The ice cover shapes the spatial and temporal characteristics of water quality in Hulun Lake during winter
Wen Ao, Hua-shan Dou, Cen-cen Yu, Wen-lin Wang, Zeng-long Wang, Qi Wang, Lu Lu, Xing-jun Zhou, Rui-ming Han and Chang-xin Zou

ABSTRACT
Being the largest boreal steppe lake in Northeast China, Hulun Lake has been characterized by eutrophication induced by abnormally high organic matter. This work investigated therefore the physicochemical and water quality parameters of Hulun Lake, and that of the inflowing Crulen River and Orshen River through winter, to reveal the spatial and temporal characteristics of water quality without impact of algal bloom, atmospheric deposition, wind or allochthonous nutrient input. Results showed that the prevention of wind-induced sedimentary resuspension accompanied with the minimized volume of tributary inflows is supposed to predominate the eutrophication alleviation. The formation of ice cover had a slight concentrative effect on water ion content. However, ice cover resulted in an increasingly homogenous distribution of phosphorus and oxygen-depleting organic matter over the entire lake. The two headwater streams demonstrated limited impact on water quality in estuaries in winter without showing evident coordination in upstream water nutrient level. It is suggested that the prevention of wind disturbance by ice cover and the subsequently modified hydrodynamic and water ecological processes are the determinant factors on water quality in Hulun Lake during winter.

Key words | eutrophication, Hulun Lake, icebound period, influencing factor, water quality

HIGHLIGHTS
- Hulun Lake is the representative lake in the cold and arid regions of northern China.
- The physicochemical and water quality parameters of Hulun Lake, and that of the inflowing Crulen River and Orshen River through winter, were investigated.
- The formation of ice had a slight concentrative effect on water ion content.
- Covering by ice dramatically reduced the wind-induced resuspension of benthic particles, resulting in an increasingly homogenous deposition of phosphorus and oxygen-depleting organic matter in overlying water.
- The prevention of wind-induced sedimentary resuspension accompanied with the minimized volume of tributary inflows is supposed to predominate the eutrophication alleviation.

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INTRODUCTION

Hulun Lake is the representative lake in the cold and arid regions of northern China, which acts as the ecological protective screen against desertification. During the last decades, Hulun Lake with its unique hydrologic characteristics has functioned in a very crucial role in northern China for fisheries, water resources and bird habitat (Guo et al. 2013). Located in the sparsely populated Hulun Buir Steppe, restricted settlement and low density of population make sure the direct anthropogenic impact is relatively limited to Hulun lake (Chen et al. 2015). However, the concentration of COD<sub>c&tau;</sub> is abnormally high and reaches about 59 mg C/L, which was several times that of many eutrophic lakes in China (e.g., 5–7 mg/L in Taihu Lake) (Tang et al. 2009). Whether the high concentrations of TN and COD in Hulun Lake come from internal ecosystems or external grassland ecosystems still remains to be revealed.

The frozen period of Hulun Lake is about 180 days a year from Oct to March, during which the ice progressively develops from the margins to the lake center until completely icebound. Ice is a temporary buffer for atmospheric sedimentation, and modifies the exchange of substances between air and water. Pollutants deposited during the winter are locked up in the ice and snow and released in the spring thaw (Mats & Granskog 2004). Whether the high concentrations of TN and COD in Hulun Lake come from internal ecosystems or external grassland ecosystems still remains to be revealed.

The migration process of pollutants in the process of ice covering has been studied and it was found that pollutants could migrate from the ice body to water, and the concentration of pollutants in the middle layer of the ice body was the smallest while that of the bottom layer was the highest (Lv et al. 2015). Comparison of the water quality during freezing and thawing processes demonstrated that the water quality progressively became worse during ice formation and gradually mitigated during melting (Song et al. 2016).

Until now, a comprehensive analysis of the dynamics of water quality in Hulun Lake during the entire ice-bound period and its relation with specific conditions such as missing wind disturbance and decreased volume of inflows is still not available. The present study detected the water quality of Hulun Lake and that of the upstream and estuary of Crulen River and Orshen River from Oct to March, (1)
to reveal the spatial distribution of water quality parameters and their changes through the icebound period; (2) to partition the exact contribution of ice cover and inlet rivers and sediment release to water quality; (3) to verify the correlation between the influencing factors and lake eutrophication level.

