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Post-dredging nitrogen dynamics at the sediment–water interface: the shallow, eutrophic Mogan Lake, Turkey

by

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Abstract

The sedimentation and resuspension of various forms of nitrogen in wetlands determines the direction of the nitrogen dynamics. Mogan Lake, in the Gölbaşı Special Environmental Protection Area, is one of the most important Ramsar-nominated wetlands in Turkey. Lake management applications have been performed by the local managers since 2008, including sediment cleaning activities such as dredging. In this context, the aim was to quantitatively predict the nitrogen dynamics (ammonium and nitrate release/uptake in the positive and/or negative direction) at the sediment–water interface, which has not been addressed in the eutrophication and sediment-related studies conducted to date on the lake in question. Sediment ammonium and nitrate flux were estimated to be between -9.16 and 0.36 μg m^{-2} d^{-1} and between -67.2 and 35.16 μg m^{-2} d^{-1}, respectively. The estimations for sediment nitrogen flux in Mogan Lake did not show a regular seasonal or spatial fluctuation. Our results demonstrate that low nitrogen release levels in Mogan Lake do not pose a threat to its nutrient level. In conclusion, both monitoring and reducing external loading is still the top priority for a long-term recovery of water quality in the process of freshwater ecosystems.

Key words: freshwater, internal nutrient release/retention, trophic lake, nitrogen flux

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1. Introduction

Scientific studies which define the importance of sediment and the role of the overlying water nutrient dynamics in the process of eutrophication are important among studies on standing water aquatic system. As a component of sediment nitrogen dynamics, the adsorption of sediment particles by positively-charged ammonium depends on the organic matter content of the sediment: Sediments rich in organic matter retain and accumulate nitrogen in their structure. The sedimentation and re-suspension of various forms of nitrogen determines the direction of the nitrogen dynamics in aquatic systems. While the retention of organic nitrogen in sediment reduces its usefulness for living plants and organisms, its release from the biomass during decomposition returns these nutrients to a useful form (Delince 1992, Hakanson & Jansson 2002). Variations in concentration at the sediment–water interface carry great importance within this dynamic for the dissolved nutrients in the uppermost sediment layer. Most sediment organic matter is mineralized in the top layer; concentration variations allow for the diffusional transport of nutrients between the sediment and the water. Although ammonium and nitrate exchange between the sediment and water vary by season and locality, the diffusional release of these ions can be modelled according to Fick's First Law of Diffusion (Serpa et al. 2007). The processes of nitrification and denitrification, components of the nitrogen cycle, are dependent on temperature. The hydrodynamics in shallow, eutrophic lakes can induce sediment nutrient release and dispersion – primarily through water temperature, but also depth, nutrient types, pH, concentration gradient, redox potential and the organisms that are present (Wu et al. 2019).

Nitrate and nitrite contamination, especially in surface waters such as lakes, has been reported to cause serious environmental and health problems in developing countries (Zhang & Angelidaki 2012). Özkundakçı et al. (2011) studied modified zeolite use and sediment nutrient release in the eutrophic, small, shallow Okano Lake in New Zealand. In terms of nutrient inactivation, they claimed that calcite, modified clay minerals and iron compounds could be used as temporary measures to reduce nutrient loads by bonding with them and trapping them in the sediment.

High concentrations of anthropogenic activity surrounding aquatic systems can cause several environmental problems, such as eutrophication and algae blooms, due to the excessive release of active nitrogen into lakes (Vitrousek et al. 1997, Seitzinger & Kroeze 1998, Zhong et al. 2021). Dredging is a practice that has been used for many years to bring the internal load of lakes under control. Its primary aim is to reduce the release of nutrients from the top layer of sediment into the water. The nitrogen load in lakes is controlled through sediment analysis and dredging.

Nitrogen dynamics in eutrophic lakes undergoes seasonal changes, but the nitrogen load limit is generally reached in summer and autumn. Denitrification takes place at the sediment–water interface, and is known to be the primary factor for nitrogen reduction in lakes. The three mechanisms controlling the denitrification process are anoxic conditions, denitrators and carbon sources that can be used by life forms. The findings of a study by Shena et al. (2020) indicate that ideal conditions for denitrification occur during algae blooms at the sediment–water interface and in the overlying water, and that this leads to nitrogen reduction.

Nitrogen has three potent effects on the underwater flora in aquatic systems, such as macrophytes: it encourages growth and shades the phytoplankton; it shades the periphyton; and it causes toxic stress by creating oxidative stress on plant metabolism and reduces photosynthesis through amino acid accumulation and dissolved carbohydrate loss, suppressing growth and resulting in chlorosis of the leaves. In a study on nitrogen's effect on the underwater plant *Vallisneria natans*, the researchers found no correlation between phytoplankton shading and nitrogen load. However, they did report that toxic stress due to nitrogen reduces the growth of macrophytes (Yu et al. 2015).

Both before and after it was declared a Special Conservation Area in 1990, studies were conducted in Mogan Lake, Ankara to determine the water quality (Burnak & Beklioğlu 2000, Pulatsü & Karabacak 2003, Karakoç et al. 2003, Gökmen 2004, Kapan 2011). Several lake management strategies have been applied by the local government – primarily bottom sediment removal, but also local macrophyte harvesting and tributary recharging. Related studies have been carried out to determine internal and external phosphorus load (Fakıoğlu & Pulatsü 2005, Topçu & Pulatsü 2008, Pulatsü & Topçu 2009). One such study, which involved measuring the chemical composition and phosphorus activity of the sediment, found that in terms of phosphorus release (between 0.1754 and 1.1249 mg m^{-2} day^{-1}), the critical value for phosphorus should be calculated by determining the adsorption capacity of the sediment (Topçu & Pulatsü 2017).

Using the AQUATOX Simulation Model, Akkoyunlu & Karaaslan (2015) projected advanced scenarios aimed at determining the toxic effects of Mogan Lake's water quality on aquatic organisms in the sediment. They reported that if external pollutant loading on the high nitrogen concentration in the lake was not eliminated, by 2020 the nutrient levels would change from eutrophic to hypertrophic, and that even if eliminative measures were taken, levels could possibly turn mesotrophic.

