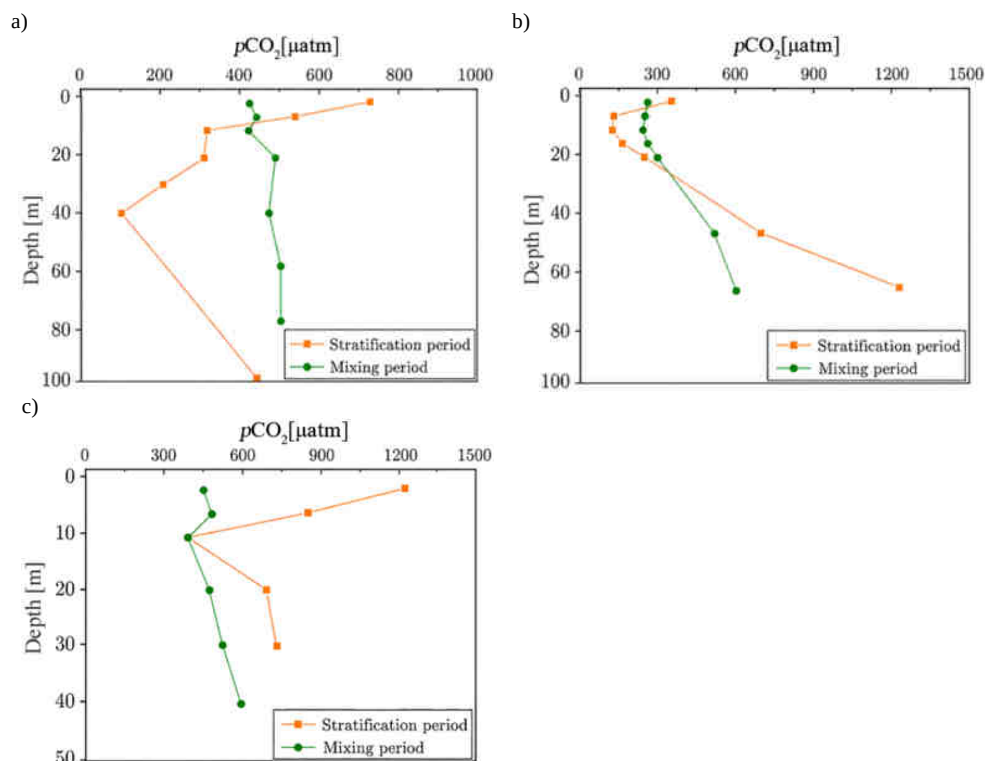


Fig. 5. Vertical profiles of $p\text{CO}_2$ in reservoir central zones: a) LYX; b) LJX; c) LJXX

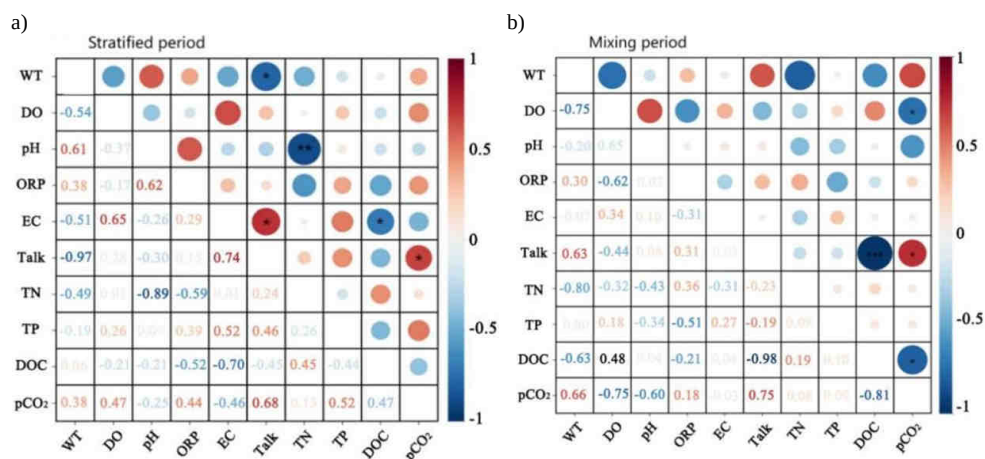


Fig. 6. Pearson correlations (longitudinal $p\text{CO}_2$ vs. parameters), * $p < 0.05$, ** $p < 0.01$: a) stratified period, b) mixing period

During the stratification period, $p\text{CO}_2$ in the water had a significant positive correlation with WT, TN, and TP ($p < 0.05$), and a significant negative correlation with DOC (Fig. 7a). During the mixing period, WT showed a significant negative correlation with DO and TN, while TN in the water had a positive correlation with TP ($p < 0.05$) (Fig. 7b).

