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Stimulating effects of submerged plants on removing of N from the water in the Daihai lake of inner Mongolia autonomous region, China

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The Daihai Lake, the third largest lake in Inner Mongolia Autonomous Region, is the cornerstone to maintain the ecosystem balance in this region, which is facing some problems including size shrinking, water quality declining and biodiversity decreasing largely in recent years. In order to quantify the N purification amount of submerged plants, Stella software was used in this study to construct a nitrogen dynamic model to simulate the nitrogen cycle process in the Daihai Lake and the participation of submerged plants in this cycle process. The results showed that based on the submerged plant growth area in 2019 in the Daihai Lake, the N uptake by submerged plants this year was 5.13t, accounting for 4.8% of all exogenous pollution (107.895t), Moreover, our model also predicted that the purification capacity of the restored submerged plants with a large area of 9.91 km^2 in the Daihai Lake was significantly higher than before restoration. And the N pollution load of 107.892t in the Daihai Lake could be purified by this stored pattern in 12 years, while during this process a regular cleaning of submerged plant residues was required. Therefore, only large area restoration of submerged plant would benefit for improving water quality.

KEYWORDS

Daihai lake, submerged plant, modelling, nitrogen removal, ecological restoration

1 Introduction

The Daihai Lake is located in Ulanqab City, Inner Mongolia Autonomous Region, which is located in the transitional zone of semi-humid and semi-arid (Yunkai et al., 2006). It is a typical inland lake on the Mongolian Plateau, and an important barrier to maintain the ecological balance of the Mongolian Plateau. It is of great significance to maintain regional groundwater stability, atmospheric humidity, and curb desertification of the surrounding grassland (Zhou and Jia, 2009). In recent years, due to the interaction of human activities and climate change, some problems such as shrinking lake surface, decreasing water volume, increasing eutrophication and decreasing ecological diversity have gradually occurred in Daihai lake. Moreover, algal blooms, vanishing fish and a decline in submerged plant species are further aggravating the deterioration of the lake's ecosystem (Shen et al., 2001; Liang et al., 2021). Nitrogen is an important indicator of pollution monitoring and eutrophication

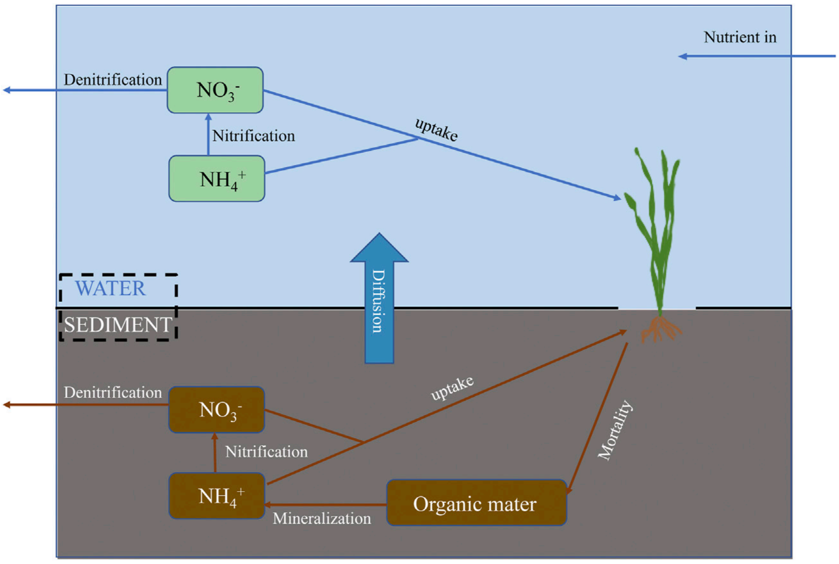

FIGURE 1
Model Concept map.

in lakes in the Mongolian Plateau (Huang et al., 2020), and then one of the most vital elements required for the growth of submerged plants (Zixian et al., 2011; Chen et al., 2013). Submerged plants can absorb a large amount of nitrogen from water during their growth, which play an excellent role in purifying water quality (Wu and Zhao, 2015). The nitrogen cycle in shallow lakes is relatively complex, and some relevant mathematical models can quantitatively analyze the nitrogen flow in lakes (Small et al., 2014; Wu et al., 2018). At present, the widely used nitrogen cycle models include WAPS model (Wang, 2022), Monod model (Saeed and Sun, 2011), CW2D model (Langergraber et al., 2009), etc., These models have strong analytical ability, while their structures are very complex and difficult to popularize and apply in the Daihai lake. Stella software with a friendly user interface can quickly transform the nitrogen cycle concept map into a model and also support the input of various kinetic formulas (Costanza et al., 1998; Mecca et al., 2004). At present, most of the models to describe the nitrogen cycle constructed by Stella software are mainly applied to study the mechanism of nitrogen removal of wetland plants based on the law of conservation of mass (Mayo et al., 2018; Dong et al., 2020), which show the nitrogen removal effects of plants on wetland restoration.

It is generally realized that two alternative states exist in the shallow lakes with average depth less than 3 m, which include a clear-water state dominated by macrophytes and a turbid water state dominated by phytoplankton (Moss et al., 1990; Van den Berg et al., 1996; Scheffer et al., 2003; Scheffer and Jeppesen, 2007), and a transition may occur between the two states under a special level of nutrient loading (Janse, 1997). Presently, a considerably general improvement in water quality, by bio-manipulation over the past decades, is witnessed in the shallow lakes, as induced the big growth area of submerged plant. The restoration of submerged plants is of great significance to the treatment of lake eutrophication, and a reasonable restoration area of submerged plants is a key step to solve the eutrophication of the Daihai Lake. Therefore, in this paper, an ecological dynamics model was established by Stella software to simulated the nitrogen cycling process including nitrification, mineralization, denitrification, diffusion and plant assimilation as well as litter decomposition after submerged plant death in the Daihai Lake and focused on the following goals: 1) To determine annual N purification amount before and after recovery of submerged plants. 2) To predict the purification time of pollution load by submerged plant under the assumption of constant external input.