Within the scope of the 'By-Law on Determination of Sensitive Water Bodies and Areas Affecting these Water Bodies and Improvement of Water Quality', the trophic state of the lake was evaluated using the Carlson Trophic Index. It was determined that the lake was hypertrophic (extremely polluted) and that the ammoniacal nitrogen levels had exceeded acceptable limits. Although one part of Mogan Lake consists of reeds and swampy areas, the number of residential settlements and touristic facilities in the vicinity is extremely high. Sudden fish die-offs occur in the lake as a result of reduced bottom oxygen levels caused by sudden algae blooms, which in turn are brought about by seasonal temperature changes, higher nitrogen and phosphorus levels in the summer months and nitrogen and phosphorus being released from the bottom sediment (Anonymous 2016).

For the first time, a study conducted on Mogan Lake, one of Turkey's important Ramsar-candidate wetlands, aims to quantitively estimate nitrogen dynamics (positive and/or negative ammonium and nitrate release/retention) at the sediment–water interface, which differs from previous studies on eutrophication and sediment performed at this site.

Accordingly:

- the ammonium and nitrate dynamic in the sediment was estimated using the appropriate diffusion coefficient for ammonium and nitrate concentrations in the overlying water and pore water, along with the sediment water content and temperature;
- the effects of certain primary factors controlling the ammonium and nitrate dynamics in the sediment (water temperature, dissolved oxygen and pH) were determined;
- the sediment pore water was sampled, and ammonium and nitrate levels and pH values were determined.

In light of the findings, recommendations for sediment management strategies to improve the lake were performed.

2. Materials and methods

2.1. Study area and sampling stations

Mogan Lake, the study area, is located in the Lower Basin of Ankara Creek, 20 km south of Ankara on the Ankara–Konya highway. It is an alluvial lake fed mostly by precipitation, along with water from more than five tributaries of various sizes. Its normal water level is at 972 m above sea level; the surface area at the normal water level is 664 km^2; the average depth is 3–5 m; and the volume at the normal water level is 13.34 million m^3. Mogan Lake has extremely few underground water sources; it is fed by irregular streams that generally dry up in the summer. The most important of these streams are located in the east and northwest sections of the basin: Sukesen, Başpınar, Gölova, Yavrucak, Çolakpınar, Tatlım, Kaldırım and Gölcük Creeks. In the gently-sloped, smooth topographical areas where these streams reach Mogan Lake, and where it connects to Eymir Lake, wetlands and swamp areas have developed. These deserve great attention from a hydrogeological, hydrological, climatic and biological standpoint (Anonymous 2016).

Some of the purposes these areas serve are supplying underground water storage for the lakes and supplying them with water during periods of drought. All of Mogan Lake's water, under the control of a regulator at the northeast end, empties into Eymir Lake, which is located on land owned by Middle East Technical University (METU). Mogan Lake is located at the edge of the Gölbaşı Special Conservation Area, and it is one of Turkey's important Ramsar-candidate wetlands. The lake receives about 4.5 million m^3 of recharge water per year from Kesikköprü Reservoir. While the first recharge took place in 2010 and was only performed during a drought, since 2014 there have been annual recharges between July and September (Anonymous 2016).

Six stations convenient for sediment sampling and thought to be representative of the lake were selected at Mogan Lake. The different stations were chosen according to the inputs of concentrated pollution inflow from plants and domestic waste. The stations were in areas with mainly water-rooted plants and dense negative construction that were subject to anthropogenic pollution sources. The study area and location of the stations are shown in Figure 1.

2.2. Field Work

Overlying water and sediment samples were obtained using Van Ween Grab at the six representative and convenient stations in Mogan Lake

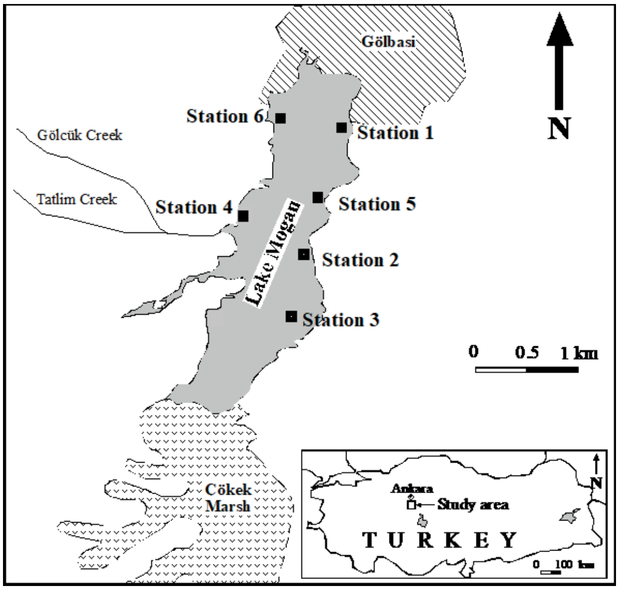

Figure 1

Study site and sampling stations in Mogan Lake (■: Station 1: 39°78'32" N 32°80'13" E; Station 2: 39°76'48" N 32°79'64" E; Station 3: 39°75'70" N 32°79'45" E; Station 4: 39°77'02" N 32°78'69" E; Station 5: 39°77'55" N 32°80'01" E; Station 6: 39°78'44" N 32°79'21" E)

(Figure 1), during a rainy period (October 2018) and a dry period (July 2019).

The redox potential of the sediment samples taken from the six stations using a Van Veen grab was measured onsite using a portable pH meter (YSI-Ecosense pH 100 A; ± 1°C sensitivity) fitted with a redox potential probe. The samples were placed in dark-coloured polyethylene bags and transferred to the laboratory.

Overlying water for the study was obtained from the indicated stations by siphoning at approximately 10 cm above the sediment, and measurements were taken onsite. Water temperature and dissolved oxygen were measured with an oxygen meter (YSI Pro 20; temperature range: 5–45°C, sensitivity: ± 1°C; dissolved oxygen range: 0–15 ppm, sensitivity: ± 0.2 ppm). pH values were measured with a field-type pH meter, and redox potential was measured with a redox electrode attached to the pH meter.

2.3. Laboratory Work

After the overlying water samples – which had been kept at +4°C until analysis – were passed through a 0.45-µm Millipore filter paper, ammonia (NH^{3+}), ammonium (NH^{4+}) and nitrate (NO^{3-}) concentrations were spectrophotometrically determined according to APHA guidelines (1995), using the Nessler method, phenate method and the brucine-sulphate method, respectively. The supernatants from the overlying water after filtering through the filter paper were analysed spectrophotometrically for total dissolved phosphorous (TDP) and soluble reactive phosphorous (SRP) with the ascorbic acid method (Shimadzu UV 1280, 220–240) according to standard analytical procedures (APHA, 1995).

