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Impact of riverine inputs on nutrient dynamics and water quality in enclosed water bodies

Jinichi Koue[1*]

Abstract

This study investigates the intricate dynamics of nutrient transport and stratification in Lake Biwa, highlighting the significant impact of river inflows on water quality. Utilizing a validated three-dimensional flow field model and ecosystem model including a bottom sediment model, the analysis revealed that nutrient concentrations, specifically NH_4^+, NO_2^-, NO_3^-, and PO_4^{3-}, exhibited pronounced seasonal variations. In the RN_double scenario, NH_4^+ and NO_2^- concentrations demonstrated a slight increase of 0.1 µg/L, respectively, while NO_3^- concentrations rose by 0.05–0.10 µg/L in response to precipitation changes. Conversely, in the RN_half scenario, NH_4^+ and NO_2^- concentrations decreased, with NO_3^- seeing a more substantial decline of approximately 0.1 µg/L, attributed to reduced precipitation. PO_4^{3-} levels exhibited a maximum decrease of 0.03 µg/L from summer to autumn. Furthermore, simulations limiting nutrient inflows indicated a modest reduction in concentrations: NH_4^+ decreased by approximately 0.03 µg/L during summer, and NO_2^- decreased by around 0.05 µg/L from spring to summer. The results suggest that while immediate improvements in dissolved oxygen levels are limited, effective long-term nutrient management could stabilize oxygen concentrations and improve overall water quality. These findings underscore the necessity for comprehensive water management strategies to mitigate eutrophication effects and support the ecological health of Lake Biwa.

Keywords River Inflows, Nutrient Dynamics, Sediment Model, Hydrodynamic Modeling

1 Introduction

In closed water bodies, a complex interplay of physical and biological processes drives the dynamics of the aquatic environment. A key physical phenomenon in these systems is overturning. This process occurs when the thermal stratification, established in spring and summer, weakens during winter due to decreased surface temperatures and seasonal monsoons. As a result, water mixing progresses from the surface to the bottom, leading to a homogenization of water temperature and dissolved oxygen concentrations throughout the water column. Such physical processes have profound implications for the water quality and ecosystem dynamics within closed water bodies.

In these environments, the extended residence time of nutrient-rich waters promotes the proliferation of phytoplankton, which in turn supports the growth of zooplankton and fish species that rely on them as a food source. The biological processes within these ecosystems, including respiration, mortality, predation, and excretion, further influence nutrient dynamics and water quality. Additionally, the inflow of water and nutrients from terrestrial sources, particularly via river inflows, can significantly impact these systems. When river waters with different thermal properties enter a closed water body, they can alter the strength of thermal stratification and induce density currents, leading to substantial mass transport. Furthermore, nutrient-rich river inflows can

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exacerbate eutrophication, significantly affecting the ecological balance of the water body.

Given the intricate interactions among these phenomena, a quantitative understanding of these processes is crucial for the effective management of aquatic environments. Numerous numerical studies have been conducted to elucidate the complex dynamics within closed water bodies (Salk et al. 2022; Keller et al. 2023; Hajiesmaeili et al. 2023).

Lake Biwa, Japan's largest freshwater lake, serves as a critical water resource for the Kansai region and plays an essential role in the local ecosystem and economy. The maintenance and management of Lake Biwa are vital for the sustainable development of the region. However, the water quality of Lake Biwa has deteriorated significantly since the 1950s due to rapid economic growth, culminating in a large-scale freshwater red tide in 1977. Despite efforts to mitigate these issues, ongoing climate change and shifts in land use patterns within the watershed have continued to impact the lake's water quality (Hsieh et al. 2010; Tsugeki et al. 2010).

Recent studies have highlighted the effects of climate change on the lake's thermal regimes, particularly the reduction in winter mixing depths and changes in thermal stratification, which contribute to the depletion of oxygen in deeper waters (Schwefel et al. 2016; Desgué-Itier et al. 2023). Koue (2024a) used a one-dimensional hydrodynamic and water quality model to examine the effects of changes in air temperature, wind speed, and precipitation on dissolved oxygen concentrations in Lake Biwa. Their findings indicate that air temperature changes significantly affect oxygen levels, while variations in wind speed influence oxygen distribution throughout the lake by enhancing vertical mixing. Lai et al. (2013) demonstrated the strong interaction between river inflows and lake dynamics using a hydrodynamic model, further underscoring the importance of these interactions in determining the lake's ecological state. Other studies have explored the impacts of river–lake interactions on ecosystem dynamics under various flow scenarios (Bjørnås et al. 2021).

The objective of this study is to comprehensively investigate the impact of river inflows on the water quality of Lake Biwa using a three-dimensional hydrodynamic model coupled with a three-dimensional water quality model, incorporating a bottom sediment model.