2 Materials and method

2.1 The study site

The Daihai Lake (40°32′-40 36′N, 112 37’–112° 45′E) is a typical inland closed saline lake in the central and southern Mongolian Plateau and located in a temperate semi-arid region (Figure 1). The rivers entering the Daihai Lake are seasonal rivers, which flow into the Daihai Lake in rainy summer and cut off in winter. The average annual temperature is 5.1°C.

2.2 Development of the mathematical model

The state variables in the model are mainly about different nitrogen contents in the lake and plants, which are shown in Figure 1. These state variables are connected to each other by the flow of nitrogen. This model is divided into three parts based on nitrogen state variables and related parameters (Table 1) including nitrogen transformations in water and soil, submerged plant growth processes and the effects of temperature on some processes. The

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TABLE 1 The parameters and constants in the model.

Var	Description	Value	Eq	Source
Knitw	Nitration rate constant	0.06	Eq 1b	Wang (2022)
θ_1^{TW-20}	Nitrification temperature correction factor	1.07	Eq 1b	Wang (2022)
rtemp	The relation between air temperature and process rate	variable	Eq 10	calculated from Eq 10
leachingrate	Leaching rate constants	0.432	Eq 1c	van der Peijl and Verhoeven, (1999)
θ_2^{TW-20}	Leaching temperature correction factor	0.6	Eq 1c	van der Peijl and Verhoeven, (1999)
c_turbdif	Bioturbation factor	5	Eq 1d	calibration
c_tep	Diffusion temperature parameter	1.02	Eq 1d	van der Peijl and Verhoeven, (1999)
Kdif	Ammonia nitrogen diffusion rate constants	0.000784	Eq 1d	van der Peijl and Verhoeven, (1999)
porosit	Porosity of the soil	0.8	Eq 1d	calibration
deepthdif	Depth of sediment	0.05	Eq 1d	calibration
nh4_outer	Ammonia nitrogen discharged into the lake	0.02	Eq 1a	calibration
no3_outer	Nitrate nitrogen discharged into the lake	0.04	Eq 2a	calibration
TK	Step function of time	(0,1)	Eq 1a,Eq 2a	Field data
Kdenw	Denitrification rate constant	0.1	Eq 2c	Wang (2022)
θ_3^{TW-20}	Denitrification temperature correction factor	1	Eq 2c	Wang (2022)
Kde	Mineralization rate constant	0.085	Eq 3a	Wang (2022)
θ_4^{TW-20}	Mineralization temperature correction factor	1.08	Eq 3a	Wang (2022)
Ksn	Nitration rate constant in soil	0.04	Eq 3b	Boyd (1970)
θ_5^{TW-20}	Nitrification temperature correction factor in soil	1.035	Eq 3b	Boyd (1970)
λ_{do}	Dissolved oxygen correction factor	0.6 mg/L	Eq 3b	Boyd (1970)
DO	Dissolved oxygen concentration	3.24 mg/L	Eq 3b	Field data
fragw	Plant shoot fragmentation rate	0.00193	Eq 5a	van der Peijl and Verhoeven, (1999)
frags	Plant root fragmentation rate	0.00584	Eq 6a	van der Peijl and Verhoeven, (1999)
rdrsh	Death rate of above-ground plant	0.04	Eq 5b	esitimate
rdrro	Death rate of below-ground plant	0.01	Eq 6b	esitimate
n_de_w	Amount of N required by the above-ground plant	variable	Eq 8	calculated from Eq 8
n_de_s	Amount of N required by the below-ground plan	variable	Eq 9	calculated from Eq 9
KNO3	Half-saturation constants of nitrate nitrogen uptake by plants	3	Eq 7a Eq 7c	Dong et al. (2020)
KNH	Plant absorption of ammonia nitrogen half-saturation constant	4	Eq 7b Eq 7d	Dong et al. (2020)
rho25	Relative process rate at 25°C	0.79	Eq 10	van der Peijl and Verhoeven, (1999)
temp_air	Temperatures	variable	Eq 10	Local weather station
Ha	The enthalpy of activation of the reaction catalysed by the enzyme	6474 cal/mol	Eq 10	van der Peijl and Verhoeven, (1999)
Hh	Change in enthalpy associated with high temperature inactivation	68,584 cal/mol	Eq 10	van der Peijl and Verhoeven, (1999)
Hi	Change in enthalpy associated with low temperature inactivation	−343,181 cal/mol	Eq 10	van der Peijl and Verhoeven, (1999)
Th	Temperature at which half of the negative effect of high temperature is effective	304 K	Eq 10	van der Peijl and Verhoeven, (1999)
Ti	Temperature at which half of the negative effect of low temperature is effective	273 K	Eq 10	van der Peijl and Verhoeven, (1999)
R	Gas constant	1,987 cal/K/mol	Eq 10	van der Peijl and Verhoeven, (1999)
sloar	Total solar radiation	4323.72 kcal/m2	Eqs. 8, 9	Local weather station
k1	Solar energy efficiency	0.025	Eqs. 8, 9	Ahn and Mitsch (2002)
k2	Bio-energy ratio per unit	4.1	Eqs. 8, 9	Ahn and Mitsch (2002)
k3	Growth period function	(0,1)	Eqs. 8, 9	Ahn and Mitsch (2002)
k4	Nitrogen absorption efficiency in water	0.02	Eqs. 8, 9	Ouyang et al. (2011)

nitrogen transformation module simulates the processes of nitrification, denitrification and the diffusion of nitrogen from the sediment to the water, as well as the effect of exogenous pollution on nitrogen concentrations in water column. The submerged plant growth module described plant growth by its photosynthesis and absorption of nutrients from water and soil. The effects of temperature on a number of nitrogen transformation processes are obtained by the temperature effect module.

The state variables in the model include ammonia nitrogen content in water (Eq 1), nitrate nitrogen content in water (Eq 2), ammonia nitrogen content in soil (Eq 3), nitrate nitrogen content in soil (Eq 4), nitrogen content of plant carcasses located in the above ground portion (Eq 5), nitrogen content of plant carcasses located in the below ground portion (Eq 6), and nitrogen content stored in plants (Eq 7). The parameters that appear in the equations are detailed in Table 1.

