



Characteristics of nutrients accumulation in the sediment of the surface-flow constructed wetlands of Mata Lake, China

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Abstract As a nutrients reservoir of surface-flow constructed wetlands (SFCWs), the substrate plays an important role in water purification, and it is significant to investigate the accumulation and release characteristics of nutrients to maximize the efficiency of constructed wetlands (CWs) for wastewater purification. In this study, we analyzed the total nitrogen (TN), total phosphorus (TP) and organic matter (OM) in the bottom sediment and conducted static release experiments on column core samples in order to evaluate the accumulation characteristics of nutrients and the current status of the ecological water environment in the SFCWs, which has been in operation for 6 years. Results showed that: (1) The average concentration of TN, TP and OM were 2.30 ± 0.006 g/kg, 0.26 g/kg and 10.49 ± 0.04 g/kg, respectively. There were differences in the spatial distribution of nutrients based on ArcGIS spatial interpolation simulation

analysis. (2) The organic index (Org-index) in the sediment was evaluated as lightly polluted and the TP was evaluated as clean, but the organic nitrogen (Org-N) index was evaluated as heavily polluted. (3) The release amount of nutrients in the static release experiment showed a general trend of ascending in about the first 10 days and then descending, and the maximum release rate was observed between 9 and 12 days.

Keywords Mata Lake · Surface flow constructed wetlands · Substrate nutrients · Accumulation · Static release

Introduction

Eutrophication is a major water environmental problem all over the world (Liu et al. 2011; O'Connell et al. 2020; Lin et al. 2021). In China, the pollution status of water bodies is extremely severe, clean water resources are scarce, and the eutrophication of water bodies is serious (Liu et al. 2011; Lin et al. 2021). In the nutrition status testing of 110 important lakes, it was found that the lakes with poor nutrition, moderate nutrition, mild eutrophication, moderate eutrophication and severe eutrophication status accounted for 9.1%, 61.8%, 23.6%, 4.5% and 0.9% respectively, in 2020 (Ministry of Ecology and Environment 2021). Faced the complex and severe pollution status, constructed wetlands (CWs) have become a common

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technology for treating wastewater domestically and abroad due to their advantages of high treatment efficiency, low economic cost and good ecological value (Saumya et al. 2015; Ma et al. 2020).

Surface-flow constructed wetlands (SFCWs) are the closest type of natural wetlands among all types of CWs. In SFCWs, the sewage mainly diffuses itself on its surface and comes into direct contact with the air. This process mainly utilizes wetlands plants, soil substrate, wetlands animals, and microorganisms among the physical, chemical and biological triple synergy effects of degradation and treatment of organic matter (OM) to achieve sewage purification (Sun et al. 2019; Wu et al. 2019; Li et al. 2021a, b, c). Compared with other types of CWs, SFCWs have the advantages of short maturity period, low operation cost, and intermittent management (Li et al. 2020; Fan et al. 2021). Therefore, the research, development and application of surface flow constructed wetland system provide a new option for comprehensively solving the low efficiency of traditional secondary treatment of nitrogen (N) and phosphorus (P) removal as well as the high investment and operation cost of tertiary treatment. At the same time, SFCWs can provide a new solution for the protection, utilization and restoration of the shrinking and degraded natural wetland areas.

The substrate is the "nutrients reservoir" of the SFCWs, which can adsorb and flocculate N, P and OM in the overlying water to achieve the water-purifying effect (Li et al. 2020; Ma et al. 2021). However, with the prolongation of the CWs operation cycle, the adsorption of nutrients such as N and P by the substrate tends to saturate, and there is a risk of release to the overlying water, which may lead to the intensification of eutrophication in the downstream water bodies, causing secondary pollution and affecting the purification effect of CWs (Pan et al. 2019; Wang et al. 2021). Some studies indicate that the nutrients enriched in the bottom mud are released to the overlying water bodies and show different release patterns (Zhu et al. 2019). Therefore, it is vital to measure and analyze the concentration, accumulation and release characteristics of TN, TP, OM and other nutrients in wetlands substrates for controlling eutrophic pollution in overlying water bodies and restoring the ecological purification function of wetlands.

In summary, the continuous purification capacity of CWs is crucial for maintaining long-term water purification effects. In this paper, we monitored the

concentration of TN, TP and OM in the bottom sediment of the SFCWs of Mata Lake after 6 years of operation. We also explored the release of nutrients to the outside using the static release experiment method of column core samples. The objectives of this study are to (1) analyze the nutrients accumulation characteristics of the substrate at different locations and evaluate their pollution status, and (2) provide a scientific basis for improving the purification efficiency of the CWs by understanding the accumulation and release patterns of nutrients in the substrate.