After 20 minutes in a centrifuge at 3,000 rpm, the clear liquid at the top of the sediment pore water sample tubes was removed with a pipette and passed through a 0.45-µm Millipore filter paper. The ammonia (NH^{3+}), ammonium (NH^{4+}) and nitrate (NO^{3-}) concentrations of the pore water were spectrophotometrically determined according to APHA guidelines (1995) using the Nessler method, phenate method and the brucine-sulphate method, respectively. The supernatants of pore water after filtering through the filter paper were analysed for TDP and SRP with the ascorbic acid method according to standard analytical procedures (APHA, 1995). The pH value of the sediment pore water and the overlying water were measured with a digital field-type pH meter with a sample range of 0–14 and a sensitivity of 0.01.

The content of the sediment water was determined by weighing the samples before and after drying at 110°C for 16 hours and calculating the difference in mass according to Shrestha and Lin (1996). After being passed through a 0.5-mm sieve, the air-dried sediment samples were weighed both before and after firing for 2 hours at 550°C. Organic matter was determined by taking the difference in weight according to Kacar's method (1995). The total organic carbon (TOC) and total nitrogen (TN) contents of the sediment were determined using the Organic Carbon Analyzer and the Total Nitrogen Measurement Unit, respectively, according to Kacar's method (1995).

To calculate ammonium and nitrate release into the lake water through molecular diffusion, the formulae developed by Lavery et al. (2001) were used.

$$F = -\varphi . D . \Delta C / (\Delta z) \quad \text{(Eq. 1)},$$

where φ is the water content (%) of the sediment (porosity), D is the molecular diffusion coefficient (for NH^{4+}, $D = 1.4 \times 10\text{-}9\ m^2\ h^{-1}$; for NO^{3-}, $D = 8.5 \times 10\text{-}9\ m^2\ h^{-1}$), ΔC is the difference between the calculated released sections for ammonium [NH^{4+}] and nitrate [NO^{3-}] concentrations and Δz is the distance (0.05 m) between the calculated released section.

2.4. Statistical analysis

Statistical analysis of the data was performed using the software programmes Minitab and Mstat according to the principles outlined by Kesici and Kocabaş (2007). ANOVA and Duncan's multiple-range test and *t*-test were used to evaluate differences in the sediment pore water, sediment overlying water and sediment samples between wet and dry periods and between stations.

3. Results

3.1. Sediment pore water

The differences between the periods and stations with regard to average values for NH_{3+}, ammonium NH_{4+}, and nitrate NO_{3-} concentrations, as well as pH and total filterable phosphorus and total filterable orthophosphate concentrations in Mogan Lake, were found to be statistically significant ($p < 0.05$). These results are presented in Table 1.

3.2. Sediment overlying water

The differences in averages for dissolved oxygen, pH, water temperature, redox values and NH_3, NH_4, NO_3, TO, TP, SRP and TDP concentrations in the overlying water were found to be statistically significant ($p < 0.05$). These results are presented in Tables 2, 3 and 4.

3.3. Sediment

Water content (%), redox values, organic matter and TOC and TN concentrations were determined for the sediment samples from the six research stations with regard to the wet and dry periods in Mogan Lake. The differences between the averages for these parameters were found to be statistically significant ($p < 0.05$). These results are presented in Table 5.

3.4. Results for nitrogen (ammonium and nitrate) release from the sediment

During each portion of the study period, ammonium and nitrate release values were calculated for each research station. For ammonium release, the values ranged between -9.16 and 0.36 μg m^{-2} day^{-1}. The lowest values were found in July 2019 at Station 2, whilst the highest were recorded in October 2018 at Station 6. For nitrate release, the values ranged between -67.2 and 35.16 μg m^{-2} day^{-1}. The lowest values were found in October 2018 at Station 3, and the highest at Station 5 in the same month. The ammonium and nitrate release values varied in October, but ammonium release values were all negative while nitrate release values were all positive in July (Figures 2 and 3).

4. Discussion and conclusion

As the first study to examine the differing nitrogen dynamics at the sediment–water interface in Mogan Lake in October and July, this study contributes

Table 1

NH_3-N, NH_4-N, NO_3-N, SRP and TDP concentrations and pH values of Mogan Lake's sediment pore water, by period and station

Parameter	Period	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
NH_3-N (mg l^{-1})	Wet	0.422 ± 0.001 Eb*	0.892 ± 0.004 Aa	0.522 ± 0.003 Ca	0.413 ± 0.002 Fb	0.582 ± 0.001 Bb	0.452 ± 0.001 Db
	Dry	0.553 ± 0.001 Ea	0.580 ± 0.001 Db	0.524 ± 0.002 Fa	1.237 ± 0.002 Aa	0.835 ± 0.004 Ca	1.232 ± 0.005 Ba
NH_4-N (mg l^{-1})	Wet	0.544 ± 0.001 Eb	1.149 ± 0.005 Aa	0.673 ± 0.003 Ca	0.533 ± 0.002 Fb	0.750 ± 0.002 Bb	0.582 ± 0.001 Db
	Dry	0.712 ± 0.001 Ea	0.747 ± 0.002 Db	0.675 ± 0.002 Fa	1.593 ± 0.003 Aa	1.076 ± 0.005 Ca	1.587 ± 0.006 Ba
NO_3-N (mg l^{-1})	Wet	0.794 ± 0.005 Fa	0.913 ± 0.035 Ea	6.549 ± 0.000 Aa	3.199 ± 0.005 Ca	1.706 ± 0.000 Da	6.267 ± 0.008 Ba
	Dry	0.707 ± 0.005 Fb	0.809 ± 0.005 Ab	0.792 ± 0.004 Bb	0.752 ± 0.004 Db	0.733 ± 0.005 Eb	0.768 ± 0.005 Cb
SRP (mg l^{-1})	Wet	0.012 ± 0.000 Bb	0.011 ± 0.000 Ca	0.013 ± 0.000 Aa	0.012 ± 0.000 Ba	0.011 ± 0.000 Ca	0.011 ± 0.000 Ca
	Dry	0.021 ± 0.000 Aa	0.010 ± 0.000 Da	0.010 ± 0.000 Db	0.010 ± 0.000 Db	0.012 ± 0.000 Ca	0.012 ± 0.000 Ba
TDP (mg l^{-1})	Wet	0.241 ± 0.000 Ab	0.202 ± 0.000 Ab	0.233 ± 0.002 Ab	0.166 ± 0.096 Ab	0.195 ± 0.000 Ab	0.200 ± 0.002 Ab
	Dry	0.892 ± 0.002 Ba	0.849 ± 0.000 Ca	0.873 ± 0.052 Ba	0.992 ± 0.003 Aa	0.894 ± 0.000 Ba	0.916 ± 0.061 Aa
pH	Wet	8.85 ± 0.06 Da	9.40 ± 0.02 Ba	9.39 ± 0.02 Ba	9.22 ± 0.02 Ca	9.50 ± 0.02 Aa	9.40 ± 0.02 Ba
	Dry	8.84 ± 0.04 Da	8.86 ± 0.04 Cb	8.97 ± 0.04 Ab	8.80 ± 0.09 Eb	8.97 ± 0.04 Ab	8.91 ± 0.01 Bb