The Eq 1 for the state variable representing the amount of ammonia nitrogen in the water is as follows:

$$NH4\_W(t) = NH4\_W(t-dt) + (in1 + le + di1 - niw - up1)^{*}dt \quad (1)$$

where NH4_W represents the concentration of ammonia in water; in1, le, di1, niw and up1 represent the increase in ammonia concentration in water due to surface pollution, and the leaching rate, diffusion rate, nitrification rate in water, and the rate of ammonia uptake by plants, respectively. The leaching rate, ammonia diffusion rate and nitrification rate are all simulated using first-order reaction kinetics (Martin and Reddy, 1997; van der Peijl and Verhoeven, 1999; Huang et al., 2020; Wang, 2022), as shown in Eqs 1b–d.

$$niw = NH4\_W^{*}Knitw^{*}\theta_1^{TW-20*}rtemp \tag{1b}$$

$$le = N\_LITTER\_W^{*}Leachingrate^{*}\theta_2{}^{TW-20} \tag{1c}$$

$$di1 = (NH4\_S - NH4\_W)^{*}c\_turbdif^{*}c\_tep^{*}Kdif^{*}porosity^{\frac{porosity+1}{deepthdif}} \tag{1d}$$

The Eq 2 for the state variable representing the nitrate-nitrogen content of the water is as follows:

$$NO3\_W(t) = NO3\_W(t-dt) + (niw + in2 - up2 - di2 - dnw)^{*}dt \tag{2}$$

where NO3_W is the concentration of nitrate-nitrogen in water; In 2 represents the increase in nitrate-nitrogen concentration in water brought about by surface source pollution, similar to that produced by surface source pollution in Eq 1, with the introduction of a time-step function Tk, which, according to the actual situation in Daihai (Chapter 4.1), reinforces the effect of seasonal changes on the state variables in the model (Zheng and Men, 2020), as detailed in Eq 1a, Eq 2a.

$$in1 = nh4\_outer^{*}TK \tag{1a}$$

$$in2 = no3\_outer^{*}TK \tag{2a}$$

where up2, di2 and dnw represent the rate of nitrate nitrogen uptake by plants, which are the rate of nitrate nitrogen diffusion and the rate of denitrification (Boyd, 1970; van der Peijl and Verhoeven, 1999; Wang, 2022),respectively. The nitrate diffusion rate and denitrification rate are simulated using first-order reaction kinetics, as detailed in Eqs 2b, c.

$$di2 = (NO3\_S - NO3\_W)^{*}c\_turbdif^{*}kdif\_NO3^{*}porosity^{\frac{porosity+1}{deepthdif}} \tag{2b}$$

$$dnw = NO3\_W^{*}Kden^{*}\theta_3^{TW-20} \tag{2c}$$

The Eq 3 for the state variable representing the amount of ammonia nitrogen in the sediment is as follows:

$$NH4\_S(t) = NH4\_S(t-dt) + (dec - up3 - nis - di1)^{*}dt \tag{3}$$

where NH4_S is the concentration of ammonia nitrogen in the sediment; dec, up3 and nis represent the rate of mineralisation, the rate of ammonia nitrogen uptake by plants, and the rate of nitrification in the sediment, respectively. The mineralization rate was simulated using first-order kinetics (Mayo et al., 2018), and the nitrification in the sediment introduced the effect of dissolved oxygen on the rate (Brown and Barnwell, 1987; Brix et al., 2002). as detailed in Eqs 3a, b

$$nis = Ksn^{*}rtemp^{*}\theta_5^{TW-20*}\left(1 - e^{-\lambda_{do}{}^{*}DO}\right)^{*}NH4\_S \tag{3a}$$

$$dec = N\_SOIL\_OM^{*}K_{de}{}^{*}\theta_4^{TW-20} \tag{3b}$$

The Eq 4 for the state variable representing the nitrate-nitrogen content of the sediment is as follows:

$$NO3\_S(t) = NO3\_S(t-dt) + (di2 + nis - up4 - dns)^{*}dt \tag{4}$$

Where NO3_S is the concentration of nitrate nitrogen in the sediment mg/L; up4 and dns are the rate of nitrate nitrogen uptake by plants and denitrification rate respectively. Denitrification rates were simulated using first-order reaction kinetics (Ying et al., 2009), as detailed in Eq 4a.

$$dns = NO3\_S^{*}Kden^{*}\theta_3^{TW-20} \tag{4a}$$

The state variables representing the nitrogen content of the plant carcasses were divided into an above-ground and below-ground fraction, with the following Eqs 5, 6.

$$N\_LITTER\_W(t) = N\_LITTER\_W(t-dt) + (desh - frw - le)^{*}dt \tag{5}$$

$$N\_LITTER\_S(\mathrm{t}) = N\_LITTER\_S(t-dt) - (dero - frs)^{*}dt \tag{6}$$

where N_LITTER_S and N_LITTER_W represent plant residues in sediment and water, respectively, and desh, frw, dero and fes represent the rate of nitrogen reduction in submerged plants and the rate of decomposition of submerged plant residues due to submerged plant mortality (van der Peijl and Verhoeven, 1999; Zhang et al., 2003; Gao et al., 2018), respectively, as detailed in Eq 5a, Eq 6a, Eq 5b, Eq 6b

$$frw = N\_LITTER\_W^{*}fragw^{*}rtemp^{*}\theta_6^{TW} \tag{5a}$$

$$frs = N\_LITTER\_S^{*}frags^{*}rtemp^{*}\theta_6^{TW} \tag{6a}$$

$$desh = N\_PLANT^{*}rdrsh \tag{5b}$$

$$dero = N\_PLANT^{*}rdrro \tag{6b}$$

Equation 7 for the state variable representing the nitrogen content of submerged plants per unit area is as follows.

$$N\_plant(t) = N\_plant(t-dt) + (up2 + up1 + up3 + up4 - desh - dero)^{*}dt \tag{7}$$