2 Methodology

2.1 Simulation model

2.1.1 Model domain

Figure 1 presents the computational domain of the three-dimensional hydrodynamic and ecosystem model for Lake Biwa. The computational domain is represented by a structured grid. The horizontal model domain spans 36 km by 65.5 km, with a horizontal grid resolution of 500 m. Vertically, the grid is divided with a resolution of 0.5 m from the water surface to the bottom layer, including the bottom mud layer. The x- and y-axes of the grid are aligned with the origin located at the southwest corner of the horizontal plane, while the z-axis extends vertically upward from the lakebed.

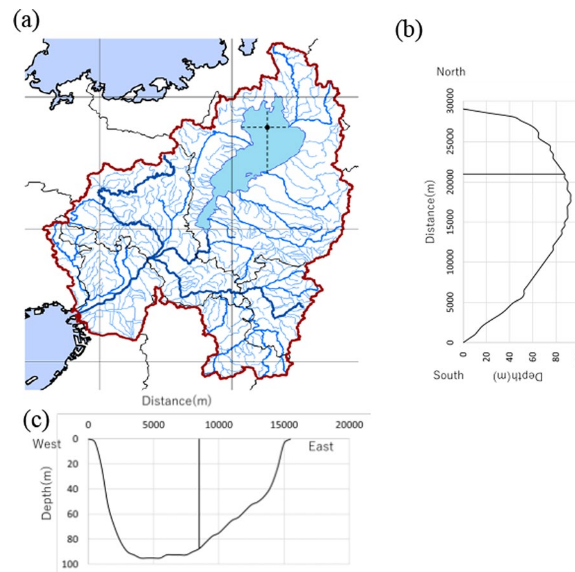

Fig. 1 Model domain in Lake Biwa: (**a**) horizontal domain, (**b**) south-north, and (**c**) west–east vertical cross sections through Imazu-oki

2.1.2 Simulation period

The simulation was conducted over a two-year period, with the first year, from April 1st, 2006 to March 31st, 2007, serving as a warm-up period. The model results were then evaluated over the subsequent year, from April 1st, 2007 to March 31st, 2008.

2.2 Hydrodynamic model

This study employs the three-dimensional hydrodynamic model developed by Koue et al. 2018. This model is designed to simulate the flow dynamics within Lake Biwa, including the computation of flow direction, velocity, and water temperature at each grid point. Data on flow velocity, temperature, and direction obtained from the flow field model are used to calculate the ecosystem model. Figure 2 shows a flowchart of the calculation methods for the flow field model and the ecosystem model.

2.2.1 Governing equations

The hydrodynamic model is grounded in the Boussinesq approximation and assumes hydrostatic equilibrium in

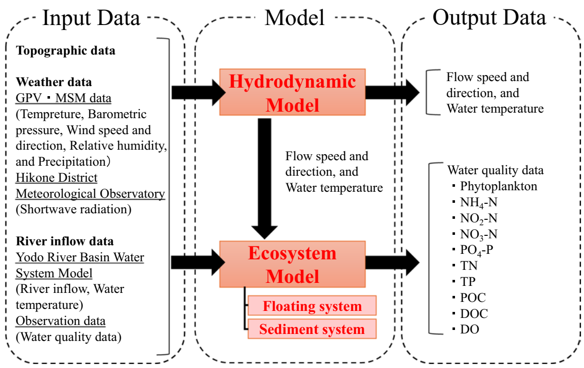

Fig. 2 Flowchart of calculation method

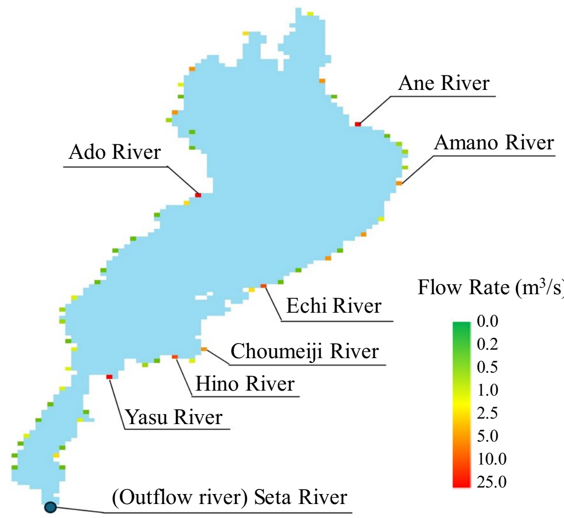

Fig. 3 The position of 56 inflow rivers and one outflow river, and annual mean river inflow

the vertical direction. The governing equations include the Navier–Stokes equations for fluid motion, the continuity equation, and the advection–diffusion equation for water temperature (Koue et al. 2018).