*The different capital letters in the same row show the differences between stations in the same period, while the different lower-case letters in the same column show the differences between the periods at the same station ($p < 0.05$).

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Table 2

O_2, pH, water temperature and redox values of Mogan Lake's sediment overlying water, by period and station

Parameter	Period	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
O_2 (mg l^{-1})	Wet	10.50 ± 0.08 Aa*	8.54 ± 0.01 Ca	8.84 ± 0.03 Ba	4.62 ± 0.01 Ea	8.27 ± 0.01 Da	8.56 ± 0.03 Ca
	Dry	8.47 ± 0.13 Ab	7.99 ± 0.01 Bb	8.23 ± 0.01 ABb	4.62 ± 0.01 Da	5.46 ± 0.04Cb	4.45 ± 0.02 Db
pH	Wet	8.65 ± 0.06 Da	9.268 ± 0.04 Ba	9.27 ± 0.01 Ba	9.00 ± 0.02 Ca	9.40 ± 0.01 Aa	9.25 ± 0.06Ba
	Dry	8.52 ± 0.01 Db	8.67 ± 0.01 Cb	8.70 ± 0.01 Bb	8.69 ± 0.00 Bb	8.72 ± 0.01 Ab	8.70 ± 0.01 Bb
Water Temperature (°C)	Wet	5.85 ± 0.06 Ab	5.58 ± 0.05 CDb	5.48 ± 0.05 Db	5.50 ± 0.08 Db	5.65 ± 0.06 BCb	5.70 ± 0.08 Bb
	Dry	18.55 ± 0.06 Aa	17.70 ± 0.00 Ca	18.48 ± 0.05 Ba	17.68 ± 0.05 Ca	17.30 ± 0.00 Da	17.65 ± 0.06 Ca
Redox (mV)	Wet	-115.00 ± 0.00 Fa	-97.00 ± 0.00 Da	-96.00 ± 0.00 Ca	-98.00 ± 0.000 Ea	-95.00 ± 0.00 Bb	-84.00 ± 0.82 Ab
	Dry	-86.00 ± 0.00 Ab	-94.00 ± 0.00 Bb	-96.00 ± 0.00 Da	-96.00 ± 0.00 Db	-96.00 ± 0.00 Da	-95.00 ± 0.00 Ca

*The different capital letters in the same row show the differences between stations in the same period, while the different lower-case letters in the same column show the differences between the periods at the same station (p<0.05).

Table 3

NH_3-N, NH_4-N and NO_3-N concentrations (filtered and non-filtered) of Mogan Lake's sediment overlying water, by period and station

Parameter	Period	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
NH_3-N (mg l^{-1})	Wet	0.339 ± 0.001 Fb*	0.354 ± 0.001 Eb	0.350 ± 0.002 Db	0.383 ± 0.001 Cb	0.475 ± 0.001 Ba	0.499 ± 0.002 Aa
	Dry	0.531 ± 0.001 Aa	0.530 ± 0.005 Aa	0.479 ± 0.001 Ba	0.422 ± 0.002 Ca	0.395 ± 0.001 Db	0.399 ± 0.002 Eb
NH_3-N Filtered (mg l^{-1})	Wet	0.341 ± 0.001 Eb	0.374 ± 0.001Db	0.286 ± 0.002 Fb	0.447 ± 0.011 Cb	0.700 ± 0.002 Aa	0.580 ± 0.002 Ba
	Dry	0.533 ± 0.001 Aa	0.510 ± 0.001 Ba	0.416 ± 0.001 Ea	0.478 ± 0.001 Ca	0.418 ± 0.001 Db	0.361 ± 0.002 Fb
NH_4-N (mg l^{-1})	Wet	0.437 ± 0.002 Fb	0.455 ± 0.001 Db	0.451 ± 0.003 Eb	0.493 ± 0.001 Cb	0.612 ± 0.002 Ba	0.642 ± 0.003 Aa
	Dry	0.684 ± 0.001 Aa	0.682 ± 0.007 Aa	0.617 ± 0.002 Ba	0.544 ± 0.002 Ca	0.509 ± 0.001 Eb	0.514 ± 0.002 Db
NH_4-N Filtered (mg l^{-1})	Wet	0.439 ± 0.001 Eb	0.482 ± 0.002 Db	0.369 ± 0.002 Fb	0.575 ± 0.014 Cb	0.902 ± 0.002 Aa	0.747 ± 0.003 Ba
	Dry	0.687 ± 0.002 Aa	0.657 ± 0.001 Ba	0.536 ± 0.001 Ea	0.590 ± 0.001 Ca	0.539 ± 0.001 Db	0.465 ± 0.003 Fb
NO_3-N (mg l^{-1})	Wet	1.277 ± 0.005 Fb	2.272 ± 0.007 Da	1.584 ± 0.005 Ea	3.235 ± 0.000 Ba	2.495 ± 0.006 Ca	7.743 ± 0.006 Aa
	Dry	1.186 ± 0.005 Aa	1.053 ± 0.000 Eb	1.160 ± 0.005 Bb	0.941 ± 0.004 Fb	1.075 ± 0.005 Db	1.130 ± 0.005 Cb
NO_3-N Filtered (mg l^{-1})	Wet	1.035 ± 0.000 Fb	1.324 ± 0.000 Db	1.228 ± 0.005 Eb	4.937 ± 0.000 Aa	4.371 ± 0.005 Ba	4.056 ± 0.006 Ca
	Dry	1.523 ± 0.005 Aa	1.528 ± 0.005 Aa	1.525 ± 0.006 Aa	1.405 ± 0.005 Cb	1.405 ± 0.005 Cb	1.461 ± 0.008 Bb

*The different capital letters in the same row show the differences between stations in the same period, while the different lower-case letters in the same column show the differences between the periods at the same station (p<0.05).