MATERIALS AND METHODS

Hulun Lake and the catchment

Hulun Lake (48°31′-49°20′N, 116°58′-117°48′E), the fifth largest lake in China, is situated northeast of Inner Mongolia where the borders of China, Russia and Mongolia converge. Located in Hulun Buir Steppe, the average water depth of Hulun Lake is 5.7 m, with the maximum of 8 m recorded in 1968 and the minimum of less than 3 m in 2009 (Li et al. 2013). The subsequent volume of water storage varied from 14 billion m$^3$ to 3.5 billion m$^3$ with the relevant lake area of 2,406 km$^2$ to approximately 1,609.6 km$^2$, respectively (Zhang et al. 2019). A National Nature Reserve of a total 7,400 km$^2$ had been designated in 1992 covering Hulun Lake and the surrounding grasslands (Zhang et al. 2019).

The entire region is sparsely populated and the anthropogenic influence has been limited to inflow quantity regulation referring to three inlet rivers, Crulen River, Orshen River and Hulun River, and one outlet river, Xinkai River (Figure 1). However, only Crulen River, headed in from the southwest, and Orshen River, from the southeast, keep offering inflows during the icebound winter from October to the next April, while Hulun River and Xinkai River are completely disconnected by artificial sluice gates. Though the year-to-year variations of inflow quantity oscillate profoundly during winter, the long-term average quantity of monthly inflow from Crulen River and Orshen River shrink dramatically from 80.13 to 69.86 million m$^3$ in October to 0.07 and 12.66 million m$^3$ in March, respectively (unpublished data, averaged from 1961 to 2017).

Sampling

Ten sites distributed in Hulun Lake (L1-L10) and four sites from both the upstream and the estuary of Crulen River (U14 and E13) and Orshen River (U11 and E12) were selected to collect water samples (Figure 1). The area of Hulun Lake is about 2,030 km$^2$. In Oct, the average depth of water in Hulun Lake is 3.81 m. In Dec, Jan and Mar, the thickness of ice layer over the lake is 82.50 cm, 95.81 cm and 68.20 cm, respectively. In addition, the wind speed reaches 5.09 m/s in Oct.

Figure 1 | Allocation of sampling sites in Hulun Lake and the two headwater streams Crulen River and Orshen River.
From October 2018 to March 2019, the frozen ice cover was drilled at the same geographic coordinates of each site before sampling. The waters 50 cm beneath the ice-water interface and 50 cm above the water-sediment interface were carefully collected and mixed as one water sample and three samples were collected from each site at the beginning of each month. Water samples were then stored in amber glass bottles under cool conditions and transported immediately to the laboratory for quantification.

Physical and chemical analytical methods

At each sampling site, water temperature, pH, dissolved oxygen (DO), oxidation-reduction potential (ORP) and electric conductivity (EC) were measured in situ using a multi-parameter water quality monitor (YSI 6600, USA). Salinity and total dissolved solid (TDS) were measured using a water quality monitor (Multi 3630, Germany). In laboratory, total nitrogen (TN) was analyzed using a UV-6100 spectrophotometer (Mapada, China) accordingly (Raveh & Avnimelech 2013). Total phosphorus (TP) was analysed by colorimetry following digestion with K2S2O8 and NaOH (Ebina et al. 1985). Chemical oxygen demand (CODMn) was determined using the acid-potassium permanganate method. The measure of chlorophyll a (Chl.a) was conducted by acetone extraction (Song et al. 2013).