Research area and methods

The study area

The CW system of Mata Lake (118° 02' 30"–118° 03' 31" E, 37° 03' 56"–37° 04' 16" N) is located in Huan-tai County, Zibo City, Shandong Province, China. The Mata Lake serves an inlet of the Zhulong River, whose main tributaries are the Wu River, the Xiaofu River, and the East and West Zhulong Rivers, etc. The CW system was built in 2011 and completed by 2014, which was put into operation at the same year, as a flood reservoir in order to recover the lake ecological function. Its average water depth is 1.2 m, flow rate is 4.17 m/h, normal reservoir capacity is 30 million m³, the daily water treatment capacity is 20,000 m³/d, the CWs covers an area of 476,000 m². More than 30 kinds of aquatic plants were planted in this CW system. The vegetation cover was high, including 94,000 m² aquatic plants which occupied one fifth of the main water surface of Mata Lake. The SFCW system is divided into six levels after the sewage inflows into the first and second ecological retention ponds. The sewage flows into the inlet of SFCWs and passes the first, second, third, fourth, fifth and sixth levels from south to the north respectively. Finally, the purified sewage is discharged at the outlet (Fig. 1).

Collection of sediment samples

On April 10, 2021, seventeen representative sampling points were selected according to the direction of water flow and other factors (Fig. 1), and the sediment sampler (model: JUYET-0205, Made in Beijing, China) was used to collect the bottom sediment (0–10 cm). The collected samples were

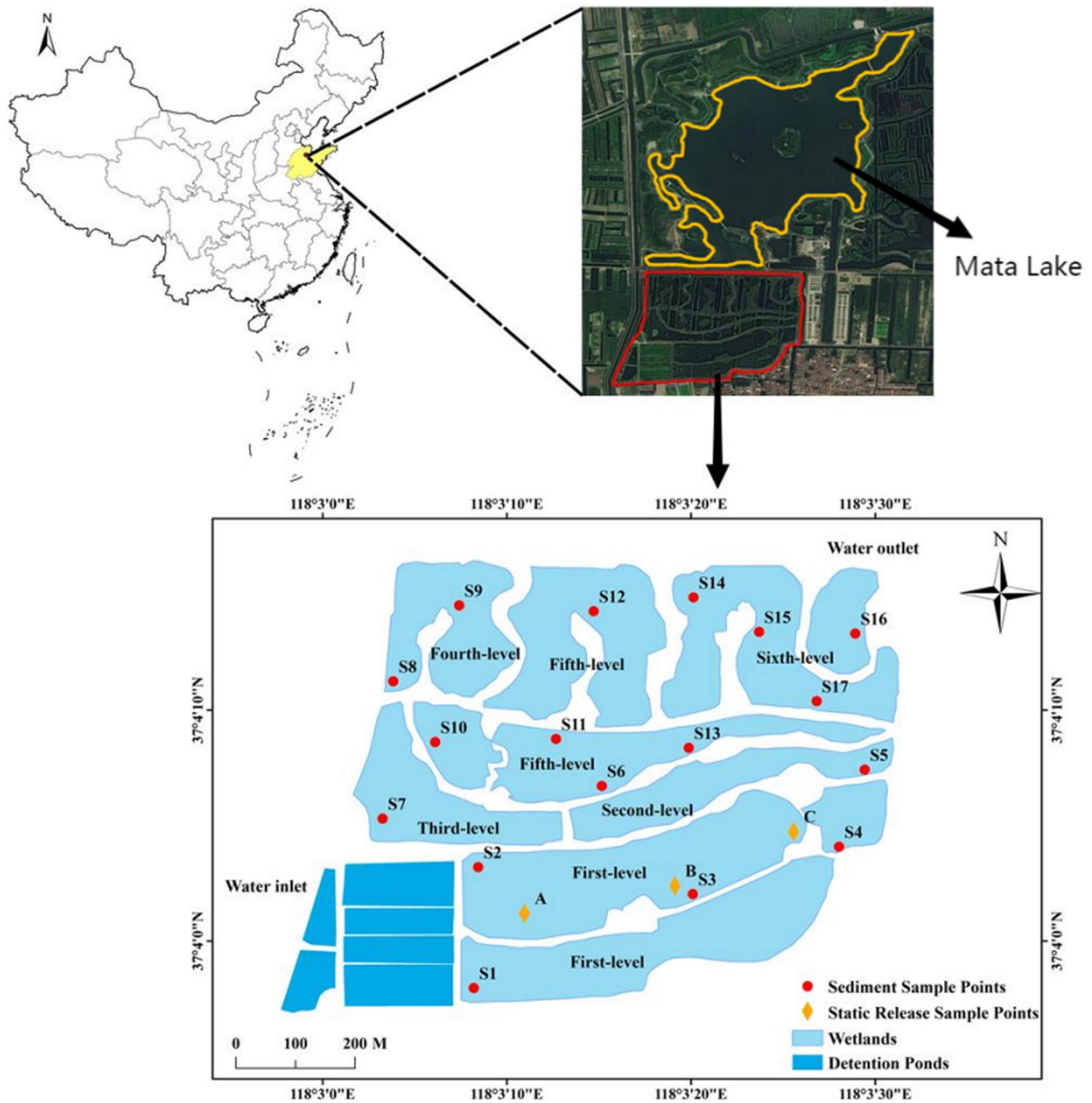


Fig. 1 Locations of sampling points

sealed in polyethylene bags, brought into the laboratory and, after naturally dried, ground, and sieved through a 100 mesh for TN, TP and OM determination. The inlet water quality was changeable with the seasons. The TP concentration of inflow in winter was 2.36 mg/L and 1.53 mg/L in spring (Zhou et al. 2020). The concentration of OM in the substrate was calculated based on the total organic carbon (TOC),

and three samples were taken in parallel at each sampling site.