Where N_plant represents the nitrogen content of submerged plants (Nmg/L), and up2, up1, up3 and up4 represent the rates at which submerged plants absorb ammonia and nitrate nitrogen from water and soil, respectively. Considering the relationship between plant growth rate and required nutrients, and considering the growth mechanism, the growth rate of a plant can be expressed by the photosynthetic rate of a plant, that is, the rate at which a plant absorbs solar radiation for photosynthesis and converts it into its own biomass (Eqs 8, 9) (Mankin and Fynn, 1996; Ahn and Mitsch, 2002; Brix et al., 2002; McAndrew and Ahn, 2017). The specific equation is as follows: Eqs 7a–d.

$$up1 = n\_de\_w^{*}\frac{NO3\_W}{KNO3w + NO3\_W}{}^{*}\frac{NO3\_W}{NO3\_W + NH4\_W} \tag{7a}$$

$$up2 = n\_de\_w^{*}\frac{NH4\_W}{KNHw + NH4\_W}{}^{*}\frac{NH4\_W}{NH4\_W + NO3\_2} \tag{7b}$$

$$up3 = n\_de\_s^{*}\frac{NO3\_S}{KNO3s + NO3\_S}{}^{*}\frac{NO3\_S}{NH4\_S + NO3\_S} \tag{7c}$$

$$up4 = n\_de\_s^{*}\frac{NH4\_S}{KNHs + NH4\_S}{}^{*}\frac{NH4\_S}{NO3\_S + NH4\_S} \tag{7d}$$

$$n\_de\_w = \frac{sloar^{*}k1^{*}k3^{*}k4^{*}A}{k2} \tag{8}$$

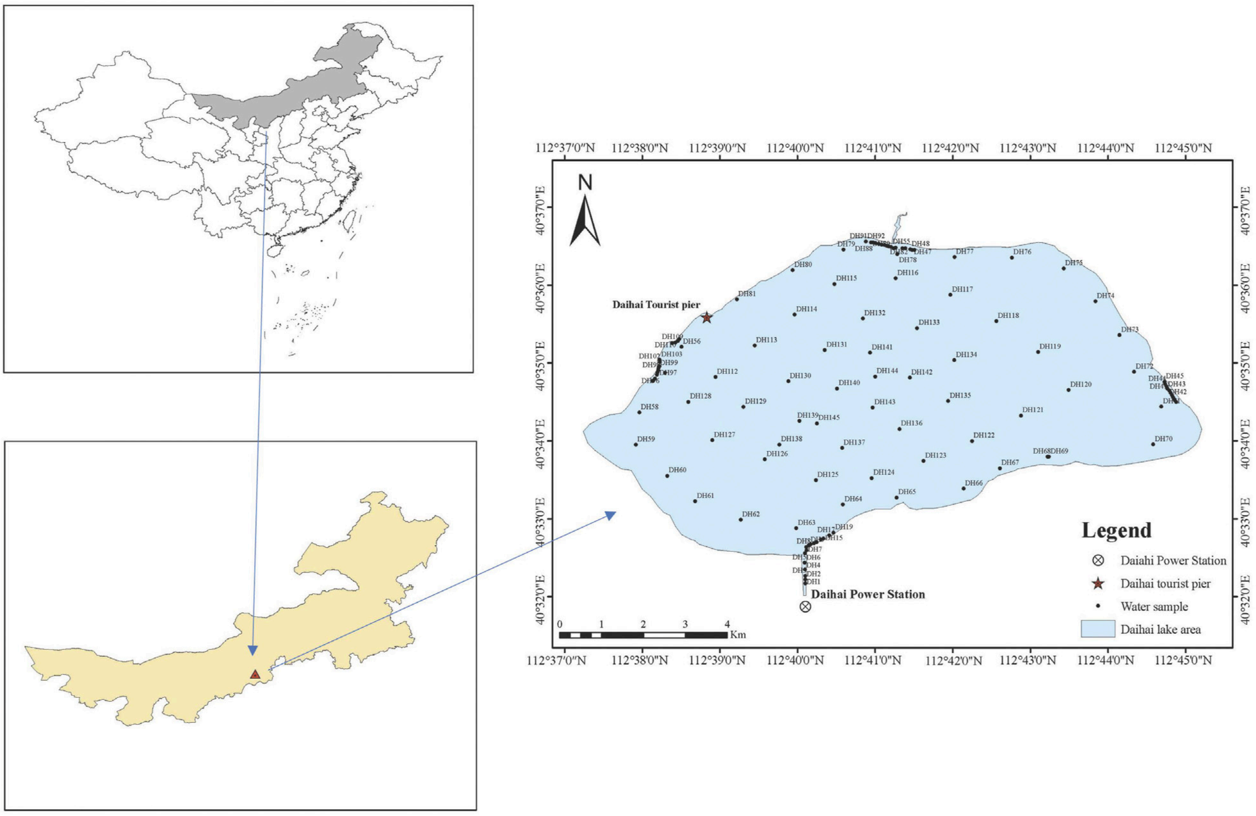

FIGURE 2
Location of the study area, transects and sampling points in Daihai Lake.

$$n\_de\_s = \frac{sloar^{*}k1^{*}k3^{*}k5^{*}A}{k2} \tag{9}$$

In order to make the rate of most of the reactions in the model change with the season, temp_airK, which can describe the annual temperature, is introduced in the model. The relationship between temperature and process rate used in the model (Eq 10) is based on the absolute reaction rate theory, but some parameter values are verified in this paper, so that the change of reaction rate is more in tune with the seasonal change (Schoolfield et al., 1981; van der Peijl and Verhoeven, 1999).

$$rtemp = \frac{rho25^{*}\frac{temp\_airK}{298}{*}10^{\frac{Ha}{r}*\left(\frac{1}{298}-\frac{1}{temp\_airK}\right)}}{1+10^{\frac{Hi}{r}\left(\frac{1}{Ti}-\frac{1}{temp\_airK}\right)}+10^{\frac{Hh}{r}*\left(\frac{1}{Th}-\frac{1}{temp\_airK}\right)}} \tag{10}$$