Eutrophication assessment

The state of eutrophication was evaluated with the Trophic Level Index (TLI) method based on Chl.a (Wang et al. 2002). First, the relative weight of water parameters adopted the empirical recommendation for lake water in China (Table 1). The comprehensive nutrient state index of water body is then calculated by weighted average with the following equation:

\[
TLI(\Sigma) = \sum_{j=1}^{m} W_j \cdot TLI(j)
\]

where \( TLI(\Sigma) \) is the trophic level index; \( W_j \) is the relative weight of the nutritional status index of the \( j \)th parameter; \( TLI(j) \) is the battalion of the \( j \)th parameter. Nutrition status index, \( m \) is the number of evaluated parameters. The equations for calculating the nutrient status index are as follows:

\[
TLI(\text{Chl a}) = 10(2.5 + 1.086 \ln \text{Chl a})
\]
\[
TLI(\text{TP}) = 10(9.436 + 1.624 \ln \text{TP})
\]
\[
TLI(\text{TN}) = 10(5.453 + 1.694 \ln \text{TN})
\]
\[
TLI(\text{CODMn}) = 10(0.109 + 2.66 \ln \text{CODMn})
\]

where Chl.a represents the reference parameter, the equation for calculating the normalized correlation weight of the \( j \)th parameter is as follows:

\[
W_j = r_{ij}^2 / \sum_{i=1}^{m} r_{ij}^2
\]

The nutritional status of lakes was graded by a series of continuous numbers from 0 to 100 as: poor nutrition, \( TLI(\Sigma) < 30 \); middle nutrition, \( 30 \leq TLI(\Sigma) \leq 50 \); mild eutrophication, \( 50 < TLI(\Sigma) \leq 60 \); moderate eutrophication, \( 60 < TLI(\Sigma) \leq 70 \); severe eutrophication, \( TLI(\Sigma) > 70 \) (Wang et al. 2002).

Statistical analysis

Data were subjected to an ANOVA I using the SPSS software (IBM® SPSS® software, version 24.0.0) with the month referring to the stage of icebound as dependent variable. The statistical significance of the results was analyzed by the Student–Newman–Keuls test at the 5% level. Relationships among water quality indices were identified by Pearson’s correlation analysis \( (P < 0.05) \). The spatial variations of TN, TP and COD in Hulun Lake were derived from Kriging interpolation with ArcGIS 10.3.

Table 1 | The correlation between chlorophyll a and the parameters of lake water (reservoir) in China [15]

<table>
<thead>
<tr>
<th>Chl.a</th>
<th>TP</th>
<th>TN</th>
<th>CODMn</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_{ij} )</td>
<td>1</td>
<td>0.84</td>
<td>0.82</td>
</tr>
<tr>
<td>( r_{ij}^2 )</td>
<td>1</td>
<td>0.7056</td>
<td>0.6724</td>
</tr>
</tbody>
</table>

Chl.a, chlorophyll a; TP, total phosphorus; TN, total nitrogen; CODMn, chemical oxygen demand based on potassium permanganate.
RESULTS

TDS, EC, DO and pH levels

Total dissolved solid (TDS) indicates the total amount of inorganic minerals dissolved in water. The concentration of TDS in Dec and Jan were significantly higher compared with those in Oct and Mar ($P < 0.01$) (Figure 2). In Oct of 2018, the concentration of TDS in Hulun Lake ranged within 825–1,068 mg/L with an average of 947.20; however, in Jan of 2019, the average concentration of TDS increased to 1,154.80 mg/L then decreased. In Orshen River, the level of TDS ranged from 269.50 to 886.50 mg/L during the entire period, and the highest value occurred in January, which was consistent with that of Crulen River (Figure 3). No significant difference was observed between upstream and estuary in both inlet rivers. According to the level of TDS, it is recommended to classify fresh water (less than 1,000 mg/L), slightly salty water (1,000–3,000 mg/L) and moderately salty water (3,000–10,000 mg/L) (Guo et al. 2011). Thus, during the ice cover formation and development, both Hulun Lake and the two inlet rivers turn from fresh water to slightly salty.

Water electrical conductivity (EC) indicates the amount of ions in water. The EC of Hulun Lake ranged from 1,417 to 1,811 $\mu$S/cm in Oct with an average of 1,664 $\mu$S/cm...
In Dec and Jan, the values of EC ranged from 1,672 to 1,957 μs/cm and 1,855 to 2,008 μs/cm respectively, without showing significant difference compared with those in Oct or Mar ($P > 0.05$). In Crulen River, the highest EC appeared in Jan to 1,905 μs/cm and in Orshen River in March to 2,087.50 μs/cm (Figure 3). Distinguished from

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TDS, the upstream in Orshen River recorded much higher EC compared with the estuary in Dec and Mar while in Crulen River, the peaks of EC that occurred in the estuary during Jan and Mar were much higher than those in the upstream.