Experiment of static release

For static release sampling, as shown in Fig. 1, we took the samples from the representative sampling points A, B and C in the first-level SFCWs of Mata Lake, and six 1600 g bottom sediment samples (two

parallel samples at each point) were collected using a Plexiglas column sampler with 100 cm outer diameter, 90 cm inner diameter and 50 cm height. As shown in Fig. 2, 1–1 and 1–2, 2–1 and 2–2, and 3–1 and 3–2 are parallel samples of sampling points A, B and C, respectively, to ensure that the samples taken have homogeneity and the same depth of the overlying water body. On days 0, 1, 2, 4, 6, 9, 12, 16, 20 and 26, respectively, 300 mL water samples were taken in sample bottles by siphon method from about 5 cm below the surface of the column sample to determine the concentration of TN, TP and COD components, and the overlying water depth height was supplemented with raw water.

Sample analysis

According to the relevant standards of the Ministry of Ecology and Environment of China, the determination of TN, TP and COD was determined by alkaline potassium persulfate digestion spectrophotometry, ammonium molybdate spectrophotometry, and potassium dichromate method, respectively (China, 2019). OM were analyzed with a Shimadzu TOC-LCSH/SSM-5000A detector. All experimental samples were tested in parallel three times, and the results are from averaging data.

Evaluation method

In this experiment, the Org-index and Org-N (Chen et al. 2010) evaluation method were used to analyze

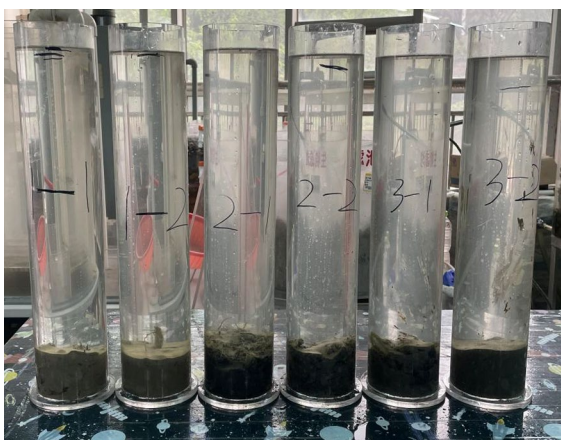


Fig. 2 Experiment of static release

the OM and N concentration in the sediment of Mata Lake wetlands and evaluate its pollution status. Meanwhile, the pollution index method was used to analyze and evaluate the pollution status of P in the sediment according to the environmental quality evaluation standard of sediment issued by the Ministry of Environment and Energy of Ontario, Canada in 1992 (Leland and Dean 1997).

The Org-index and Org-N are calculated as follows, and the evaluation criteria are shown in Table 1 (Liang et al. 2018; Wang et al. 2018).

$$\text{Org-index} = \text{Org-C}(\%) \times \text{Org-N}(\%)$$

$$\text{Org-N}(\%) = \text{TN}(\%) \times 0.95$$

The pollution index (P_i) for P is calculated as follows (Wang and Wu 2018):

$$P_i = C_i \times C_{0i}^{-1}$$

C_i =the measured concentration of the i -th nutrients; C_{0i} =Evaluation standard of the i -th nutrients, 600 mg/kg (Table 2).

The formula for calculating the static release rate of sediment nutrients (Zhang et al. 2020).