2.3 Sampling method

In 2019, 118 sampling sites were set up and corresponding samples were collected in the Daihai (Figure 2), which covered the entire lake area as much as possible in order to study the exogenous pollution in summer. Submerged plant samples were collected by a submerged plant collection rake and weighed on site. After returning to the laboratory, the samples were weighed after over-dried at 105°C for about 30 min and then dried to constant weight at 70°C, and grinded into powder for detection of total nitrogen, ammonia nitrogen and nitrate nitrogen contents. Water samples with a 0.5 m water depth were collected by using a water sample collector and a total of five indicators in them were measured: Turbidity, PH, dissolved oxygen content, and nitrate nitrogen, ammonia nitrogen and total nitrogen concentration. The total nitrogen, the ammonia nitrogen and the nitrate nitrogen concentrations were measured by SKALAR Continuous Flow Analyzer. Dissolved oxygen, Turbidity and PH were measured on site with a portable instrument. All measurements were made in accordance with standard methods (Rice et al., 2012). In addition, the area of submerged plants in the Daihai Lake used in this study were obtained from "Concluding Report on the Construction of Water Ecological Security Assessment and Management Decision Support System of One Lake and Two Seas", and the meteorological data used were collected from the local meteorological stations.

2.4 Calculation method of nitrogen pollution load into lake

The calculation of the total nitrogen pollution load into Daihai Lake is divided into five main components: Rural living, livestock breeding, agricultural cultivation, atmospheric deposition, and soil erosion (Zheng and Men, 2020). According to the statistics of the Daihai watershed and related research literature, the rural population of the Daihai watershed in 2019 was 94,000 and the rural arable land was 63,000 hm2; and the livestock stock was 559,000, including 53,000 cattle, 500,000 sheep as well as 0.6 million pigs (Tang, 2021).

The formulae for calculating the total nitrogen pollution load for rural living, livestock breeding and agricultural cultivation is shown in Eq 11.

$$W_1 = N^{*}\alpha_1{}^{*}\beta_1 \tag{11}$$

Where, W_1 is the total nitrogen load into the lake, N_1 is the quantity in the region (all livestock stock is converted into pigs for calculation, such that one cow is converted into five pigs, three sheep are converted into one pig). α_1 is pollution production coefficient with 1.5g/(person*d) in rural domestic pollution, 1.27kg/(n*a) in livestock and 2.64 kg/(hm^{2*}a) in farmland (Council, 2009). β_1 is lake input coefficient with 0.15% for rural household pollution, 10% for livestock breeding pollution, and 7% for farmland pollution (Zhu, 2011).

The formula for calculating the total nitrogen pollution load from atmospheric deposition is expressed in Eq 12.

$$W_2 = A^{*}\alpha_2 \tag{12}$$

Where W_2 is the total nitrogen load to the lake, A is the total area of the Daihai Lake, α_2 is the atmospheric nitrogen deposition flux with 532.53kg/(km^{2*}a) (Lu et al., 2015).

The formula for calculating the total nitrogen pollution load for soil erosion is described in Eq 13.

$$W_3 = SDR^{*}X^{*}C^{*}\eta^{*}\alpha_3 \tag{13}$$

Where W_3 is the total nitrogen load into the lake from soil erosion. SDR is the sediment transport ratio, which in China varies little between 0.1 and 0.4, and is taken as 0.25 (Jiang and Xi, 2011). X is the amount of soil erosion. C is the background content of nitrogen and phosphorus in the soil at 0.9 g/kg (Kalin and Hantush, 2006). η is the soil enrichment ratio of nitrogen (dimensionless). α_3 is the coefficient of entry into the lake with 0.7% (Zhu, 2011).

2.5 Validation of the model

Theil's Inequality Coefficient (TIC) is used as the evaluation index of the calibration results of the evaluation model, which can be used to quantitatively describe the degree of coincidence between model simulation results and measured data and shown in Eq 14 (Min et al., 2010). TIC is generally between 0 and 1 and 0 represents a perfect fitting with the actual monitoring value. In general, when TIC is less than 0.5, it can be considered that the simulation value is in good agreement with the monitoring value. The concentrations of NO_3 and NH_4 in water were verified in our study.

$$TIC = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(C_{i,sim} - C_{i,obs}\right)^2}}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}C_{i,sim}^2} - \sqrt{\frac{1}{n}\sum_{i=1}^{n}C_{i.obs}^2}} \tag{14}$$

$C_{i,sim}$ is the model simulation value at time i; $C_{i,obs}$ is the actual monitoring value at time i; n is the number of data points used for model verification.

The final calculated TIC of NH_4 is 0.018 and TIC of NO_3 is 0.25. This shows that the simulated values of the model are in good agreement with the measured values, and the calibration of the model is successful.

3 Results

3.1 Calculation of total nitrogen load to the daihai lake

It was calculated that the N pollution load in the Daihai Lake in 2019 was 107.895t (Figure 3), which were mainly contributed by soil erosion, atmospheric deposition, agricultural cultivation, livestock breeding and rural living and carried by rivers into the lake. Among the pollution source, livestock raising was the largest contributor of the total N pollution load, which produced 52.44 tN pollution load accounting for 48.6% of the total annual N pollution load. Rural life was the least contributor of the total N pollution load with 0.055t, which only occupied 0.05% of the annual total N. These implied that external pollution would being the main pressures in the lake ecosystem health.

3.2 Simulating the variations of N contents in the daihai lake

Based on Figure 4A, it can be seen that the NH_4^+-N and NO_3^--N contents in the water column of the Daihai Lake increased more rapidly after July, reached a maximum and then decreased after October, which was confirmed by the measured data, because of exogenous pollution entering the lake by rivers in summer. NH_4^+-N and NO_3^--N contents in the soil column of the Daihai Lake were higher in the dry season than in the wet season, and this was possible for N absorption by plants in the wet season.

The N content of submerged plants relied on nutrient uptake from the water and soil. The N content of submerged plants per unit area could to some extent reflect the growth and quantity of submerged plants. According to Figure 4B, the area of the Daihai decreased continuously and the area of submerged plants increased constantly. By comparison, the nitrogen uptake rate of submerged plants was highest from May to July, with the rate gradually decreasing towards the end of August and gradually ceasing to grow from November.