DO values affect the survival of aquatic organisms and determine the self purification ability of a water body. The average levels of water DO in Hulun Lake were 11.70, 14.84, 14.99 and 15.90 mg/L in Oct, Dec, Jan and Mar respectively (Figure 2). Statistically, DO in Oct, during which the ambient temperature first dropped to around zero and the ice cover started to form, was significantly lower than those in Dec, Jan and Mar ($P < 0.01$). In the two main inlet rivers, the highest DO concentrations were observed in March; however, in Crulen the estuary had significantly higher DO than upstream and in Orshen the opposite in accompaniment with EC (Figure 3).

As shown in Figure 2, the water of Hulun Lake was weakly alkaline, with the pH value ranging from 8.85 to 9.02. In Orshen River, the pH in sampling sites ranged from 8.00 to 8.85, where the higher pH appeared at the upstream (except in March). In Crulen River, the average pH were 7.65, 7.80, 9.00 and 8.45 in Oct, Dec, Jan and Mar, respectively, and the higher values appeared at the estuary (Figure 3). However, there was no significant difference in pH among all sampling sites and months.

The average levels of water salinity in Hulun Lake were 0.77‰, 0.82‰, 0.88‰ and 0.76‰ in Oct, Dec, Jan and Mar respectively (Figure 2). In Crulen River, the highest salinity appeared in Jan to 0.90‰, and in Orshen River to 0.70‰ (Figure 3). The upstream in Orshen River recorded much higher salinity compared with the estuary while in Crulen River, the peaks of salinity that occurred in the estuary were much higher than those in the upstream.

**TN, TP and COD concentrations**

As shown in Figure 4, the TN of Hulun Lake ranged from 0.99 to 2.41 mg/L, with an average value of 1.64 mg/L. In Oct, the highest TN was recorded in the northern lake (L4) with an average of 2.28 mg/L. The level of TN then oscillated from 1.52 to 2.41 mg/L in Dec, 1.15 to 1.54 mg/L in Jan and 0.99 to 2.01 mg/L in Mar with an average of 1.81, 1.34 and 1.43 mg/L respectively. The level of TN in Oct and Dec was significantly higher than those in Jan and Mar ($P < 0.01$). The TP ranged from 0.15 to 0.26 mg/L in Oct, 0.11 to 0.19 mg/L in Dec, 0.10 to 0.17 mg/L in Jan and 0.08 to 0.21 mg/L in Mar, with an average values of 0.19, 0.12, 0.13 and 0.14 mg/L respectively. The level of TP in Oct was significantly higher than those of Dec, Jan and Mar ($P < 0.01$). Similarly with the distribution of TN, the level of TP was higher in the northern lake (L4) than other sites in October.

Chemical oxygen demand based on dichromate (COD) is an indicator of the total amount of reducing substances in water, out of which organic substances are the most common composite. In Hulun Lake, the highest level of COD appeared in Dec with an average of 184.40 mg/L, while the lowest average of 87.10 mg/L appeared in Mar. The level of COD ranged from 108 to 149 mg/L in Oct and 81 to 108 mg/L in Mar, with average values of 134.50 and
92 mg/L respectively. COD significantly decreased during the study period ($P < 0.01$) from Oct to Jan.

The distribution of TN, TP and COD of Hulun Lake manifested distinct spatial characteristics and changes over time (Figure 5). All three parameters uniformly culminated in Oct, and distributed heterogeneously among the northern and southern, eastern and western lake, except that of TP and COD in March. For TN, it was apparent that the higher values appeared frequently in the northern-centre part of the Lake, while the estuary of Orshen River and Crulen River either recorded very high or low TN values occasionally. This spatial heterogeneity remained over the entire study period. However, for both TP and COD, the northern-centre lake recorded the highest level in Oct and the hotspots moved to the west lake in Jan, then became homogenous dramatically all over the lake in March.