$$v = 0.3 \times \frac{C_n - C_{n-1}}{0.0064 \times (t_n - t_{n-1})}$$

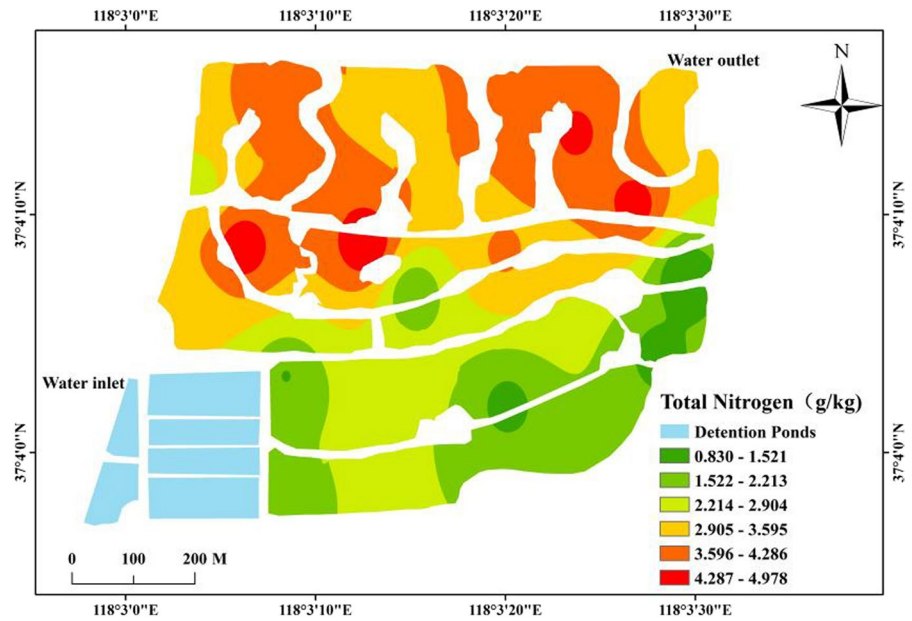
v =Release rate of nutrients in bottom mud, mg/(m^2 d); 0.3=Sampling volume per time, L; C_n , C_{n-1} =Medium nutrients concentration of the overlying water at the n -th and $(n-1)$ -th sampling, mg/L; 0.0064=The contact area between the bottom mud and the overlying water body, m^2 ; t_n , t_{n-1} =the time of the n th and $(n-1)$ th sampling, d.

All data in this experiment were processed by Origin 8.0 and ArcGIS 10.5 were used for drawing.

Result and discussion

Analysis of accumulation characteristics of TN, TP and OM in sediment

TN is an important indicator to evaluate the nutrient concentration of the substrate, and it plays an important role in the eutrophication state of the substrate. When the N in the substrate exceeds the extreme

Fig. 3 Spatial distribution pattern of sediment TN concentration**Table 1** Evaluation standards of Org-index and Org-N in sediments

Level	Org-index	Org-N	Pollution degree
I	<0.05	<0.033	Clean
II	0.05–0.20	0.033–0.066	Slight pollution
III	0.20–0.50	0.066–0.133	Moderate pollution
IV	≥0.50	≥0.133	Heavy pollution

Table 2 Evaluation standards of TP in sediments

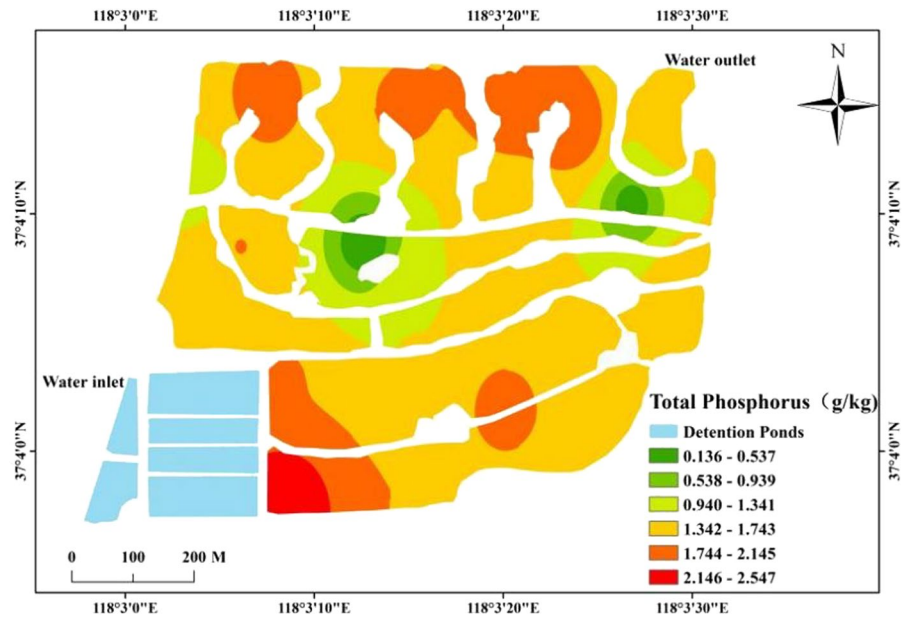
Level	Pollution index	Pollution degree
I	<0.5	Clean
II	0.5–1.0	Slight pollution
III	1.0–1.5	Moderate pollution
IV	≥1.5	Heavy pollution

capacity it can accommodate, the "supersaturated" substrate becomes a source of pollution, releasing N and other nutrients to the external water body, intensifying the eutrophication state of the water body, and even destroying the nutrients cycle in lakes and wetlands (José et al. 1999; Zhang et al. 2018; Huang et al. 2021). Figure 3 shows how the concentration of TN in the substrate varies in SFCWs at all levels, and how its concentration ranges from 0.65 to 3.78 g/kg, with an average value of 2.30 ± 0.006 g/kg. The

concentration is higher in the fourth, fifth and sixth level areas, which may be related to the water flow rate factor. Comparing with the studies on the sediment of Baiyangdian Lake, Zhongba River and Yanlong Lake, the sediment of Mata Lake has a higher TN concentration indicating a eutrophic state, which may be related to factors such as the presence of aquatic and terrestrial organisms inside the wetlands of Mata Lake, rich in species and a more complex environment (Zhu et al. 2018, 2019; Yang et al. 2021). In the same area, the TN concentration in the sediment of the first-level SFCWs is decreasing along the direction of water flow, probably because the hydraulic load at the first-level SFCWs of Mata Lake is small, so that the sewage can stay in the SFCWs for a longer time, and the nutrients in the sediment are fully purified at the inlet and the middle, and less accumulated at the outlet. However, excessive N accumulated in the substrate at the northern outlet area of the SFCWs may exacerbate the risk of eutrophication in the SFCWs and have a negative impact on the growth of reeds and other SFCWs plants, which is detrimental to the purification of the overlying water bodies and reduces the operational efficiency of the SFCWs.