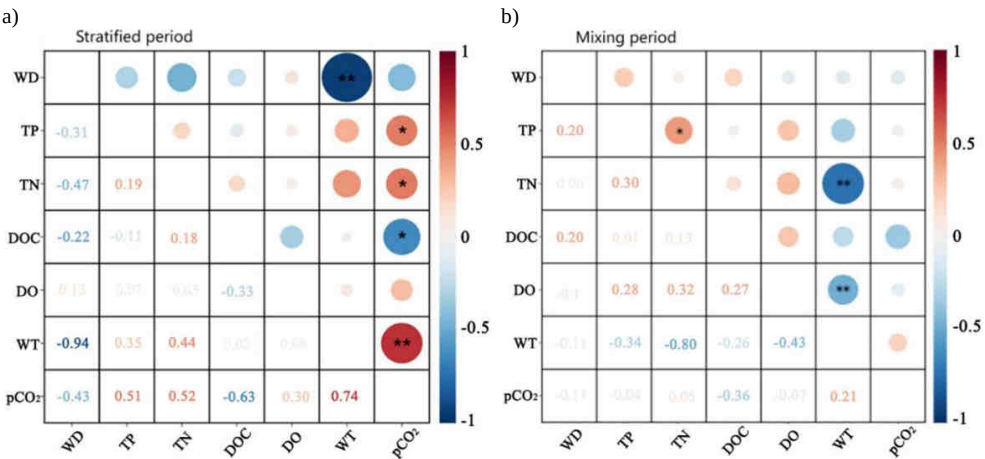


Fig. 7. Pearson correlations (vertical $p\text{CO}_2$ vs. parameters), * $p < 0.05$, ** $p < 0.01$

During the stratification period, $p\text{CO}_2$ in the water having a significant negative correlation with DOC, while has a significant positive correlation with WT, TN, and TP. During the mixing period, WT showed has a negative correlation with TN and DO, and TN in the water has a significant positive correlation with TP.

Spatial and temporal distributions of F_{CO_2}

The F_{CO_2} in this area exhibit obvious specificity in temporal and spatial distribution, with different reservoirs showing distinct source-sink relationships (Fig. 8).

During the stratified period, CO_2 exchange fluxes across the air-water interface ranged from $-5.1 \text{ mmol}/(\text{m}^2 \cdot \text{d})$ to $48.4 \text{ mmol}/(\text{m}^2 \cdot \text{d})$ (Fig. 8). In contrast, Liujiaxia Reservoir (LJX) and Liujiaxia Gorge Reservoir (LJXX) exhibited significantly higher mean fluxes of $50.4 \text{ mmol}/(\text{m}^2 \cdot \text{d})$ and $52.0 \text{ mmol}/(\text{m}^2 \cdot \text{d})$ (Figs. 8b, c). The highest CO_2 efflux was observed at the tail area of LJX Reservoir. Collectively, these large, deep reservoirs functioned, on average, as net sources of atmospheric CO_2 during the stratified period.

CO_2 exchange fluxes during the mixed period exhibited greater variability (Fig. 8). Notably, the deep-water sections predominantly released CO_2 to the atmosphere during this period. The highest efflux was recorded at the dam front area of LYX Reservoir.