2.2.2 Initial conditions

The initial water temperature on April 1st, 2006, was derived through linear interpolation between temperature measurements taken on March 20th and April 10th, 2006. These measurements were conducted at 10 different depths (0.5 m, 5 m, 10 m, 15 m, 20 m, 30 m, 40 m, 60 m, 80 m, and approximately 90 m) as part of bi-monthly observations carried out by the Lake Biwa Environmental Research Institute at Imazu-oki.

2.2.3 River conditions

To accurately capture the influence of river inflows on Lake Biwa, simulated data were used as boundary conditions in place of direct field observations. Water temperature and discharge rates for 56 rivers were calculated daily by a hydrological model and subsequently interpolated. Figure 3 illustrates the locations of these 56 inflow points and their annual mean discharge rates. The Seta River, the only outflow from Lake Biwa, is located at the lake's southernmost tip, marked by the blue point in Fig. 3. River inflow data were updated daily to ensure precision in the analysis. Boundary conditions for water volume and temperature, corresponding to each river's inflow and outflow, were determined using the hydrological model (Shrestha and Kondo 2015). Figure 4 displays the concentrations of total nitrogen (TN) and total phosphorus (TP) from the seven major inflowing rivers, the average concentrations from all inflowing rivers, and the precipitation data recorded at the Hikone District Meteorological Observatory.

2.3 Ecosystem model

In this study, the vertical one-dimensional ecosystem model originally developed by Koue (2024b) was extended to a three-dimensional framework. This enhanced model integrates 11 state variables, including "phytoplankton (Chlorophyll-a, b, and c)," "zooplankton," "suspended organic matter (POC)," "dissolved organic matter (DOC)," "ammonium nitrogen (NH_4-N)," "nitrite nitrogen (NO_2-N)," "nitrate nitrogen (NO_3-N)," "phosphate phosphorus (PO_4-P)," "dissolved oxygen (DO)," "total nitrogen (TN)," and "total phosphorus (TP)." The model quantitatively tracks the dynamic changes

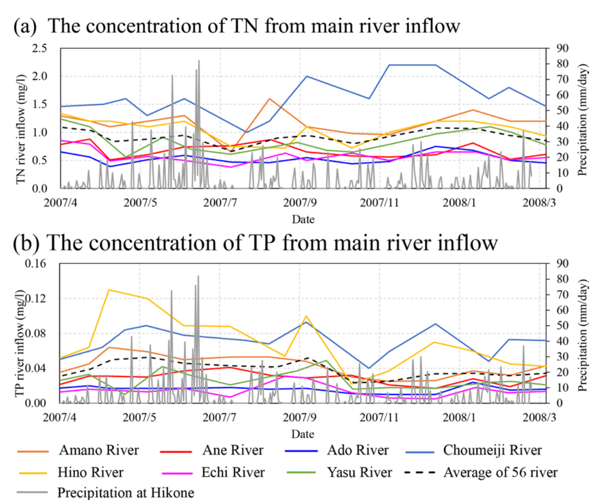

Fig. 4 The concentration of TN and TP from main river inflow and the average value of all inflow rivers. **a** The concentration of TN from main river inflow, **b** The concentration of TP from main river inflow

in the concentrations of these variables. Additionally, to account for the oxygen consumption and nutrient dynamics within the sediment, the sediment model was incorporated as a sub-model in this model within the broader ecosystem framework.

2.3.1 Governing equations

The water quality calculations are based on solving the vertical advection–diffusion equation to determine the mean concentration of each layer. The model accounts for the influence of chemical and biological processes, as well as diffusion, on each component. The temporal variation of these processes is described by the following equation:

$$\frac{\partial C_i}{\partial t} + u\frac{\partial C_i}{\partial x} + v\frac{\partial C_i}{\partial y} + w\frac{\partial C_i}{\partial z} = \kappa_h\frac{\partial^2 C_i}{\partial x^2} + \kappa_h\frac{\partial^2 C_i}{\partial y^2} + \kappa_z\frac{\partial^2 C_i}{\partial z^2} + Q_{C_i} \tag{1}$$

The left-hand side of the equation represents the time-dependent term, while the right-hand side accounts for diffusion and changes resulting from chemical and biological processes (Q_{C_i}). The suspended sediment dynamics are detailed in Table 1, whereas the bottom sediment dynamics are presented in Table 2.

2.3.2 River conditions

The nutrient concentrations in the inflow water of 7 rivers (Ane, Amano, Echi, Hino, Yasu, Azumi, and Chomeiji) were input based on observed values, while the other 49 rivers were input based on the average of the 7 major rivers.