TP is not only an important criterion for indicating eutrophication of the substrate, but also important for maintaining the dynamic balance of P interchange between the substrate and aquatic plants (Chen et al. 2020a,b; Gurung et al. 2020). Figure 4 shows that

Fig. 4 Spatial distribution pattern of sediment TP concentration



the TP concentration in the sediment of Mata Lake SFCWs ranged from 0.02 to 0.46 g/kg, with a mean value of 0.26 g/kg, being highest at the SFCWs inlet and in the northern region, showing some variability. The overall TP concentration in Mata Lake was lower compared to that in Dongping Lake, Dongting Lake, Baiyangdian Lake and other lakes, which may be related to the inlet water quality conditions, vegetation cover and other factors which present better results for plant growth, adsorption of pollutants by the substrate, and thus purification and treatment of sewage (Chen et al. 2014; Zhu GR et al. 2018; Li et al. 2021a, b, c). Vergeles et al. (2016) studied the nutrients of substrate in an CWs in Ukraine that had been in operation for 8 years, and the better water quality of the influent water may be an important reason for the lower TP concentration in the substrate.

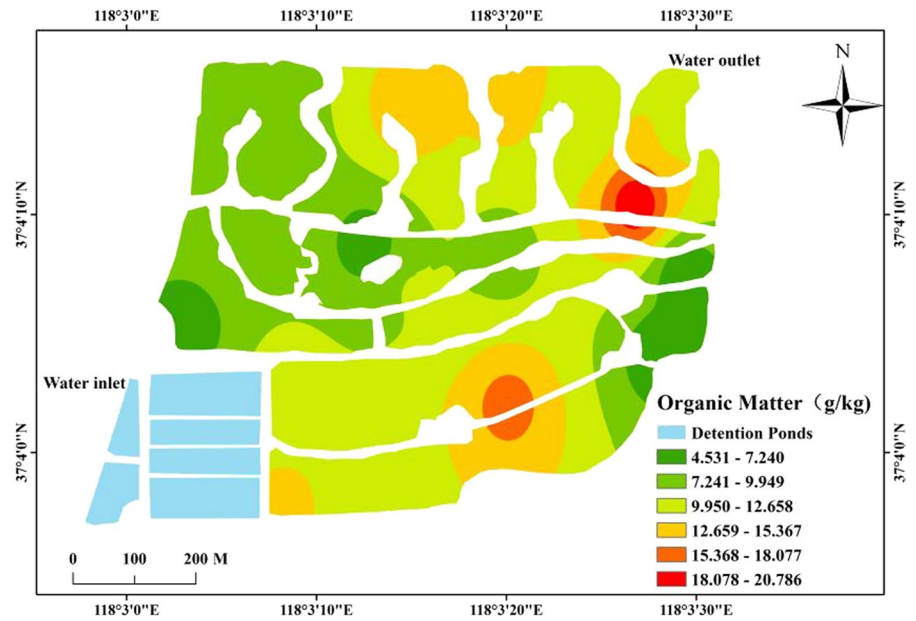
OM can reflect the organic pollution status in the substrate and also plays an important role in the transport of nutrients such as carbon (C), N and P (Zhao et al. 2019). It has been shown that when OM in the substrate undergoes mineralization, it releases C, N, P, and other nutrients into the water column, causing eutrophication in the water column (Yuan et al. 2021). Figure 5 shows that the OM concentration in the sediment of Mata Lake SFCWs ranged from 4.53 to 20.79 g/kg, with a mean value of 10.49 ± 0.04 g/kg and a maximum concentration of 20.79 g/kg. Notably, the concentration was higher in the middle of the

first-level SFCWs and the sixth-level SFCWs area, which may be related to the influence of P concentration in the sediment. An imbalance between the release and adsorption of P can cause the accumulation of OM in large quantities, thereby increasing the adsorption of P. However, this increase in OM concentration can also aggravate the release of P, creating a vicious cycle (Teng et al. 2021). The OM was found to be enriched in the surface substrate, resulting in a high OM concentration. However, when compared with Lihu lake and Nanhu lake, the overall concentration of OM in the bottom sediment of Mata Lake is lower. Several factors may contribute to this difference, including the high oxygen concentration in the surface sediment of Mata Lake SFCWs, which facilitates the mineralization of organic carbon, and the strong plant growth stage, which has a significant effect on the absorption and utilization of organic carbon in the sediment (Guo et al. 2020; Li et al. 2021a, b, c; Qiao et al. 2021; Wu et al. 2021).