3.3 Calculating the N purification capacity of submerged plants in water

In this study, the purification amount of submerged plants referred to the difference between the amount absorbed by submerged plants and released by the decomposition of death plant residues in water. Based on Figure 5A, the N

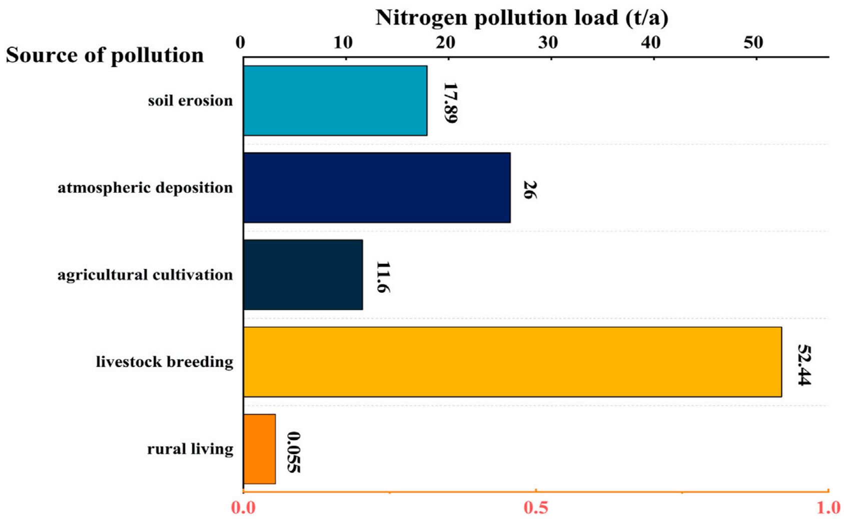

FIGURE 3
Pollution load calculation results.

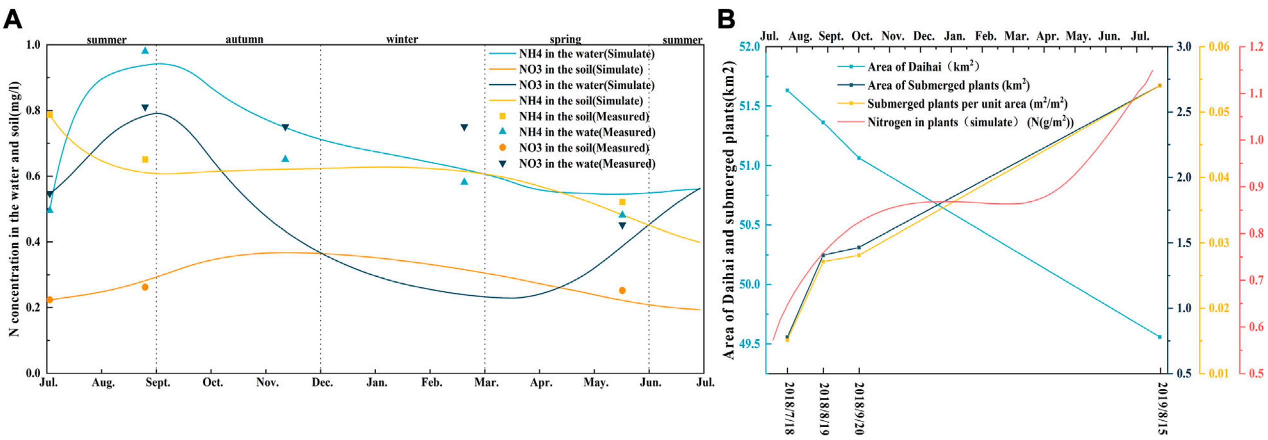

FIGURE 4
Varification of model **(A)** Verification of nitrogen concentration **(B)** Verification of submerged plant area.

absorption amount of submerged plants mainly occurred during the growing season from May to October. Due to a relatively simple mortality rate being positively correlated with the biomass of submerged plants, the N release amount of submerged plants was almost always in an increasing state except for the time of winter growth stagnation (Figure 5B). The variation trend of the N purification amount of submerged plants was almost similar to that of the N absorption amount of submerged plants, as gradually decreased from October to January and then gradually increased. And this N purification amount was negative in January because the N release amount was greater than the N absorption amount for submerged plants (Figure 5C). Therefore, the N purification capacity of submerged plants depended on the biomass of the submerged plants in this lake.

3.4 Predicting the effects of different submerged plant restoration on N loads

In this study, the expansion of submerged plant area and the decrease of turbidity in the Daihai Lake caused by increased submerged plant area were mainly considered in the ecological restoration of submerged plants in the Daihai Lake. In this model, the area of submerged plant restored from 4.95 km^2 to 9.91 km^2, and light utilization increased from 0.02 to 0.022. The variation trend of NO_3^- concentration in water column was similar before and after recovery, while the NO_3^- concentration after recovery was significantly lower than before recovery (Figure 6A). The concentrations of NH_4^+ before and after recovery gradually kept stable after the third year, and the NH_4^+ concentrations after recovery were lower than before recovery (Figure 6B).