Table 4

TO, TP, SRP and TDP concentrations of Mogan Lake's sediment overlying water, by period and station

Parameter	Period	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
TO (mg l^{-1})	Wet	0.090 ± 0.000 Db*	0.097 ± 0.001 Bb	0.285 ± 0.001 Aa	0.090 ± 0.001 Db	0.091 ± 0.001 Db	0.095 ± 0.001 Cb
	Dry	0.095 ± 0.001 Ea	0.106 ± 0.000 Da	0.092 ± 0.001 Fb	0.284 ± 0.000 Ca	0.362 ± 0.002 Aa	0.360 ± 0.000 Ba
TP (mg l^{-1})	Wet	0.479 ± 0.000 Aa	0.381 ± 0.001 Ba	0.255 ± 0.001 Da	0.203 ± 0.001 Ea	0.480 ± 0.001 Aa	0.379 ± 0.001 Ca
	Dry	0.113 ± 0.000 Eb	0.128 ± 0.000 Bb	0.123 ± 0.001 Db	0.150 ± 0.001 Ab	0.125 ± 0.001 Cb	0.124 ± 0.001 CDb
SRP (mg l^{-1})	Wet	0.011 ± 0.000 Ba	0.011 ± 0.000 Ba	0.010 ± 0.000 Ca	0.011 ± 0.000 Ba	0.012 ± 0.000 Aa	0.010 ± 0.000 Ca
	Dry	0.011 ± 0.000 Ba	0.011 ± 0.000 Ba	0.011 ± 0.000 Ba	0.011 ± 0.000 Ba	0.012 ± 0.000 Aa	0.011 ± 0.000 Ba
TDP (mg l^{-1})	Wet	0.087 ± 0.000 Fb	0.110 ± 0.000 Ca	0.108 ± 0.000 Ea	0.119 ± 0.000 Aa	0.114 ± 0.001 Ba	0.109 ± 0.001 Da
	Dry	0.095 ± 0.000 Da	0.078 ± 0.000 Bb	0.099 ± 0.001 Eb	0.095 ± 0.001 Db	0.102 ± 0.002 Ab	0.097 ± 0.001 Cb

*The different capital letters in the same row show the differences between stations in the same period, while the different lower-case letters in the same column show the differences between the periods at the same station (p<0.05).

findings to fill a gap in the literature. Diffusion coefficients were used in the study to estimate the amount of ammonium and nitrate released from the sediment into the lake water (in a positive and/or negative direction), the ammonium and nitrate concentrations in the overlying water and pore water and the water content and temperature of the sediment for two different periods, representing wet and dry seasons. The ammonium and nitrate release values from the sediment varied between -9.16 and 0.36 µg m^{-2} day^{-1} for ammonium release – with the lowest value being reported in July 2019 at Station 2 and the highest in October 2018 at Station 6 – and for nitrate release, between -67.2 and 35.16 µg m^{-2} day^{-1}, with the lowest value being found in October 2018 at Station 3 and the highest value coming in the same

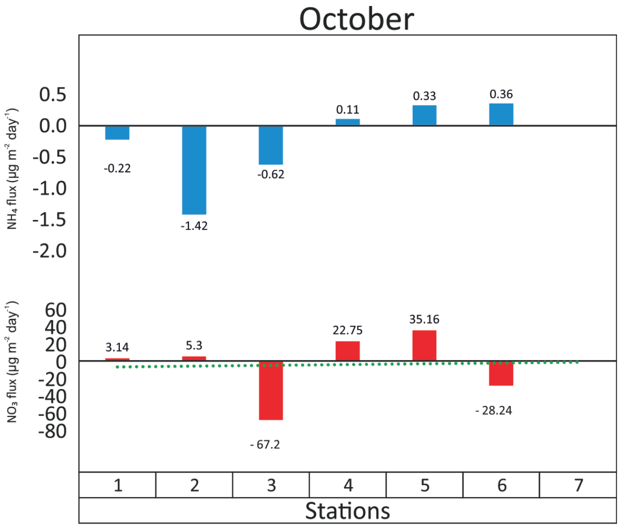

Figure 2

Ammonium and nitrate flux in Mogan Lake in October

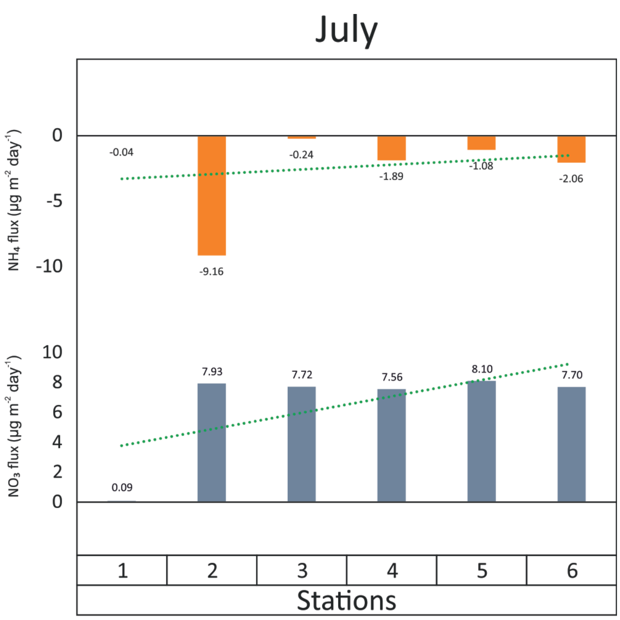

Figure 3

Ammonium and nitrate flux in Mogan Lake in July

month at Station 5. Additionally, factors that affect ammonium and nitrate release from sediment, such as water temperature, dissolved oxygen and pH, were determined. Delince (1992) and Hakanson and Jansson (2002) reported that absorption/retention of pore water ammonium particles in the sediment depends on the organic matter content of the sediment. In aquatic systems where the proportion of organic matter is below 20%, the level of humic acid in the organic matter structure is proportionally higher, and this is known to affect the nutrient retention of the sediment. During the study period, the highest and lowest OM values in Mogan Lake were determined to be 0.04% and 0.1%, respectively; the low values for organic matter in the sediment support the idea that the sediment functions as a nitrogen trap from time to time. In shallow aquatic systems, 30% of photosynthetically produced organic matter is deposited in the sediment and re-released into the water. Oxygen consumption during the circulation of organic matter causes it to be a nutrient source in the water column or a nutrient trap. A portion of organic matter is re-mineralized through denitrification, and this causes unused nitrogen to be biologically converted into gaseous form. Denitrification in water near the shoreline is the most important process affecting nitrogen removal. Under low oxygen conditions, nitrification/denitrification in the sediment is hindered, and re-mineralized nitrogen transforms into NH_4 on its way to becoming the primary nitrogen supplier of the water body, thus increasing eutrophication (Laurent et al. 2016).