For the 9 variables considered in this study, POC, DOC, NH_4-N, NO_2-N, NO_3-N, TN, PO_4-P, and TP, the simulation was performed by setting conditions based on the coefficient of variation CV for each variable from 2007 to 2014 (Table 3). RN stands for the volume of concentration of river nutrients. The coefficient of variation CV (σ/μ) was calculated from the mean value (μ) and standard deviation (σ) of the daily mean of each variable. The coefficient of variation CV (σ/μ) is 49.1% for POC, 23.6% for DOC, 44.0% for NH_4-N, 30.4% for NO_2-N, 25.1% for NO_3-N, 16.0% for TN, 28.6% for PO_4-P and 23.6% for TP. Cases were set up for nutrient concentrations to be double and half the observed values, and for +CV/2 and −CV/2 of the mean of each variable in 2014 to be the upper and lower limits.

3 Results

3.1 Effects of changes in nutrient concentrations in inflowing rivers

The reproducibility of this flow field model, as validated against observed water temperature data, has been demonstrated by Koue et al. (2018), yielding favorable results. The one-dimensional ecosystem model has been shown to effectively represent nutrient concentrations (Koue (2024b); in this study, it was further extended to a three-dimensional model. Figure 5 depicts the seasonal variations in the differences of (a) NH_4-N, (b) NO_2-N, (c) NO_3-N, (d) PO_4-P, and (e) DO between the BASE and

Table 1 Balance equations for each chemical and biological process (Floating system)

Phytoplankton	Phytoplankton Growth by photosynthesis—Phytoplankton respiration—Predation by zooplankton—Sedimentation—Extracellular secretion—Death
Zoo plankton	Growth by phytoplankton feeding—Zooplankton death—Zooplankton feces—Zooplankton excretion by respiration
POC	Phytoplankton die-off + Zooplankton feces + Natural mortality of zooplankton—Mineralization of suspended-Form organic matter—Generation of decomposition surplus + sedimentation of suspended-form organic matter
DOC	Extracellular secretion + decomposition surplus generation—mineralization of dissolved organic matter by aerobic bacteria
NH_4-N	-Phytoplankton ingestion by photosynthesis + phytoplankton respiration + zooplankton excretion by respiration + mineralization of suspended organic matter + mineralization of dissolved organic matter by aerobic bacteria + leaching of nitrogen from bottom sediment—nitrification of ammonia-form nitrogen
NO_2-N	Nitrification of ammonia nitrogen—Nitrite nitrogen
NO_3-N	-Phytoplankton uptake by photosynthesis + Nitrification and denitrification of nitrite nitrogen
PO_4-P	-Phytoplankton ingestion by photosynthesis + phytoplankton respiration + zooplankton excretion by respiration + mineralization of suspended organic matter + mineralization of dissolved organic matter by aerobic bacteria + leaching of phosphorus from bottom sediment
DO	Supply by photosynthesis—Consumption by respiration of phytoplankton—Consumption by respiration of zooplankton—Oxygen consumption by suspended-form organic matter—Oxygen consumption by dissolved-form organic matter—Oxygen consumption by nitrification of ammonia nitrogen—Oxygen consumption by nitrite nitrogen
TN	N/C ratio in phytoplankton* amount of variation in phytoplankton + N/C ratio in zooplankton* amount of variation in zooplankton + N/C ratio in POM* amount of variation in POM + N/C ratio in DOM* amount of variation in DOM -Variable amount of TOC + Variable amount of ammonia nitrogen + Variable amount of nitrite nitrogen + Variable amount of nitrate nitrogen
TP	P/C ratio in phytoplankton* variation in phytoplankton + P/C ratio in zooplankton* variation in zooplankton + P/C ratio in POM* variation in POM + P/C ratio in DOM* D Fluctuation in -TOC + Fluctuation in phosphate-form phosphorus

Table 2 Balance equations for each chemical and biological process (Sediment System)

Substrate	IN	Sedimentation + decomposition of organic nitrogen in bottom sediment (anaerobic/aerobic) + adsorption/desorption on mud particles
	IP	Sedimentation + decomposition of organic phosphorus in bottom mud + adsorption/desorption on mud particles + adsorption/desorption on pore water (anaerobic/aerobic)
	ON	Sedimentation—Decomposition in bottom sediment (anaerobic/aerobic)
	OP	Sedimentation—Decomposition in Sediment
	TOC	Sedimentation—Decomposition in Sediment
Pore water	NH_4–N	Decomposition of organic nitrogen in sludge (anaerobic/aerobic)—adsorption/desorption on mud particles + diffusion—nitrification to nitrite nitrogen
	NO_2–N	Diffusion + nitrification from ammonia nitrogen—nitrification to nitrate nitrogen
	NO_3–N	Diffusion + nitrification from nitrite-nitrogen—denitrification
	PO_4–P	Degradation of organic phosphorus in bottom sediment—adsorption/desorption on mud particles + diffusion + adsorption/desorption in pore water (anaerobic/aerobic)
	TOC	Decomposition + diffusion—dissolution of organic matter in bottom sediment
	DO	Diffusion—Oxygen consumption associated with nitrification of ammonia nitrogen—Oxygen consumption associated with nitrite nitrogen—Oxygen consumption associated with decomposition of organic matter