Evaluation of nutrients pollution in sediment

The nutrients pollution status of the substrate at each sampling location was evaluated as shown in Table 3. The Org-index, Org-N index and TP pollution index were used to evaluate the pollution status.

The range of Org-index in the sediment of each sampling point was 0.02–0.41, and the average value

Fig. 5 Spatial distribution pattern of sediment OM concentration**Table 3** Evaluation results for pollution in sediments

Sample points	Org-index evaluation results			Org-N evaluation results			TP evaluation results		
	Org-index	Level	Pollution degree	Org-N/%	Level	Pollution degree	P _i	Level	Pollution degree
1	0.11	II	Slight pollution	0.14	IV	Heavy pollution	0.64	II	Slight pollution
2	0.07	II	Slight pollution	0.11	III	Moderate pollution	0.45	I	Clean
3	0.10	II	Slight pollution	0.10	III	Moderate pollution	0.47	I	Clean
4	0.03	I	Clean	0.10	III	Moderate pollution	0.43	I	Clean
5	0.02	I	Clean	0.06	II	Slight pollution	0.39	I	Clean
6	0.07	II	Slight pollution	0.12	III	Moderate pollution	0.33	I	Clean
7	0.07	II	Slight pollution	0.21	IV	Heavy pollution	0.34	I	Clean
8	0.10	II	Slight pollution	0.19	IV	Heavy pollution	0.28	I	Clean
9	0.12	II	Slight pollution	0.27	IV	Heavy pollution	0.49	I	Clean
10	0.18	II	Slight pollution	0.35	IV	Heavy pollution	0.44	I	Clean
11	0.11	II	Slight pollution	0.36	IV	Heavy pollution	0.08	I	Clean
12	0.21	III	Moderate pollution	0.25	IV	Heavy pollution	0.47	I	Clean
13	0.13	II	Slight pollution	0.27	IV	Heavy pollution	0.39	I	Clean
14	0.24	III	Moderate pollution	0.28	IV	Heavy pollution	0.51	II	Slight pollution
15	0.19	II	Slight pollution	0.32	IV	Heavy pollution	0.52	II	Slight pollution
16	0.17	II	Slight pollution	0.24	IV	Heavy pollution	0.39	I	Clean
17	0.41	III	Moderate pollution	0.34	IV	Heavy pollution	0.77	I	Slight pollution
Average value	0.14	II	Slight pollution	0.22	IV	Heavy pollution	0.43	I	Clean

was 0.14. The comprehensive evaluation of Org-index was slight pollution, and the pollution status of 17 sampling points were clean, slight pollution and moderate pollution. Of these, 11.8% were in the clean

level, 70.6% were in the slight pollution level, and 17.6% were in the moderate pollution level (Table 3).

The range of Org-N was 0.06–0.36, with the mean value of 0.22. The comprehensive evaluation result of Org-N is heavy pollution, with the mean

value of 0.22, which is about 1.65 times of the limit value of 0.133 for heavy pollution. This evaluation suggests that the pollution condition of Mata Lake is serious. Four medium pollution sampling points exist in the evaluation of Org-N among the sediment of 17 sampling points, and there is a possibility that they may further develop into heavy pollution.

The evaluation results of TP range from 0.08 to 0.77, with a mean value of 0.43, and the comprehensive evaluation of the pollution index is clean. Among these 17 sampling points, there are four sampling points evaluated as lightly polluted, accounting for 23.5% of all sampling points, and the rest of the pollution conditions are evaluated as clean, indicating that the sediment of Mata Lake is less polluted by P.

Studies have shown that when $C/N < 10$, the source of OM pollution is usually considered as endogenous. When $C/N \approx 10$, it indicates that the endogenous and exogenous sources of OM pollution are in balance, while $C/N > 10$ means that the source of OM pollution is exogenous (Zhang et al. 2015; Liang et al. 2018). The maximum value of C/N in the wetlands sediment of Mata Lake was 9.18, the minimum value was 0.84, and the average value was 3.26. The C/N values of all sampling sites were less than 10, and their OM pollution thus showed strong signs of endogenous pollution.

Studies have shown that plankton in water will absorb or release N and P elements in a certain proportion during the growth, reproduction and decay stages, and if N/P is close to 16, it indicates that the source of P is endogenous pollution (Li et al. 2017; Li et al. 2021a, b, c). None of the N/P values in the sediment sampling sites of Mata Lake wetlands were in the range of 14–18, indicating that the source of P in the sediment of Mata Lake wetlands was exogenous pollution.