Nutrient loadings from Orshen River and Crulen River demonstrated the dissimilarity in TN, TP and COD inflows during the ice-bound period (Figure 6). In Orshen River, the content of TN ranged from 0.77 to 2.25 mg/L, where the estuary had relatively higher TN than upstream during Dec and Jan. In Crulen River, TN oscillated from 0.62 to
1.79 mg/L with the average of 1.07 mg/L in Oct, 0.98 mg/L in Dec, 0.74 mg/L in Jan and 1.36 mg/L in Mar respectively. TP concentrations of Orshen River varied from 0.06 to 0.09 mg/L in Oct, 0.01 to 0.03 mg/L in Dec, 0.08 to 0.09 mg/L in Jan and 0.14 to 0.16 mg/L in Mar respectively. In Crulen River, TP oscillated from 0.06 to 0.24 mg/L with an average of 0.21 mg/L in Oct, 0.06 mg/L in Dec, 0.12 mg/L in Jan and 0.14 mg/L in Mar respectively. In Orshen River, COD ranged from 22 to 224 mg/L with an average of 31.30 mg/L in Oct, 153.50 mg/L in Dec, 92.50 mg/L in Jan and 71.50 mg/L in Mar respectively. COD in Crulen River oscillated from 21 to 282 mg/L, and the maximum value occurred in Dec. In both inlet rivers, COD tended to increase two to three times once the ice cover completely formed (Dec and Jan) compared with the beginning of ice formation (Oct).

**Figure 6** The average concentration of total nitrogen (TN, a and b), total phosphorus (TP, c and d) and chemical oxygen demand (COD, e and f) of water samples in the two headwater streams, Orshen River, and Crulen River through the icebound period from October, the beginning of ice cover formation, to March, the onset of thaw.
Characteristics of eutrophication condition

The Trophic Level Index (TLI) measures the trophic state of an entire lake based on various water quality constituents. From Dec to Jan, Hulun Lake was in a mild eutrophication state during the ice-covered period, with TLI values higher than 60 (Figure 7). In March, the TLI value greatly reduced to 44.33 and the lake turned to a middle nutrition status. The correlation between TLI and water quality revealed that salinity had a strong positive correlation with TDS and EC (Table 2). Significant correlations were also found between EC and TDS, DO and EC. A positive correlation was observed between TP and TN as well ($P < 0.01$). However, there were strong negative correlations between temperature and TDS, DO and EC ($P < 0.01$), and TP and DO ($P < 0.01$). According to the statistical analysis, it is found that TN/TP in Hulun Lake was in the range of 8.00–18.90, 65% of which are in the optimal TN/TP range for algae growth.

DISCUSSION

The concentrative effect of icing process on water soluble ions

As the ice starts to form in Hulun Lake in Oct, water discharges salt and a large amount of ions is concentrated in the water layer under the ice, which leads to the increase of salinity level. Previous investigations have indicated that ice formation can greatly affect the distribution of solutes within the ice and in the underlying water column (Redfield 1960; Imhoff et al. 1979). In the present study, TDS and EC values of Hulun Lake are relatively higher during icebound period (in December and January) than those in Oct and Mar (Figure 2), which was similar to the trend of COD level (Figure 4). Guo et al. (2017) also found the average value of TDS is 831.31 mg/L in the non-frozen period, which is lower than that of the average value of 976.57 mg/L in the frozen period in Hulun Lake. And the annual extreme value of EC is 2.120 ms/cm in the frozen period in the water body under the ice cover. From the thermodynamic point of view, with the decrease of system temperature and energy, the solvation effect of water molecules on pollutant molecules will be weakened. Water molecules then form precipitation under the action of the hydrogen bond, and the pollutant molecules will be squeezed out and escape to the water body, resulting in the concentration of pollutants in the system (Zhang et al. 2011). Our results also revealed that the positive correlation between EC and TDS became much more significant with the progressive freezing of Hulun Lake (Table 2).