Table 3 Scenarios in numerical experiments

Case name	Nutrient concentration
BASE	Original
RN_double	Double
RN_half	Half
RN_+CV/2	+CV/2 (Upper)
RN_−CV/2	−CV/2 (Lower)

RN_double or half scenarios in the surface layer (0.5 m), thermocline (20 m), and deep layer (90 m) at Imazu-oki from 2007 to 2008.

For the RN_double scenario, NH_4-N concentrations at Imazu-oki increased by 0.1 μg/L during spring to summer (April-August) and winter (December-February), but remained unchanged during fall (September–November). This suggests a seasonal variation in river inflows for that year. NO_2-N concentrations also increased by approximately 0.10 μg/L during the same periods as NH_4-N, with decreases noted in the fall, reflecting changes in precipitation (Fig. 4). The nitrification of NO_2-N to NO_3-N was influenced by oxygen concentration, with NO_3-N rising by 0.05–0.10 μg/L from spring to winter in response to precipitation changes.

In the RN_half scenario, concentrations of NH_4-N and NO_2-N decreased, while NO_3-N concentrations saw a more substantial decline compared to NH_4-N and NO_2-N. It was considered in general that the reduction in NO_3-N was notably affected by decreased precipitation. PO_4-P concentrations varied with precipitation levels. Dissolved oxygen (DO) concentrations showed a slight decrease with increasing nutrient levels and a slight increase with decreasing nutrient levels.

Figures 6, 7, 8, 9, 10 illustrate the nutrient concentrations of NH_4-N, NO_2-N, NO_3-N, and PO_4-P in the surface layer of Lake Biwa, with RN_double shown in the upper panels and RN_half in the lower panels. The nutrient concentrations are depicted for May 15th, 2007, August 15th, November 15th, 2007, and February 15th, 2008, from left to right. In the RN_double scenario, high NH_4-N concentrations were observed, particularly from major rivers from spring to fall, with the Choumeiji River exhibiting especially high levels. For NO_2-N, elevated concentrations were noted from the Ane, Amano, Echi, Hino, Yasu, Ado, and Choumeiji Rivers during spring and summer, while NO_3-N concentrations remained relatively low. PO_4-P levels were notably high in the Hino and Choumeiji Rivers and their surrounding areas. Nutrients flowed along the lakebed, with a more pronounced impact on the central lake region in the RN_double scenario compared to RN_half. Variations in river nutrient inflow caused fluctuations in nearshore nutrient levels, with minimal impact on offshore bottom areas. This reflected annual nutrient fluctuations, with accumulating nutrients affecting oxygen concentrations over time.

According to Koue (2023), river-induced changes in water temperature and density flow can alter the strength of lake stratification and thus affect vertical mixing processes and the distribution of dissolved oxygen, which are essential elements for maintaining the ecological balance of a lake. On the other hand, it is clarified that an increase or decrease in nutrient concentrations in the inflow river alters the distribution of each nutrient concentration in the area surrounding the inflow river, but has little effect on the offshore area.