Nitrogen release in wetlands occurs through the sedimentation and re-suspension of various forms of nitrogen; plants are a critical factor that either directly or indirectly influence nitrification and denitrification processes (Tang et al. 2020). As ammonium is a positively-charged ion, its particles are thus adsorbed in the sediment. The adsorbed ammonium level and the ammonium concentration in the water are balanced, and any change in water chemistry can cause it to be released into the water (Delince 1992, Hakanson & Jansson 2002). Researchers Klapwijk and Snodgrass (1982) determined that ammonium concentrations in the sediment pore water in Lake Ontario, Canada were 2 to 100 times greater than those in the overlying water (Delince 1992). The sediment pore water ammonium concentration in Mogan Lake was found to be on average twice as high as that of the overlying water.

Excess nitrogen in the water can easily transfer to the sediment and collect there; in this way, the sediment can become a potential nitrogen source. Sediments play an important role in chemical and biological processes. Nitrogen release from the sediment affects nitrogen concentrations in the water, and if the entry of external nutrients is controlled, this will cause the lake to remain in a eutrophic state throughout the year. Nitrogen in the sediment and water is absorbed by plants as NH_4-N, and this nitrogen can – through diffusion, resuspension of the sediment and bioturbation – be released into the overlying water. Transfer of dissolved ammoniacal nitrogen into the water at the sediment–water interface is the most important method of nitrogen release, and this can lead to potential ammonium release, creating a risk of a change in the water's trophic state to eutrophic (Zhu et al. 2019). In Mogan Lake, ammonium release was generally at low levels, ranging between -9.16 and 0.36 μg m^{-2} day^{-1}. The fact that ammonium concentrations were low indicates that ammonium nitrogen was balanced within the nitrogen cycle, and that nitrification/denitrification and the microbial communities that host the anaerobic oxidation of ammonia were stable. This study reinforced the hypothesis that concentrated microalgae growth can serve as a filter, reducing the release of nutrients into the water column.

Table 5

Water content, redox, OM, TOC and TN values of Mogan Lake's sediment, by period and station

Parameter	Period	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
Water Content (%)	Wet	0.89 ± 0.01 Aa*	0.88 ± 0.02 ABa	0.86 ± 0.01 Ca	0.89 ± 0.01 Aa	0.90 ± 0.01 Aa	0.87 ± 0.01 BCa
	Dry	0.77 ± 0.01 BCb	0.79 ± 0.01 Ab	0.71 ± 0.00 Eb	0.78 ± 0.01 Bb	0.81 ± 0.01 Ab	0.76 ± 0.01 CDb
Redox (mV)	Wet	-21.20 ± 0.11 Da	-34.75 ± 0.25 Ba	-38.92 ± 1.22 Ba	-45.10 ± 2.13 Aa	-23.60 ± 2.02 Db	-28.00 ± 1.15 Ca
	Dry	-17.75 ± 0.50 Cb	-27.75 ± 0.01 BCb	31.25 ± 1.21 ABb	37.50 ± 2.69 Ab	-24.00 ± 2.03 BCa	-19.25 ± 1.89 Cb
OM (%)	Wet	0.05 ± 0.01 Ba	0.09 ± 0.00 Aa	0.04 ± 0.00 Bb	0.10 ± 0.02 Aa	0.10 ± 0.01 Aa	0.09 ± 0.02 Aa
	Dry	0.04 ± 0.02 Ba	0.04 ± 0.01 Bb	0.09 ± 0.02 Aa	0.09 ± 0.02 Aa	0.07 ± 0.01 Ab	0.05 ± 0.02 Bb
TOC (%)	Wet	2.42 ± 0.03 Fa	3.91 ± 0.04 Eb	6.25 ± 0.05 Bb	5.80 ± 0.12 Ca	5.39 ± 0.01 Da	7.10 ± 0.11 Aa
	Dry	2.04 ± 0.15 Ea	7.25 ± 0.55 Aa	6.40 ± 0.12 Ba	5.83 ± 0.14 Ca	2.30 ± 0.00 Db	5.68 ± 0.27 Cb
TN (%)	Wet	0.25 ± 0.02 Fa	0.35 ± 0.01 Eb	0.47 ± 0.01 Db	0.50 ± 0.03 Ca	0.53 ± 0.01 Ba	0.57 ± 0.01 Aa
	Dry	0.13 ± 0.01 Fb	0.59 ± 0.11 Aa	0.55 ± 0.02 Ba	0.49 ± 0.03 Ca	0.21 ± 0.00 Eb	0.40 ± 0.03 Db

*The different capital letters in the same row show the differences between stations in the same period, while the different lower-case letters in the same column show the differences between the periods at the same station ($p<0.05$).

Release levels of inorganic nitrogen fractions (NO_2, NO_3 and NH_4) were studied in Lake Illawarra, Australia in July, August and September 2001 (Qu et al. 2003). It was reported that ammonium's portion of release was maximal (> 80%) and that ammonium release levels increased between July and September due to increasing water temperature and macrophyte density in the littoral zone. When examining the results of the present study in Mogan Lake, it was determined that ammonium release increased during the rainy period, in the same manner as indicated by Qu et al. (2003).

Together with the intensification of anthropogenic activity, underwater macrophytes in some lakes play an important restructuring role; in shallow lakes they aid in protecting the clear water state (Moss 1990, Jeppesen et al. 2007, Scheffer 1998, Yu et al. 2015). Furthermore, aquatic vegetation has substantial effects on the spatial distribution of nutrient and OM concentrations at the sediment–water interface of aquatic ecosystems. The carbon/nitrogen mass ratio (CNMR), ranging from 10 to 23, is believed to correspond to aquatic plants that can qualitatively identify the origins of OM in sediment (Zhang et al. 2021, Deng et al. 2022). Nitrification and denitrification, components of the nitrogen cycle, are dependent on water temperature: in periods of high temperature, denitrification into gaseous forms of nitrate and nitrogen (N_2 and N_2O) and ammonium lead to decreasing nitrate levels in the sediment pore water, as reported by Serpa et al. (2007). The lowest level of NO_3-N in the sediment pore water in Mogan Lake was 0.71 mg l^{-1} in July, the hottest period; this finding is in line with those of the above-mentioned studies.