Trends in nutrients release

With regarding to the release trends of TN, the three column samples A, B, and C were roughly the same with the release which was more stable in the first 4 days, experiencing a rising state from days 4 to 12, and reaching a peak on day 12 before decreasing to a steady state with a peak of 19.00 mg/L (Fig. 6). The release of nitrogen in the sediment leads to the enhancement of microbial activity in water, resulting

the decrease of nitrogen in water and rising the concentration difference between water and sediment. This increased concentration difference enhances the release rate, causing the N in the sediment to release on the 4th day. The increasing trend of TN concentration in the water column with time indicates that the bottom sediment acts as the water column pollution "source", which can release N to the overlying water bodies (Yuan and Zhong 2020). The TN concentration of the three column samples A, B and C remained low and stable for the first 4 days, indicating that the adsorption of N in sediment by the overlying water is in equilibrium. The TN concentration in the bottom sediment was higher than that in the overlying water, and the release of N from the bottom sediment to the overlying water led to the increase of TN concentration in the water. This indicates that the release of N from the bottom sediment may be the main reason for the increase of N concentration in the overlying water. It has been shown that when the equilibrium between the N concentration in the overlying

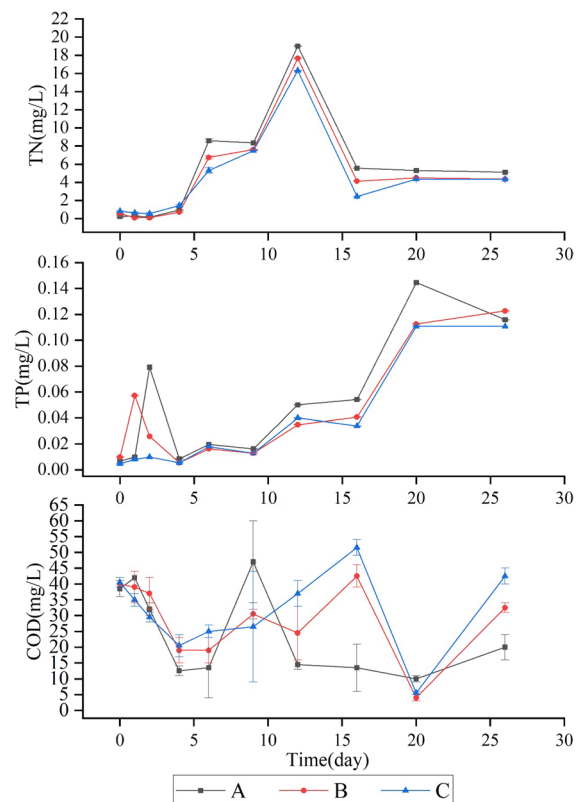


Fig. 6 Trend of nutrients in overlying water

Table 4 Release rate of nutrients in sediment/mg (m² d)⁻¹

Times/d	TN			TP		
	A	B	C	A	B	C
0–1	2.81	- 20.77	- 8.67	0.14	2.22	0.16
1–2	- 6.8	0.00	- 4.45	3.25	- 1.46	0.08
2–4	18.28	14.37	20.91	- 1.65	- 0.48	- 0.10
4–6	179.20	141.28	90.73	0.26	0.25	0.29
6–9	- 3.83	13.67	34.06	- 0.05	- 0.05	- 0.08
9–12	166.59	156.91	138.00	0.53	0.34	0.42
12–16	- 157.57	- 158.45	- 162.49	0.05	0.07	- 0.07
16–20	- 2.95	4.31	22.48	1.06	0.84	0.90
20–26	- 1.48	- 1.21	- 0.20	- 0.22	0.08	0.00

Negative values indicate that the nutrients in the sediment are adsorbed

water column and the substrate is broken, the difference in TN concentration between the both becomes the driving force for N migration (Chen et al. 2020a, b). Therefore, during 12–16 days, the imbalance of N caused the substrate to adsorb TN from the water column again, resulting in a decrease in the TN concentration of the overlying water column. And return to a stable TN concentration in the water at the end of the experiment under the exchange of TN between the overlying water and the substrate.

The TP concentration in the overlying water column A sample was stable from day 0 to day 1, then increased and then decreased from day 1 to day 4. It remained stable for a period until it gradually increased after day 9 and reached a peak on day 20, then showed a decreasing trend with a peak of 0.145 mg/L. In water column B sample, the TP concentration increased first and then decreased, and then kept rising steadily after day 4, and continued to increase after reaching a high concentration on day 20. The migration factors of P and N in the bottom sediment are similar. When the TP concentration in the bottom sediment is higher than that in the overlying water body, the bottom sediment will release P to the overlying water body, and vice versa: if the TP concentration in the bottom sediment is less than that in the overlying water body, the sediment absorbs P from the water body. It has been shown that the adsorption capacity of the substrate is related to the OM and calcium concentration (Zhang et al. 2016), and the TP concentration of column A and B samples showed a large fluctuation at the first 4 days, which may be attributed to the higher levels OM concentration in the substrate at the inlet and the middle areas compared to the

outlet, and to the fact that the mineralization process of OM has a facilitating effect on the release of OM (Cao et al. 2011). Therefore, column A and B samples showed a different trend from column C samples in the first 4 days. After reaching the maximum release rate between days 16 and 20, column A, B, and C samples showed a decreasing, increasing, and stabilizing trend, respectively, which may be related to the saturation of TP adsorption by the substrate in the column samples.