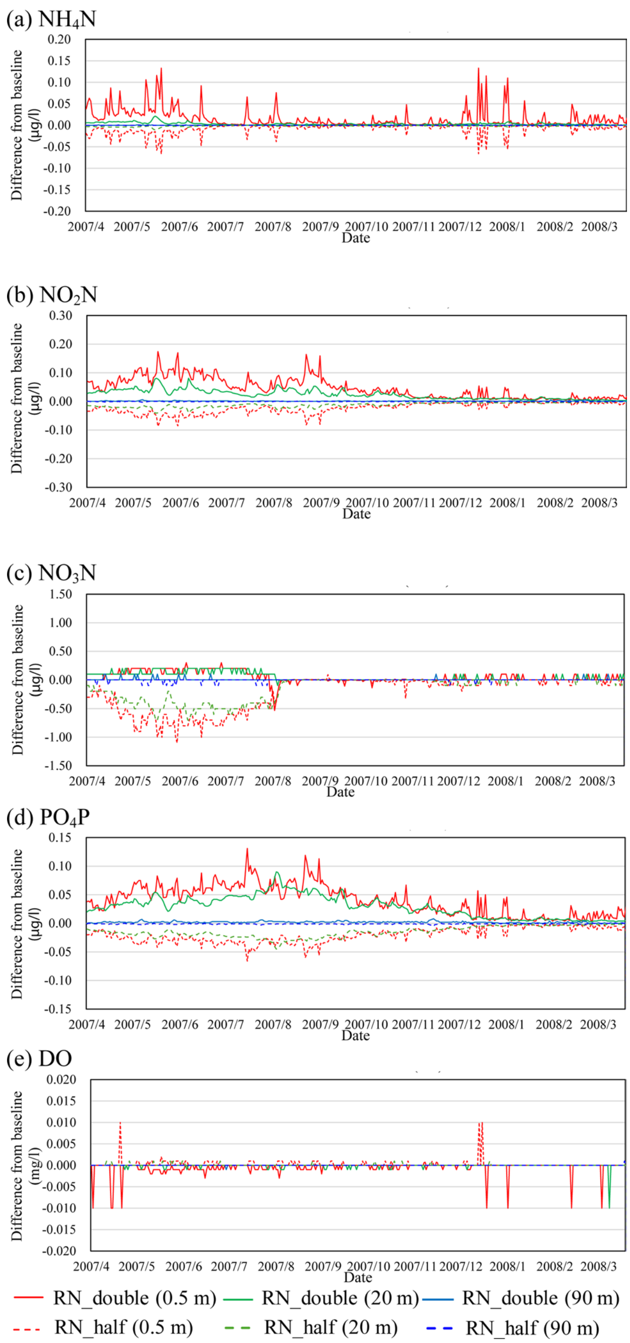

Fig. 5 Seasonal change of difference of (**a**) NH_4-N, (**b**) NO_2-N, (**c**) NO_3-N, (**d**) PO_4-P, and (**e**) DO between BASE and RN_double, or half in the surface layer (0.5 m depth), thermocline (20 m depth) and deep layer (90 m depth) from 2007 to 2008 at Imazu-oki

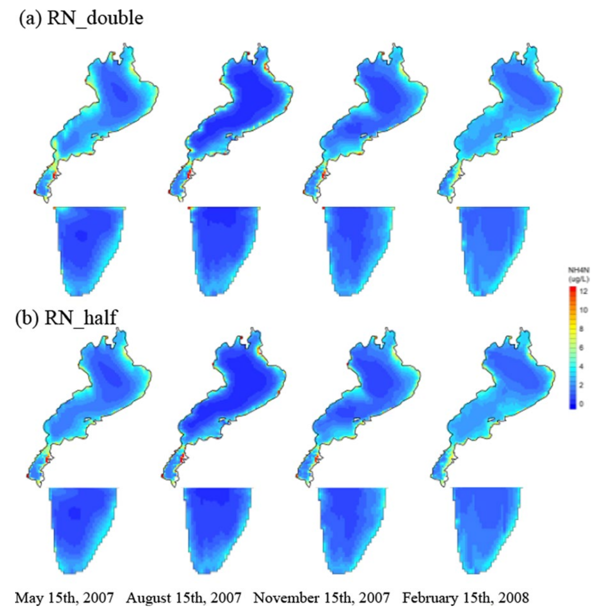

Fig. 6 Concentrations of NH_4-N in the surface layer and vertical section from east to west through the Imazu-oki in Lake Biwa, with (**a**) RN_double and (**b**) RN_half

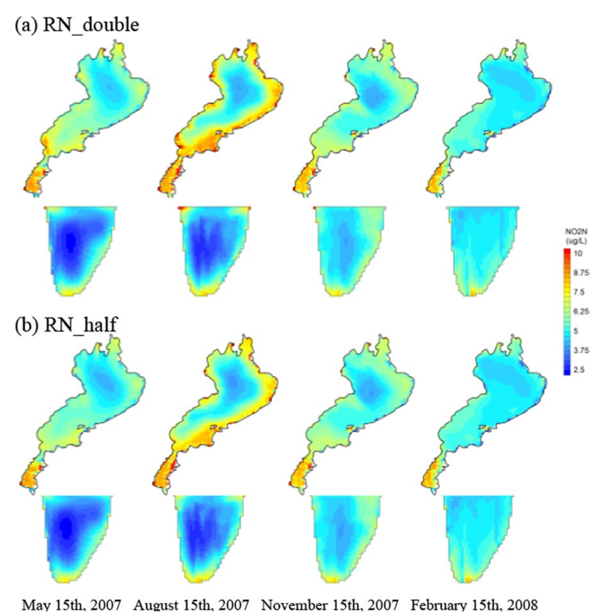

Fig.7 Concentrations of NO_2-N in the surface layer and vertical section from east to west through Imazu-oki in Lake Biwa, with (**a**) RN_double and (**b**) RN_half