Levels of ammonium, nitrate and phosphate release from the sediment were studied in Machado Lake (Anonymous, 2007) – which is located in Los Angeles City Park, California and subject to nutrient-related water quality problems – as well as in the Mapopme River (Mohammed & Johnstone, 2002); the remobilization of nitrogen and phosphate from the sediment into the surface water, especially during the summer, was shown to be the most important source of these nutrients. In Mogan Lake, contrary to these findings, the highest estimated nitrogen release values were measured during the rainy period. Inorganic nitrogen fraction (NO_2, NO_3 and NH_4) release was studied in Lake Illawarra from the summer through the early autumn, and ammonium's portion of release values was reported to be maximal (>80%) (Qu et al. 2003). In Mogan Lake, however, in contrast to the reports of the above-mentioned researchers, NO_3-N release from the sediment was observed to be approximately 100 times higher than ammonium release.

Nowlin et al. (2005) estimated ammonium release from the sediment in a small, shallow eutrophic reservoir with hard water; while ammonium release rates showed no difference between stations – as with our findings in Mogan Lake – the autumn circulation had a clear effect on ammonium release, which was in line with our findings and in contrast to those of the previously mentioned studies.

Özkundakçı et al. (2011) studied modified zeolite use and nutrient release from the sediment in Lake Okano, a small, shallow, eutrophic lake in New Zealand. The release of ammoniacal nitrogen from the sediment into the overlying water reached its maximum value in November, at 440 mg N m^{-2} day^{-1}, while the minimum value was estimated at -251 mg N m^{-2} day^{-1}. During summer stratification, hypolimnetic sediments function as a source or a trap in terms of ammonium release. As for nitrogen release from the sediment during the summer stratification period in Mogan Lake, the sediment functioned as a trap by retaining NH_4-N.

In China's shallow, eutrophic Lake Chaohu, nitrogen in the lake water and sediment pore water was measured monthly, and local and seasonal changes were observed (Zhang et al. 2008). While the dominant form of nitrogen in the overlying water of Mogan Lake was nitrates, as in Lake Chaohu; the dominant form in the sediment pore water was to be ammonium for Lake Chaohu unlike Mogan Lake representing a non-stable fluctuation between ammonium and nitrate concentrations. This situation indicates the development of strong oxidative nutrient degeneration at the sediment–water interface. Among the nitrogen forms in the sediment, ammonium generally functions as a source and nitrate serves as a trap. Ammonium release in aquatic environments is governed by various factors, such as sediment type, organic matter oxidation, water temperature and dissolved oxygen concentrations. In Mogan Lake, in parallel to other researchers' findings, a negative correlation was found between ammonium concentrations in the sediment and dissolved oxygen concentrations.

In New Zealand, Burger et al. (2007) carried out a seasonal study using benthic chamber incubation on SRP and ammonium release rates from the sediment. Ammonium release ranged between 2.20 and 270 mg m^{-2} day^{-1}. The high ammonium release rate in the summer was found to be correlated with the high percentage of organic matter in the sediment. The highest nitrogen release values in Mogan Lake (NO_3-N: 35.16 µg m^{-2} day^{-1} in October) were also found to be related to high levels of sediment organic matter in the same month; this is thought to have occurred following a measured reduction in sediment organic matter after dredging was performed in the lake.

Lavella et al. (2019) conducted a study on the River Thames in London, demonstrating the effects of restoration efforts on the nitrogen dynamic at the sediment–water interface in rivers. In the restored areas of the river, ammonium release was calculated to be between -8.9 and 5.0 µg N m^{-2} h^{-1}, and the average nitrate release was between -33.6 and 97.7 µg N m^{-2} h^{-1}. In Mogan Lake, ammonium and nitrate release was calculated between -9.16 and 0.36 µg m^{-2} d^{-1} and -67.2 and 35.16 µg m^{-2} d^{-1}, respectively. While neither ammonium nor nitrate release can be said to be directly affected by environmental conditions in the sediment, the small range of values for nitrogen release can be attributed to the retention capacity of the sediment, biochemical transformation, anthropogenic pollutants and specific restoration efforts for the lake, such as sediment dredging.

In the nitrogen cycle, while dissolved oxygen concentrations at the sediment–water interface reflect redox potential, they affect ammoniacal nitrogen and nitrate–nitrogen and nitrite–nitrogen exchange. As Mu et al. (2017), Yan et al. (2020), Wang et al. (2020) and Wang et al. (2022) reported, nitrification occurs easily under aerobic conditions, the nitrate/nitrogen concentration in the sediment increases even more and there is nitrate/nitrogen release into the overlying water. In line with this, in Mogan Lake the highest value for nitrate/nitrogen was measured during October, when the oxygen level was at 10.50 mg l^{-1}. Sustained low nitrogen release from the sediment can be evaluated as a sign that the overlying water in the lake has not reached an anoxic state.

Low concentrations of ammoniacal nitrogen indicate that it is balanced within the nitrogen cycle, and that the microbial communities that contribute to nitrification/denitrification and anaerobic oxidation of ammonia are stable. While Zhu et al. (2019) found ammoniacal nitrogen release to be generally high – ranging between 5.35 and 48.76 mg m^{-2} day^{-1} – in Mogan Lake there was a low level of ammonium release (-9.15 to 0.36 µg m^{-2} day^{-1}). Low oxygen conditions prevent nitrification/denitrification in the sediment, and re-mineralized nitrogen transfers into the water column as NH_4, ready to be used by primary producers; this is how eutrophication increases. In Mogan Lake, there are high concentrations of macrophytes, the oxygen levels generally range between 4.45 and 10.5 mg l^{-1} and the overlying water is aerobic. These conditions foster the decomposition of the organic matter that has collected in the sediment, and thus, low levels of organic matter were observed in the sediment of the lake. As a result of all these factors in the lake, limited nitrogen release from the sediment occurred during the summer months.