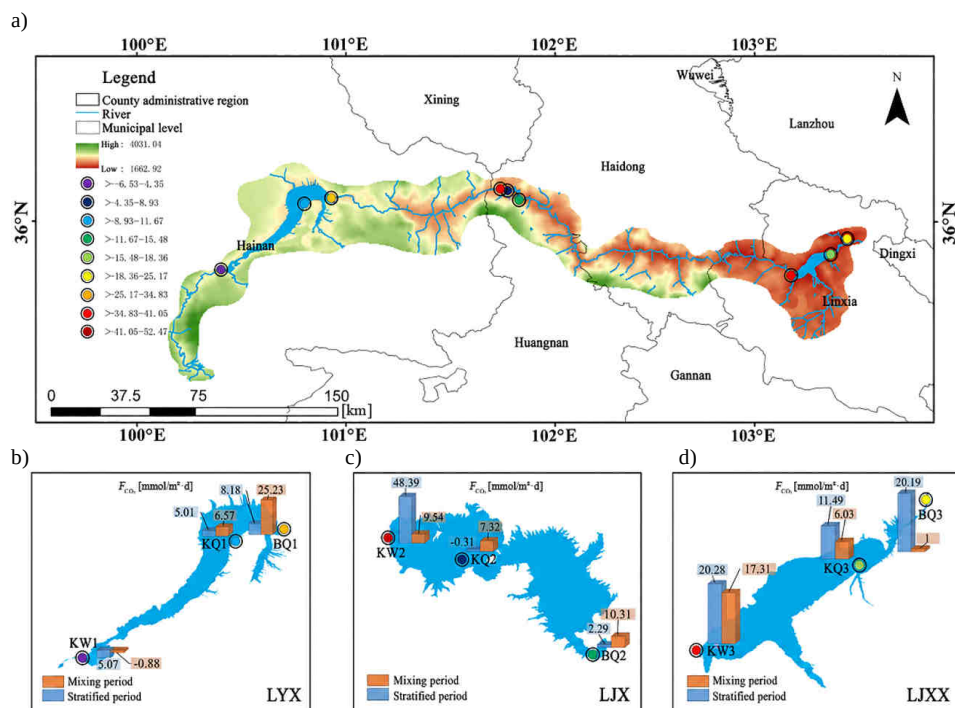


Fig. 8. Spatiotemporal distribution of F_{CO_2} : a) the locations of the three reservoirs, b) LYX; c) LJX; d) LJXX

Discussion

The direction and flux of CO₂ exchange between water-air are primarily governed by the pCO_2 in the atmosphere and the surface water [14]. In this study, the water pCO_2 in the upper reaches of the Yellow River exhibited significant spatiotemporal variation. Dam alters the original hydrodynamic conditions and significantly impacts the physicochemical properties of the water body [15].

(1) Influence of water temperature:

WT is a key factor influencing the thermodynamic equilibrium of the carbonate system. Under normal circumstances, an increase in temperature drives the equilibrium of the carbonate system to shift left, which in turn leads to a rise in the partial pressure of carbon dioxide with increasing temperature [16]. Therefore, WT will significantly alters the gas solubility of CO₂ in reservoirs and exerts a distinct regulatory effect on the carbon cycling process [17]. Consistent with previous research [18], a positive correlation ($P < 0.05$) was observed between vertical pCO_2 and WT during the stratified period in this study (Fig. 7a). This relationship is attributed to elevated temperatures enhancing microbial activity and metabolic rates, which subsequently increases dissolved CO₂ concentrations [19]. Alternatively, this pattern may arise from increased zooplankton abundance and enhanced respiratory activity at higher temperatures [20], contributing to elevated pCO_2 .

(2) Influence of dissolved oxygen:

DO is primarily controlled by the balance between photosynthetic activity and respiratory processes of aquatic organisms [21]. $p\text{CO}_2$ typically exhibits an inverse relationship with DO, as a significant portion of aquatic CO_2 originates from respiratory processes; hence, CO_2 production is typically accompanied by O_2 consumption [22]. A significant negative correlation was observed between longitudinal $p\text{CO}_2$ and DO during the mixed period. During the mixed period, lower WT suppress microbial activity, leading to higher DO concentrations. Elevated DO levels enhance respiratory activity in aquatic organisms, consuming nutrients and potentially shifting carbonate equilibria, ultimately resulting in decreased $p\text{CO}_2$. However, during the stratified period, DO values showed minimal variation. This indicates that, besides biological photosynthesis and respiration, $p\text{CO}_2$ may be controlled by other influencing factors [23].

(3) Influence of dissolved organic carbon:

Sources of DOC in reservoirs include both allochthonous (externally derived) and autochthonous (internally produced) origins [24]. Autochthonous DOC originates from processes such as phytoplankton photosynthesis and bacterial decomposition within the reservoir, while allochthonous DOC primarily stems from the degradation of soil organic matter and anthropogenic discharges [25]. If the organic carbon content in lakes or reservoirs is relatively high, microorganisms will decompose allochthonous dissolved organic carbon; this decomposition process releases CO_2 , which in turn increases the concentration of partial pressure of carbon dioxide in the water [26]. Consequently, a good positive correlation is observed between $p\text{CO}_2$ and DOC concentrations. Conversely, in reservoirs with thin soil layers and low allochthonous DOC inputs, or where phytoplankton actively fix CO_2 through photosynthesis to produce organic matter, $p\text{CO}_2$ often exhibits a negative correlation with DOC concentration [26]. Furthermore, the relatively long hydraulic retention time in reservoirs promotes autochthonous DOC dominance, while the relatively quiescent aquatic environment favours phytoplankton CO_2 consumption via photosynthesis [27]. Consequently, in this study, DOC concentration exhibited a negative correlation with $p\text{CO}_2$ both longitudinally and vertically (Figs. 6 and 7), with significant negative correlations observed during the mixed period longitudinally and the stratified period vertically ($P < 0.05$; Figs. 6b and 7a). Overall, $p\text{CO}_2$ levels were higher during the stratified period compared to the mixed period. This pattern may be attributed to increased rainfall and higher temperatures during the stratified period, elevating inputs of organic matter like DOC [21], intensifying respiratory processes of aquatic organisms, and enhancing DOC degradation to dissolved inorganic carbon, releasing CO_2 into the water, thereby elevating $p\text{CO}_2$.

(4) Influence of dissolved inorganic carbon and alkalinity:

DIC, comprising CO_2 , HCO_3^- , and CO_3^{2-} , constitutes the carbonate system in water. In such high-alkalinity waters, the influence of aquatic phototroph photosynthesis and respiratory degradation of organic carbon on $p\text{CO}_2$ becomes relatively secondary [28]. The linkage between high DIC content and elevated $p\text{CO}_2$ levels is intrinsically tied to the soil characteristics, hydrological conditions, and geomorphological environment of the upper Yellow River cascade reservoir region.

(5) Influence of nutrients (TN, TP):

Nutrients enhancing primary productivity, and supporting aquatic carbon cycling. Long-term sufficient supply of nutrients like N and P can not only promote carbon cycling and primary productivity but also lead to substantial CO_2 emissions [29]. In this study,

vertical $p\text{CO}_2$ during the stratified period showed significant positive correlations with TN and TP (Fig. 7a), aligning with previous research [30]. This positive correlation is primarily attributed to the stimulatory effect of nutrients on microbial metabolic activity. Furthermore, research in Three Gorges Reservoir area showed a significant positive correlation between $p\text{CO}_2$ and TN during the dry season, suggesting nitrogen enrichment boosts biological productivity and consequently CO₂ emissions. Similarly, in a karst river system [31], $p\text{CO}_2$ exhibited a significant coupling relationship with TP, demonstrating that TP variations directly influence riverine $p\text{CO}_2$, supporting the role of TP as a controlling element for microbial metabolism. Collectively, nutrients (e.g., TN, TP) stimulate microbial growth and metabolic activity, increasing biological activity and carbon mineralisation processes within the water body. This enhanced activity leads to greater CO₂ production and consequently higher $p\text{CO}_2$, explaining the observed significant positive correlations [32-34].

(6) Effects on the spatial and temporal variability of reservoir F_{CO_2} :

The diffusive flux of CO₂ at the water-air interface is a key parameter for assessing the source-sink relationship of CO₂ in reservoirs. Similar to $p\text{CO}_2$, the F_{CO_2} of the three reservoirs also exhibited distinct spatiotemporal variations (Fig. 8). Overall, fluxes were slightly higher during the stratified period than during the mixed period, with negative fluxes mainly occurring in the warmer stratified period, likely due to enhanced plant photosynthesis consuming dissolved CO₂.

The study showed that negative CO₂ fluxes occurred at the tail of Longyangxia Reservoir and in the central area of Liujiaxia Reservoir, where average dissolved oxygen levels were higher, consistent with photosynthetic activity. Spatially, Longyangxia and Liujiaxia reservoirs, which displayed clear thermal stratification, released CO₂ in the order: dam front > central zone > tail. This may be attributed to water discharge near the dam increasing flow velocity and thus promoting gas release. In contrast, Liujiaxia Gorge Reservoir showed the opposite trend: tail > central zone > dam front, possibly because this downstream reservoir accumulates nutrients that promote phytoplankton growth, leading to greater CO₂ uptake via photosynthesis.

Throughout the year, $p\text{CO}_2$ values at sampling sites in Liujiaxia Gorge Reservoir were generally higher, likely due to external organic carbon inputs from the Tao River confluence, resulting in greater CO₂ emissions. In summary, the Longyangxia-Liujiaxia reservoir system in the upper Yellow River generally functioned as a carbon "source" to the atmosphere.