3.2 Changes in offshore nutrient concentrations when nutrient levels in river inflows are restricted

Figure 10 depicts the seasonal variations in the differences of (a) NH_4-N, (b) NO_2-N, (c) NO_3-N, (d) PO_4-P, and (e) DO between the BASE and RN_ ± CV/2 scenarios in the surface layer (0.5 m), thermocline (20 m), and deep layer (90 m) at Imazu-oki from 2007 to 2008. As a method of setting a limit on the inflow of nutrients in each river, the mean value and standard deviation of each nutrient from 2007 to 2014 were determined, and

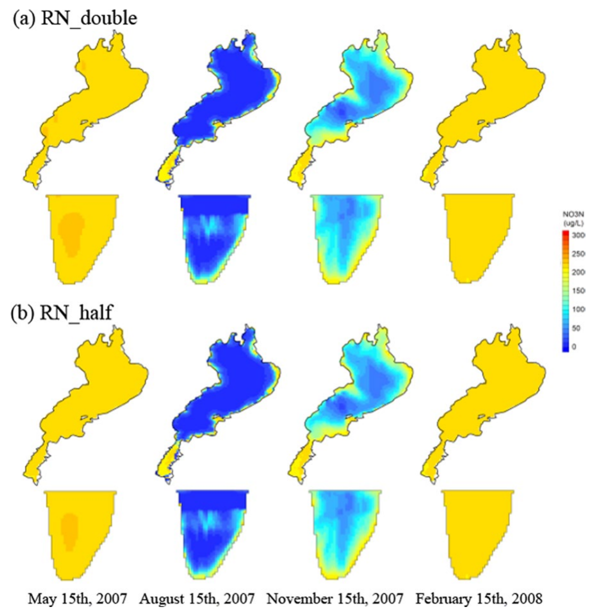

Fig. 8 Concentrations of NO_3-N in the surface layer and vertical section from east to west through Imazu-oki in Lake Biwa, with (**a**) RN_double and (**b**) RN_half

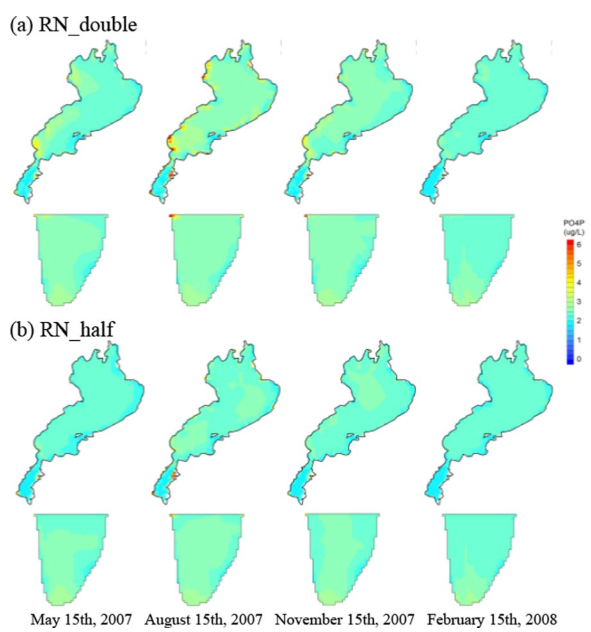

Fig. 9 Concentrations of PO_4-P in the surface layer and vertical section from east to west through Imazu-oki in Lake Biwa, with (**a**) RN_double and (**b**) RN_half