In frozen lakes, several studies have indeed reported much lower concentration of nutrients in the ice than in the underlying waters (Belzile et al. 2002; Zhang et al. 2012a, 2012b; Xue et al. 2016), suggesting an exclusion of nutrients during ice formation (Mullen & Warren 1988). The extent of exclusion varies with the chemical species, as determined the hydrated radius, diffusivity and solubility of ions through the ice crystal (Belzile et al. 2001). Exclusion factors for water parameters were determined as the ratio of concentrations in water to the concentration in ice (Belzile et al. 2002). At the field scale, the process can additionally be controlled by the rate of ice formation, and lake water composition at the time of ice crystal initiation.

On the other hand, it has been found that the exclusion factor for pH was close to unity, suggesting that the acid-base status of the lake waters was not significantly altered during ice formation (Song et al. 2017). As shown in Figure 2, the values of pH ranged from 8.85 to 9.02 in Hulun Lake, with imperceptible variations. This was consistent with the previous report from an investigation conducted at
Ulansuhai Lake in Northern China (Imhoff et al. 1979). During the freezing process, changes of pH are related to the distribution of water ions between the liquid and ice phases, in which anions and cations are distributed between liquid and ice phases in different fashions. This partition imbalance is relaxed by the transfer of H\(^+\) and OH\(^-\) to each phase, resulting in the acidification of the liquid phase when the cation is better distributed in the ice phase than the anion, and in the basification in the opposite situation (Gro & John 2008). At the same time, the respiration and photosynthesis of aquatic animals and plants indeed affect the concentration of CO\(_2\) in the water and further affect the pH value (Guo et al. 2014). The alkaline environment is conducive to the photosynthesis of algae, making the CO\(_2\) in the atmosphere easier to be captured (Song et al. 2019).

**Effect of internal release of sediment on nutrient concentrations in overlying water**

In the study, TN, TP and COD uniformly culminated in October. Sediment not only accepts the sinking pollutants from the water column, but also releases pollutants to the overlying water. The release of pollutants via resuspension of sediment is an important reason for the change of water nutrient concentrations. The transport and transformation of nutrients at the water-sediment interface are affected by environmental factors such as water temperature, pH, DO value and wind wave disturbance (Zhang et al. 2022a, 2022b). Previous research has shown that the closer the pH value is to 7.5, the greater the release of N and P from the sediment (Shi et al. 2019). When the pH value is about 7 and DO > 5 mg/L, the release of sediment and nitrification occur simultaneously, leading to a continuous increase of nitrate nitrogen in water (Li et al. 2021). The wind speeds were the major factor leading to the increase of the suspended solids in the water, resulting in the increase of nutrient concentrations. In October, the wind speed of Hulun Lake reached 5.09 m/s. In Hulun Lake, however, the ice cover prevents the wind-induced water disturbance and consequently eliminates the partial contribution to nutrient release from resuspension of sediments as proven by the homogenous distribution of TP and COD in March (Figure 5). Considering the ice-induced concentrative effect according to TDS and EC, this prevention of resuspension might have an even greater impact on water quality since the comprehensive results showed the ubiquitous decrease of nutrients either spatially or temporally all over the lake (Figure 5). It is worth mentioning that TN during the ice-bound period might not be influenced profoundly by the prevented resuspension, since no homogenous distribution was observed through the entire winter.

In sediment, a reducing environment is beneficial to the mineralization and degradation of nutrients; the subsequent

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**Table 2 | Pearson’s correlation matrix of the water quality indices in Hulun Lake**