The higher COD concentration in the water body, the more dissolved oxygen needs to be consumed, and the more likely it is to cause water body anoxia, which is adverse to the growth and reproduction of aerobic organisms in the water body. Excessive COD concentration can even cause the death of aerobic organisms and proliferation of anaerobic organisms, and thereby accelerating the deterioration of water quality (Li et al. 2018). From days 0–4, the COD concentration in the overlying water of the three column samples A, B and C decreased and then fluctuated to different degrees from day 4 to 20, with the concentration of column A increasing to a peak (47 mg/L) on day 9 and the concentration of columns B and C increasing to their peaks (43 and 52 mg/L, respectively) on day 16. In all three columns, the COD concentration decreased to the lowest point on day 20, with the lowest value being in column B (4 mg/L). After day 20, all three columns showed an increasing trend again.

The maximum release rate of TN from column A appeared on days 4–6, while the maximum release rate of TN from columns B and C was on days 9–12. (Table 4) This maybe relate to the addition of raw water quality and the disturbance to the water, resulting in accumulation of TN in surface sediment; the

maximum release rate of TP from column A appeared on days 1–2, while the maximum release rate of TP from column B was on days 0–1, and the maximum release rate of TP from column C was observed on days 16–20. (Table 4)

Through the analysis of the static release pattern of nutrients in the bottom sediment of Mata Lake wetlands, it was found that the TN concentration in the water body was stable on the first 4 days and increased on the 5th day; although the TP concentration of the columns A and B fluctuated in the first few days (C column held steady), it was reduced to a stable state on the 4th day; the COD concentration of the water body showed a overall trend of reduction on the first 4 days. In summary, the optimal hydraulic retention time of the SFCWs in Mata Lake should be 4 days.

Enlightenment of eutrophication prevention

Through analyzing the pollution of TN, TP and OM in the bottom sediment, the high TN and OM concentration in the bottom sediment of Mata Lake wetlands has seriously exceeded the standard of eutrophication. Wetlands plants can be planted in order to absorb and utilize nutrients in the substrate, and at the same time, proper harvesting time can also enable to obtain maximum nutrients removal efficiency. Studies have shown that in addition to using wetlands plants to purify wetlands substrate, wetlands organisms such as grass carp, earthworms and snails in long-running wetlands also play an important role in substrate purification (Deng et al. 2018). By matching and combining different species of wetlands animals and plants, maximum purification effect can be achieved.

The OM pollution in the sediment of Mata Lake wetlands is mainly endogenous, and the treatment of OM pollution should be started from the inside of the wetlands by planting plants with strong pollution tolerance, developed root system, and strong environmental adaptability to adsorb and utilize OM in the sediment to reduce the OM concentration in the sediment (Zhu et al. 2019). The source of P pollution is mainly exogenous, so controlling the water quality monitoring of the wetland's intake, optimizing the water intake pattern, and reducing the P are the key issues here.

According to the static release simulation experiment, the analysis of the release pattern of nutrients

in the bottom mud of Mata Lake wetlands after long-term operation shows that the increase of TN and TP in the overlying water body is mainly due to the imbalance of N and P concentration in the bottom mud and the overlying water body, resulting in the release of N and P elements from the bottom mud to the water body, thus increasing its N and P elements concentration and aggravating the eutrophication of the water body.

According to the analyses of the release patterns of TN, TP and COD concentration from the substrate to the overlying water body, it is believed that the releases can be inhibited in certain degree by increasing the hydraulic load in the short term. Studies have shown that submerged plant can not only dissipate the N and P released from the sediment, but also prevent the release of N and P from the substrate to the water body substrate (Wang et al. 2018; Andrzej et al. 2019; Haziq Jamil et al. 2019). Thus, the release of nutrients from the substrate can be inhibited by planting. Indeed, the nutrients concentration of the overlying water body can be improved by planting plants with better inhibitory effect on nutrients release from the substrate; meanwhile, the nutrients concentration in the substrate should be monitored regularly, and timely analysis, treatment and dredging work can be done.

Conclusion

- (1) The TN concentration in the sediment of the SFCWs of Mata Lake was high and the overlying water was in a eutrophic state, and the analysis of the ArcGIS spatial interpolation simulation showed the high spatial variability of the nutrient concentration in the sediment.
- (2) OM pollution showed strong signs of endogenous pollution, while the source of P was mainly exogenous pollution. Among them, the evaluation result of Org-N showed heavy pollution, and it is necessary to strengthen its detection and treatment.
- (3) The static release amount of nutrients from the bottom sediment basically showed a trend of ascending and then descending, and the change of trend was more stable from 0 to 4 days, when the nutrient concentration were low. The release rate reached the maximum between 9 and

12 days, and the best hydraulic retention time of the SFCWs of Mata Lake was 4 days.

- (4) In view of the endogenous pollution problem, the monitoring of nutrients in the bottom sediment should be strengthened, and effective prevention and control measures such as plant selection and regular dredging should be taken.

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Data availability All data generated or analysed during this study are included in this published article (and its supplementary information files).

Declarations

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

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