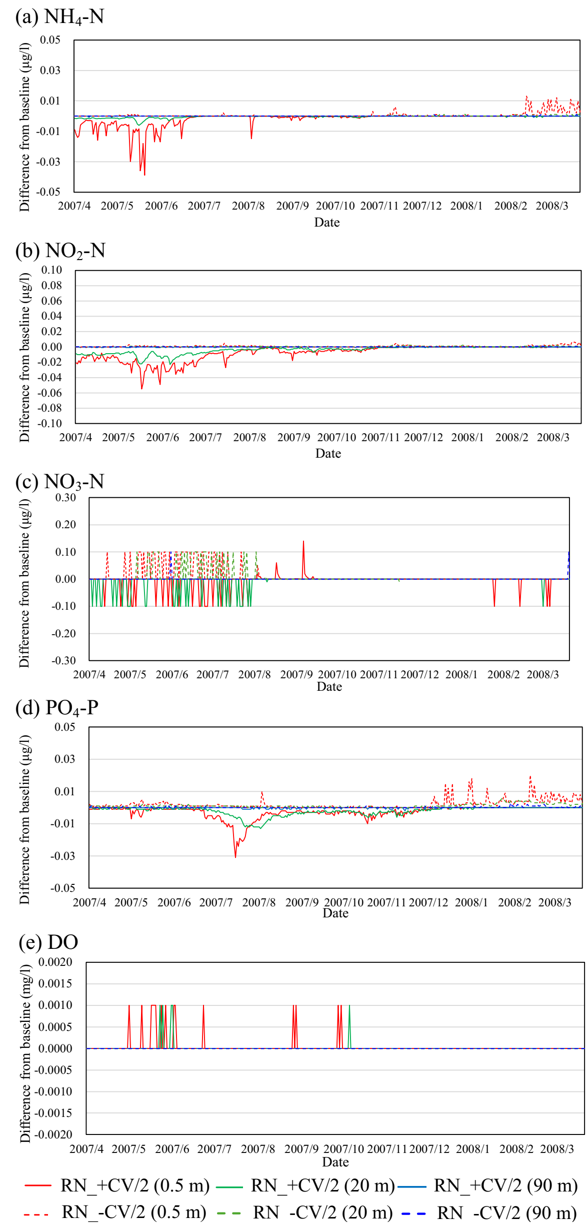

Fig. 10 Seasonal change of difference of (**a**) NH_4-N, (**b**) NO_2-N, (**c**) NO_3-N, (**d**) PO_4-P, and (**e**) DO between BASE and RN_+CV/2, or –CV/2 in the surface layer (0.5 m depth), thermocline (20 m depth) and deep layer (90 m depth) from 2007 to 2008 at Imazu-oki

when the inflow of each nutrient was regulated within the range of increasing and decreasing up to 1/2 of the deviation, how the nutrient concentration at Imazu-oki within Lake Biwa would change was analyzed. Simulations with upper and lower limits for nutrient inflow were performed considering water quality standards for water discharge at a storage dam that controls the amount of river water entering Lake Biwa. Water quality limits feasible in terms of dam performance were considered as a countermeasure in the event of climate change. According to the results, when the upper limit of increase in each nutrient concentration was restricted to 1/2 of the standard deviation, NH_4-N decreased by about 0.03 μg/l in summer; NO_2-N decreased by about 0.05 μg/l from spring to summer; NO_3-N was originally difficult to change but decreased by 0.1 μg/l; PO_4-P decreased from summer to autumn by decreased by up to 0.03 μg/l. DO was almost unchanged but increased slightly.

These results indicate that limiting nutrient inflows in each river resulted in a small but significant decrease in nutrients in the central part of the North Lake, offshore of Imazu. If this is restricted over time, there could be a significant impact on the central part of the North Lake.

In this scenario, no significant changes in dissolved oxygen concentrations due to limitation of incoming nutrient concentrations were observed in the short term. However, long-term management of nutrient concentrations may result in greater fluctuations in dissolved oxygen concentrations due to nutrient accumulation.

4 Conclusions

This study meticulously elucidates the intricate dynamics of nutrient transport and stratification in Lake Biwa, highlighting the substantial impact of river inflows on the lake's water quality. Utilizing sophisticated three-dimensional modeling techniques, this research demonstrates how variations in nutrient concentrations from river inflows significantly influence the seasonal and spatial distribution of essential nutrients, including NH_4^+, NO_2^-, NO_3^-, and PO_4^{3-}, within the lake ecosystem.

The analysis reveals pronounced seasonal variations in nutrient concentrations, with NH_4^+, NO_2^-, and PO_4^{3-} peaking during spring and summer. These elevated concentrations correlate with increased river inflows, underscoring the crucial role of seasonal precipitationin driving nutrient loading and subsequent water quality fluctuations. Notably, nutrient-rich inflows from major rivers, such as the Choumeiji River, significantly impact the spatial distribution of nutrients within the lake, leading to localized areas of high nutrient concentration. It can be considered that elevated nutrient inflows exacerbate eutrophication, contributing to increased phytoplankton biomass and affecting downstream components of the aquatic ecosystem, including zooplankton and fish populations.

Scenario analysis, designed to limit nutrient inflows, indicates a modest reduction in concentrations of NH_4^+ and NO_2^-, along with a trend towards decreased NO_3^- and PO_4^{3-} levels. These findings suggest that while immediate improvements in oxygen levels are modest, strategic nutrient management over time could lead to more substantial benefits, including enhanced stabilization of oxygen concentrations and improved overall water quality.

The study underscores the necessity for comprehensive and integrated water management strategies that address both hydrodynamic and nutrient dynamics. Effective management of river inflows is essential for mitigating the effects of eutrophication and ensuring the long-term ecological health of Lake Biwa. By advancing understanding of the complex interplay between physical and biological processes in this closed water body, this research provides valuable insights crucial for developing informed and effective management practices, thereby supporting the sustainable development and ecological preservation of the surrounding region.

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Author contributions
Jinichi Koue designed the research plan, executed the numereical simulation, analyzed the data, and wrote the manuscript.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Competing interests
The authors declare no competing interests.

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