<table>
<thead>
<tr>
<th></th>
<th>TDS</th>
<th>EC</th>
<th>DO</th>
<th>pH</th>
<th>TN</th>
<th>TP</th>
<th>COD</th>
<th>T</th>
<th>Salinity</th>
<th>TLI</th>
<th>N/P</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDS</td>
<td>1</td>
<td>0.367*</td>
<td>0.293</td>
<td>-0.179</td>
<td>-0.190</td>
<td>-0.238</td>
<td>-0.305</td>
<td>-0.410**</td>
<td>0.577**</td>
<td>-0.407*</td>
<td>0.056</td>
</tr>
<tr>
<td>EC</td>
<td>1</td>
<td>0.559**</td>
<td>0.220</td>
<td>0.239</td>
<td>0.011</td>
<td>-0.086</td>
<td>-0.366*</td>
<td>0.668**</td>
<td>-0.394*</td>
<td>0.283</td>
<td></td>
</tr>
<tr>
<td>DO</td>
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<td>-0.560**</td>
<td>-0.614**</td>
<td>0.265</td>
<td>-0.635**</td>
<td>0.370*</td>
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<tr>
<td>pH</td>
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<td>0.087</td>
<td>0.333*</td>
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<td>-0.134</td>
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<tr>
<td>TN</td>
<td>1</td>
<td>0.564**</td>
<td>0.716**</td>
<td>0.545**</td>
<td>0.109</td>
<td>0.260</td>
<td>0.407**</td>
<td></td>
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<tr>
<td>TP</td>
<td>1</td>
<td>0.622**</td>
<td>0.664**</td>
<td>0.047</td>
<td>0.412*</td>
<td>0.510**</td>
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<td>T</td>
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<td>0.409*</td>
<td>0.199</td>
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<td>Salinity</td>
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</table>

Significant correlation at the *P < 0.05 and **P < 0.01 levels. TDS, total dissolved solids; EC, electrical conductivity; DO, dissolved oxygen; TN, total nitrogen; TP, total phosphorus; COD, chemical oxygen demand; T, temperature; salinity, dissolved salt content of water; TLI, trophic level index; N/P, the ratio of TN to TP.
products are accumulated in the sediment then released to the overlying water. On the contrary, under the oxidation environment, iron and manganese oxides form at the interface between sediment and water, which absorb and precipitate soluble nutrients and reduce the content of nutrients in the overlying water (Wu et al. 2019). A primary microcosm system containing in situ water and sediment has been established to evaluate the static release of nutrients from the sediment of Hulun Lake (unpublished). The TN concentration in the overlying water increased rapidly and reached the peak on the first day, then declined gradually until nearly stable after around twenty days. The variation of TN value might involve two pathways (Downes 1988). First, particulate organic nitrogen (PON) could produce NH$_4^+$-N directly by ammonification or convert to dissolved organic nitrogen (DON) and then gradually mineralize into NH$_4^+$-N. Second, NO$_3^-$-N could be reduced to NH$_4^+$-N through ammonia dissimilation. Furthermore, NO$_3^-$-N and NO$_2^-$-N could be reduced to N$_2$ and N$_2$O by denitrification or nitrate dissimilation, which resulted in the N loss in the system (Smith & Kalff 2002).

The transfer direction of P at the interface of the sediment–water boundary is controlled by multiple abiotic and biotic factors (Huang et al. 2011). In the present study, pH value was weak alkali, between 8 and 9, in Hulun Lake all through the period, which was favorable for the adsorption of phosphorus by sediment. The dynamics of the TP concentrations were essentially the same as TN according to the static release test. Phosphorus was also released and increased rapidly with the peak appearing on the first day. In the following days, TP content decreased until stable to the lowest value, which appeared after around ten days. When the value of pH in the overlying water is near neutral, the phosphate in water mainly exists in the form of HPO$_4^{2-}$ and H$_2$PO$_4^-$, which easily combine with the metal elements in the sediment (Jiang et al. 2008).

CONCLUSIONS

In Hulun Lake, the decreased wind disturbance is supposed to predominate the eutrophication alleviation in accompaniment with diffusion, deposition, sediment release processes and lake current. The formation of ice had a slight concentrative effect on water ion content. However, covering by ice dramatically reduced the wind-induced resuspension of benthic particles, resulting in an increasingly homogenous deposition of phosphorus and oxygen-depleting organic matter in overlying water. The two headwater streams, Crulen River and Orshen River, bore a minimized volume of inflows during the icebound period and demonstrated limited impact on water quality in estuaries. Attention needs to be paid to the organic matter imported before the lake is completely icebound followed by the cumulated dry and wet deposition on/in the ice cover, which together contribute to the increased poorly biodegradable organic matter in Hulun Lake.

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CONFLICT OF INTEREST

All authors claim that they do not have any actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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