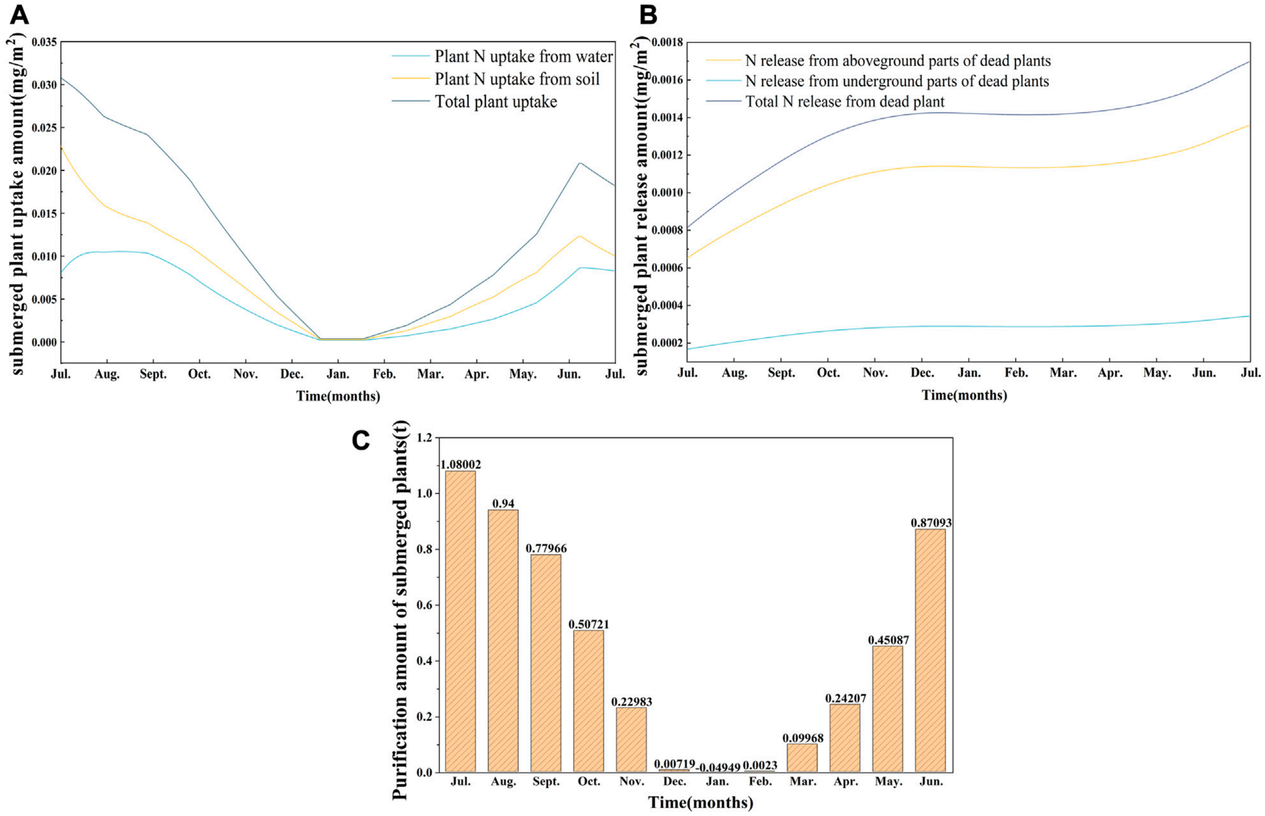

FIGURE 5
Simulation results from July 2019–July 2020 **(A)** Simulation results of submerged plants uptake amount. **(B)** Simulation results of submerged plant release amount. **(C)** Simulation results of submerged plant purification amount.

In order to better compare the purification capacity of submerged plants before and after restoration, when the external non-point source N pollution load is only 107.895t, it can be seen that the restored submerged plants will spend 12 years on purifying 107.895t of N pollution load (Figure 6C). However, the purification speed of submerged plants before recovery is very slow, and the time required before recovery is much longer than after restoration. Under the two conditions, the annual purification amount of submerged plants decrease basically with time, which is basically consistent with the variations of N concentration in water column.

4 Discussions

4.1 Analysis of different pollution loads to the daihai lake

By comparison, the N pollution load of the Daihai Basin in 2019 calculated in this study was similar to that in 2017 referenced from the study of (Wu and Zhao, 2015). This indicated that non-point source pollution has been reduced to some extent in rural life, atmospheric subsidence and soil erosion. We found that the loss of population in the villages and towns around the Daihai Lake led to the reduction of N pollution load brought by rural life (Zheng and Men, 2020; Tang, 2021), with the decreasing of the Daihai Lake's area year by year, the N pollution load caused by atmospheric subsidence would become reduction, and N pollution load caused by soil erosion also reduced for the depletion of river channels and the decrease of rainfall. However, because of increasing in farmland and livestock raised in the countryside, N pollution load from both agricultural cultivation and livestock raising would increase obviously (Tang, 2021), which was proved by our conclusion, too. Therefore, how to controlling N pollution load from both agricultural cultivation and livestock raising was important for the management of the Daihai Lake ecosystem.

4.2 The role of the restored area of submerged plant in N purification

In this study, due to the impact factors being complex and difficult to simulate perfectly in the model, we adopted some parameters from some references such that the growth of submerged plants was expressed by using the plant growth coefficient (Guan, 2021; Li et al., 2021), and a relatively simple mortality rate was used to calculate the N release amount of submerged plants (van der Peijl and Verhoeven, 1999). Therefore, the N release amount of submerged plants was positively correlated with the biomass of submerged plants, which would have a certain impact on annual purification