In summary, the $p\text{CO}_2$ dynamics in the Longyangxia-Liujiaxia reservoirs result from the complex interplay of multiple factors. Thermal stratification, climatic variations, and inherent reservoir characteristics significantly alter the biogeochemical processes involving aquatic organisms within the carbon cycle, and these alterations ultimately influencing $p\text{CO}_2$ levels [35-63].

(7) A comparison with the reservoirs and lakes in different regions:

A comparison of the Long-Liu reservoir with other reservoirs and lakes across different regions is presented in Table 1. Regionally, the CO₂ fluxes of the three reservoirs fall within the range of northern temperate reservoirs - slightly higher than in some other temperate areas, slightly lower than in subtropical reservoirs, and substantially lower than in tropical reservoirs. The latitudinal pattern (tropical > subtropical > temperate > high frigid) further supports climate as a key controlling factor [58]. Regarding reservoir age, the Long-Liu reservoirs (all >25 years old) show CO₂ flux levels comparable to those of natural

lakes [2] and much lower than reservoirs around five years old [51]. This aligns with Tremblay et al. [55], who found that newly impounded reservoirs emit large amounts of CO₂ due to abundant organic matter in flooded soils, whereas reservoirs over ten years old behave like natural lakes.

Table 1
Comparison of CO₂ fluxes at the water-gas interface in lakes and reservoirs in different regions [40, 42, 55, 57]

Type	Research location	[CO ₂ /(mg/(m ² ·h))]
Northern temperate reservoir	Longyangxia Reservoir, China	23.86
	Nihe Reservoir, China	28.78
	Liujiaxia Reservoir, China	46.62
	Lijiaxia Reservoir, China	47.38
	Res. Porttipahta, Finland	64.2
Temperate lake	Shingobee Lake, America	66.9
	Priest Pot, America	73.3
Subtropical reservoir	Shuibuya, China	27.9-304
Tropical reservoir	Samuel, Brazilian	337

Conclusion

This study investigated three large, deep reservoirs (Longyangxia, Liujiaxia, Liujiaxia) of the upper Yellow River. Utilising hydrochemical equilibrium calculations and the thin boundary layer (TBL) diffusion model, we estimated the $p\text{CO}_2$ and F_{CO_2} across different temporal periods (stratified, mixed) and spatial locations. By integrating these estimates with relevant physicochemical indicators and water quality parameters, we comprehensively analysed the spatiotemporal distribution patterns and influencing factors of $p\text{CO}_2$ and F_{CO_2} . Finally, we compared the CO₂ emission characteristics of these reservoirs with those reported for other global reservoirs and lakes, clarifying the role of the studied reservoirs as net sources or sinks of atmospheric CO₂ during the investigation period. Our conclusions are as follows:

- (1) Spatiotemporal Dynamics of $p\text{CO}_2$: The $p\text{CO}_2$ in the Longyangxia-Liujiaxia reservoirs exhibited significant spatiotemporal variability. $p\text{CO}_2$ ranged from 198 μatm to 1333 μatm during the stratified period and from 364 μatm to 1432 μatm during the mixed period. Spatially, during stratification, longitudinal $p\text{CO}_2$ initially decreased downstream before increasing, while vertically, higher $p\text{CO}_2$ values were observed in surface and bottom waters compared to the intermediate layer. During the mixed period, surface $p\text{CO}_2$ fluctuated longitudinally, but showed minimal vertical variation.
- (2) Key Drivers of $p\text{CO}_2$: Significant positive correlations were observed between $p\text{CO}_2$ and WT , T_{alk} , TN , and TP . Conversely, significant negative correlations were found with DOC and DO . Collectively, $p\text{CO}_2$ distribution was governed by the interplay of thermal stratification, climatic conditions, and inherent reservoir characteristics. These factors altered the biochemical processes of carbon cycling involving aquatic organisms, disrupting the original carbonate equilibrium within the water body, thereby directly influencing $p\text{CO}_2$ levels.
- (3) CO₂ Fluxes and Reservoir Role: The F_{CO_2} across the air-water interface displayed significant seasonal and spatial heterogeneity. Mean F_{CO_2} was slightly higher during the stratified period compared to the mixed period, and exhibited distinct longitudinal distribution patterns between periods. Overall, the Longyangxia-Liujiaxia reservoirs consistently functioned as net sources of atmospheric CO₂ during the study period.

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