In seasons when algae blooms occur, dissolved inorganic nitrogen in the water is consumed by the algae, and this in turn limits nitrogen utilization in the water. While the nitrogen dynamics in eutrophic lakes vary by season, nitrogen limitation generally occurs in the summer and autumn. In this study, the low levels of organic matter during the study period, the generally aerobic state of the system and the presence of macrophytes at the stations – as also reported by Shena et al. (2020) – encouraged nitrogen retention in the sediment.

In large, shallow, eutrophic lakes, hydrodynamics plays an important role in sediment nutrient dynamics. Wu et al. (2019) examined nitrogen and phosphorus exchange in the sediment in Taihu Lake in terms of hydrodynamic transport relative to high sediment solubility and coastal conditions, and compared numerical simulations with long-term ecological data analysis. Total sediment organic carbon content in Taihu Lake was between 1.28% and 3.52%, with an average value of 1.87%. The sediment nitrogen content (TN) varied between 319.4 and 3,123.80 mg kg^{-1}, and the average value was 1,256.8 mg kg^{-1}. In Mogan Lake, while the TOC content of the sediment ranged between 2.04% and 7.25% and was higher than that reported in Taihu Lake, the sediment TN concentrations varied between 0.13% and 0.59% – extremely low when compared to other findings. Even if the nitrogen control factors in this type of eutrophic aquatic system are not entirely clear, it is known that the responsible biochemical processes, the corresponding transport rates and nitrogen removal activities cause differences between lakes in terms of their sediment nutrient release/retention.

Freshwater lakes are important and sensitive points for the removal of anthropogenic nitrogen loads transported from the land to the coastal waters of the oceans. Accordingly, in a study carried out by Müller et al. (2021) on the eutrophic Baldegg Lake and the oligotrophic Sarnen Lake in Switzerland, the aim of which was to reveal the differences between nitrogen removal strategies, a close link was demonstrated between annual nitrogen loads and removal rates in eutrophic lakes, as was a statistically significant correlation between the overlying water nitrate concentrations and removal rates. While NO_3-N release in Baldegg Lake ranged between 15 and 55 mg N m^{-2} day^{-1}, NO_3 concentrations in the overlying water ranged between 1.2 and 1.4 mg N l^{-1} and did not show significant seasonal fluctuations. The NO_3 concentrations in Mogan Lake's overlying water varied between 1.04 and 4.94 mg N l^{-1}, close to the values for Baldegg Lake, but Mogan Lake's values for NO_3-N release (-67.2 to 35.16 µg N m^{-2} day^{-1}) were significantly lower than those reported for Baldegg Lake. The low NH_4 release levels in Mogan Lake increased to 0.36 µg N m^{-2} day^{-1} in October, following the stratification period; this is thought to have been caused by the mineralization of organic matter deposited in the sediment over the high primary production season. According to the researchers, seasonal increases in nitrogen removal rates in eutrophic lakes are linked to seasonal oxygen release variations at the sediment–water interface. The results indicate that increasing oxygen levels stimulate mineralization in the sediment, which in turn contributes to denitrification.

Nitrogen and phosphorus concentrations in lake water can be affected by internal nutrient loading from the sediment. To determine the effect of internal nutrient loading from the sediment on water quality in Euiam Lake in South Korea, Lee et al. (2019) conducted modelling in experimental benthic chambers based on a three-way hydrodynamic and transport model. At -7.915 to 0.074 mg N m^{-2} day^{-1} for NH_4-N release and -17.940 to 1.209 mg N m^{-2} day^{-1} for NO_3-N release, the values in the study were much higher than the estimated ammonium and nitrate release values for Mogan Lake.

Zhong et al. (2021) studied the long-term effects of nitrogen loading on the sediment–water interface in Meiling Bay of Taihu Lake, where dredging was practiced. Sediment dredging helps to reduce organic matter in the surface sediment as well as total nitrogen content, and it improves redox potential at the sediment–water interface. At the same time, the study posited that sediment dredging in shallow lakes is both advantageous and disadvantageous for controlling internal nitrogen loading. While the practice helps to reduce inorganic nitrogen flow at the sediment–water interface, it also induces nitrogen removal through denitrification and anammox. In the present study in Mogan Lake, which aimed to determine post-dredging sediment nitrogen release values, it was concluded that dredging, a management practice, aided in keeping sediment nitrogen release at low levels. In order to control internal nitrogen loading with dredging, external particulate matter should be prevented from entering the lake and the nitrogen release process from the sediment into the water should be observed carefully.

The fact that the highest release values during the study period in Mogan Lake were linked to the high pH levels measured in October shows that the pH level of sediment pore water has a direct effect on nitrogen release from the sediment. The presence of macrophytes at the Mogan Lake stations supports the idea that rooted aquatic macrophyte systems reduce nutrient concentrations. Macrophyte roots provide oxygen to the sediment and prevent nutrient transfer from the sediment into the lake water; however, when macrophyte density is too great the sediment becomes anoxic, and this can cause nutrient release. One finding of this study is that macrophyte roots are an oxygen source for the sediment and prevent nitrogen release from it. Accordingly, macrophyte harvesting, currently practiced by the local government to control macrophytes in the lake, seems to be beneficial.

In this context, sediment is a sink, not a source in terms of nitrogen in Mogan Lake. It was determined in this study that low nitrogen release levels in the lake do not pose a threat to its nutrient level. Physical, chemical and biological measures can be taken to control eutrophication in lakes and prevent internal nutrient loading. However, when external nutrients are prevented from entering the lake, this can activate internal nutrient loading from the sediment into the lake water and increase its share in eutrophication. As sediment nitrogen release in Mogan Lake is extremely low, it is thought that dredging serves to deepen the lake; however, the lack of previous data with nitrogen parameters in the sediment prevented us drawing any conclusions with regard to the internal nitrogen loading.

The study data, including concentrations of various forms of nitrogen in the lake water and the sediment, will provide a basis for future studies aiming to control the lake's water quality. In the light of this fact, monitoring nitrogen fraction variations in the pore water and the overlying water could potentially result in changes to the lake's nitrogen cycling mechanisms, with lake sediments switching from net sinks to net sources of nitrogen. This feature is potentially important to management strategies related with lake sediment. Accordingly, as the first scientific record of estimated sediment nitrogen release/retention, the data can be used advantageously to develop strategies to improve the lake. Moreover, considering the evaluation of the findings, the goal should be to implement a monitoring programme for the lake's trophic level.

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