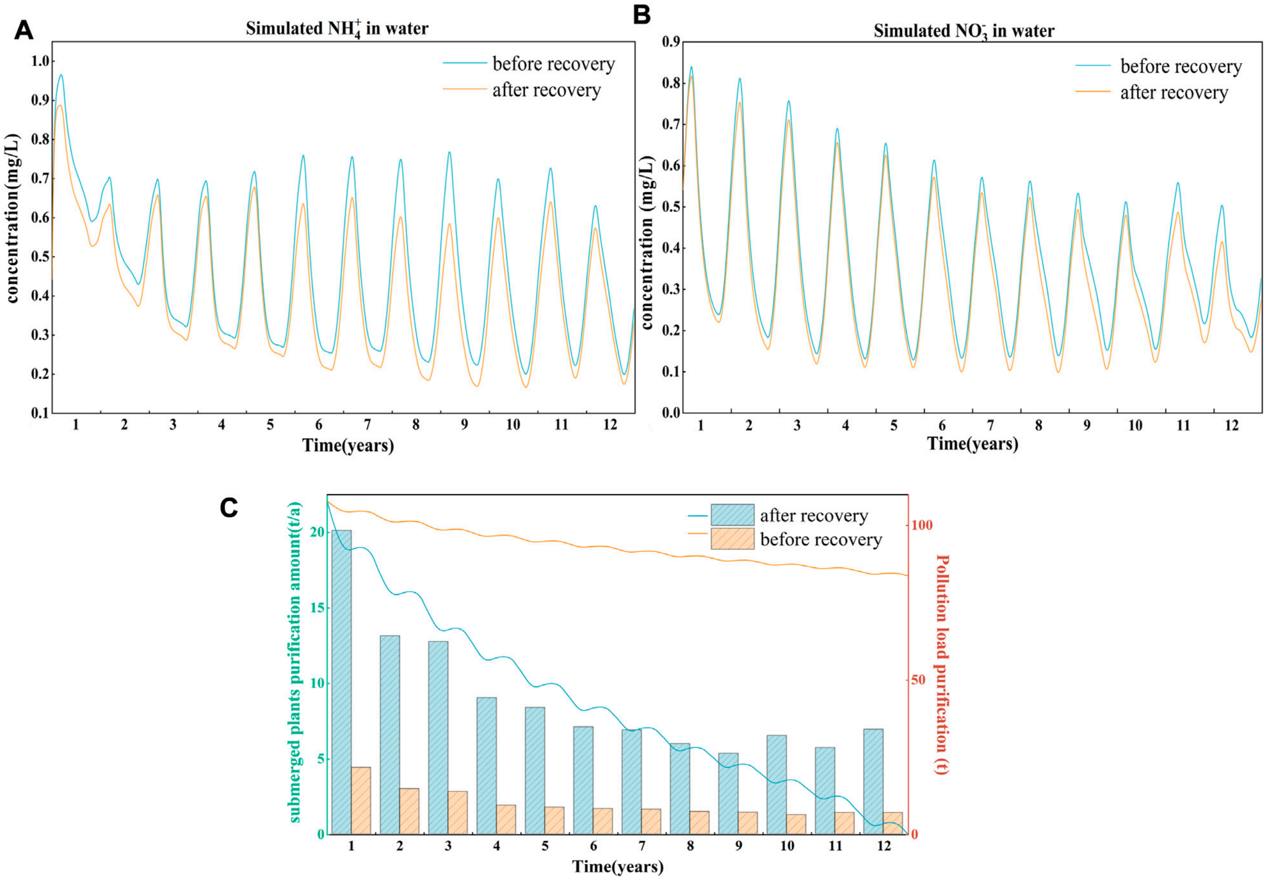

FIGURE 6
12-year simulation results of before and after recovery **(A)** NO3+ concentration before and after recovery **(B)** NH4+ concentration before and after recovery **(C)** Pollution load reduction and annual purification of submerged plants.

amount of submerged plants. This also led to the amount of purification in the front growing season being higher than that in the back growing season.

The restoration of submerged plants would be realized by changing their area and light utilization efficiency. In this model, the area of submerged plants will affect the total amount of light absorbed by submerged plants, and the light utilization efficiency will affect the N absorption efficiency of submerged plants, which was very important for restoration of submerged plants. Because the growth of submerged plants was largely restricted by the water depth (Li et al., 2021), and the area suitable for submerged plant growth during the water depth less than 2.5 m in the Daihai Lake accounted for 23% of the lake area (Zhao et al., 2020), we chose 20 percent of the Daihai area (9.91 km^2) to restore submerged plants. In addition, the turbidity of lake water in Daihai Lake would decrease due to the expansion of submerged plants, and the light utilization efficiency would be further improved due to the decrease of turbidity. According to the influence of turbidity on photosynthesis, the photosynthetic rate increased by about 5%–10% when turbidity recovered from 60NTU to 30NTU (Li et al., 2006; Xue et al., 2007). According to the field investigation, the turbidity in the whole Daihai Lake was between 15.6–75.8NTU, and between 40–70NTU in most of the areas where submerged plants grew, which need to increase photosynthesis rates to reduced turbidity by submerged plants (Li et al., 2006; Xue et al., 2007). Ultimately, the simulation results showed that an increase in the area of submerged plants in Daihai Lake can significantly increase the total amount and rate of N uptake by submerged plant.

Liu et al. (2020) found that the assemblage of three or more submerged macrophyte species only significantly improved water clarity, but not water quality. Our findings were that it can be seen that annual N purification amount in the water of the Daihai Lake before and after restoration was different, the purification speed of submerged plants before recovery was very slow, and the recovery time required before recovery was much longer than after restoration. This also proved that small area submerged plant could not improve water quality obviously and only restoration of large area submerged plant benefited for the nutrient N absorption of submerged plants.

In addition, the death parameters of submerged plants used in the model only generally calculated the normal death and loss of each part of submerged plants in the natural growth process, and other biomass of submerged plants would be not considered next year, which indicated that most submerged plants would be removed from the lake and not re-pollute the lake water. Therefore, it is necessary to carry out the salvage work of plant residues in winter every year to maintain normal plant growth and prevent from submerged plant nutrient N releasing into the water.

4.3 The effect of submerged plants in reducing endogenous N pollution

Endogenous pollution was also one of the main reasons for the deterioration of water quality in Daihai Lake (Zheng and Men, 2020). Submerged plants could fix and absorb various types of N in the sediment, which was an effective means to control endogenous pollution in the lake (Jingbo et al., 2007; Huang et al., 2019). In this study, because the N in the sediment lacked exogenous recharge, it was found that the concentration of various types of N in the sediment continuously decreased, which was continuously consumed by submerged plants. As the N concentration in the sediment decreased, the nitrogen concentration in the water would also decrease accordingly, which was the main reason why the model simulated a gradual decrease in purification capacity before reaching stability. Therefore, the restoration of submerged plants in the Daihai Sea could effectively slow down the release of endogenous N pollutants to water, which was of a great important role in N purification in sediments.

5 Conclusion

The ecological dynamics model of nitrogen flow in the Daihai Lake was constructed to simulate the growth and nitrogen uptake of the submerged plants in the Daihai Lake. In 2019, the pollution load into Daihai Lake was calculated to be 107.895 t/a. The nitrogen purification by submerged plants in Daihai Lake in 2019 was obtained by model simulation to be 5.13 t/a, accounting for 4.8% of the total exogenous pollution. The purification capacity of the restored submerged plants with a large area of 9.91 km^2 in the Daihai Lake was significantly higher than before restoration. It would spend 12 years on purifying 107.895 t of nitrogen pollution for the restored submerged plants under the conditions of regular cleaning of submerged plant residues.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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