Distributions of four taste and odor compounds in the sediment and overlying water at different ecology environment in Taihu Lake

Heyong Huang1,3, Xiaoguang Xu2, Xiansheng Liu2, Ruiming Han2, Jine Liu4 & Guoxiang Wang2

Organic matter-induced black blooms, such as cyanobacterial and vegetation blooms, are a serious ecosystem disasters that have occurred in Taihu Lake. After large-scale outbreaks of blooms in eutrophic water, a large number of cyanobacterial and vegetation residue accumulate in the coastal areas, and rapidly fermented into odorous compounds. In this study, four taste and odor compounds have been analyzed in sediments and overlying water of different ecology environment in Taihu Lake. High concentrations of DMDS (up to 7165.25 ngg\(^{-1}\) dw\(^{-1}\)), DMTS (up to 50.93 ngg\(^{-1}\) dw\(^{-1}\)), \(\beta\)-cyclocitral (up to 5441.69 ngg\(^{-1}\) dw\(^{-1}\)), \(\beta\)-ionone (up to 1669.37 ngg\(^{-1}\) dw\(^{-1}\)) were detected in sediments. Also, the spatial distributions of DMDS, DMTS, \(\beta\)-cyclocitral and \(\beta\)-ionone in the sediments were investigated. As the depth of sediment increases, nutrients and odorous compounds are greatly reduced. The results showed that during the degradation of cyanobacterial and vegetation residues, DMDS, DMTS, \(\beta\)-cyclocitral, \(\beta\)-ionone and nutrients are gradually released. In addition, when assessing the source of odorous compounds in overlying water, it should also be considered that it may be released from the sediment. This study shows that odorous compounds are ubiquitous in near-shore zones Taihu Lake, and may take potential hazard to aquatic ecosystems.

Massive cyanobacterial and vegetation blooms are a visible ecosystem response to advanced eutrophication1,2. However, the decrease in dissolved oxygen (DO) levels in bottom waters that results from the degradation of large amounts of organic matter is regarded as the most serious threat from these blooms3,4. Moreover, excessive organic matter in the water column can result in hypoxia, even anoxia, in the water and surface sediments. Hypoxia and anoxia can induce black water bloom disasters in freshwater lakes5,6. Because of the degradation of organic matter from cyanobacteria blooms and/or polluted sediments, some of the most important freshwater lakes in China, such as Lake Dianchi, Lake Chaohu, and Lake Taihu, have been suffering from black blooms for many years. These black blooms have drawn the attention of the government and academicians. All the black blooms occurred unpredictably in late spring or early summer, were near the shore, and usually lasted from 24 hr to 2 weeks. Black blooms are identified by the black color of the water and are often accompanied by taste and odor (T&O) compounds.

Therefore, more attentions has been drawn to T&O compounds. In the past years, odorous compounds, such as hydrogen sulfide, methanethiol, 2-methylisoborneol, geosmin and 2-isopropyl-3-methoxypyrazine have been extensively investigated8-11. Recently, \(\beta\)-cyclocitral and \(\beta\)-ionone8-10, two metabolites of cyanobacteria10,11, have been monitored several times in environment8-10 and have attracted great attention. Dimethylsulfide (DMS), dimethyldisulfide (DMDS) and dimethyltrisulfide (DMTS), originate from the decomposition of sulfur-containing organic matter are the major components responsible for the strong offensive odor of black bloom13. Because these T&O compounds often break out in natural waters simultaneously14, investigation of these compounds will provide valuable information to assess their fates in water environment. Until now, there have been numerous research on odorous compounds in drinking water or lakes, reservoirs and rivers15-18; however, few studies have investigated the distribution of these compounds in sediment and water. Understanding the fates

1School of Geography Science, Nanjing Normal University, Wenyuan Road 1, Nanjing, 210023, P. R. China. 2School of Environment, Nanjing Normal University, Wenyuan Road 1, Nanjing, 210023, P. R. China. 3Analysis and Testing Center, Nanjing Normal University, Wenyuan Road 1, Nanjing, 210023, P. R. China. Correspondence and requests for materials should be addressed to J.L. (email: liujine@njnu.edu.cn) or G.W. (email: wangguoxiang@njnu.edu.cn)
of T&O compounds in different environmental compartments (e.g., sediment, surface water) will be useful to assess the behavior of T&O compounds in aquatic environment.

Lake Taihu, the third largest freshwater lake and important water-source lake in China. Over the past years, algae-induced black blooms have occurred frequently in the west of Lake Taihu and caused serious disasters to ecological environment. Although odor-producing cyanobacteria and odorous compounds have been frequently occurred in surface water of Lake Taihu, odorants in sediment and their potential contribution to the overlying water have not been systematically investigated. We have studied the distributions of two odorous compounds in the overlying water and sediment of the typical sites of Taihu Lake. However, further studies must be extend to more T&O compounds distribution between sediments and overlying water is necessarily. In recently year, continuous ditch digging, reed planting, sludge dredging and so on have increase the environmental complexity of Taihu Lake, which simultaneously influence the production-release-degradation of odorous compounds.

The goal of our research aims to monitor the residues of DMDS, DMTS, β-cyclocitral and β-ionone in the sediment and overlying water off the different environmental condition of Taihu Lake. Specifically, concentration of total nitrogen, total phosphorus, total organic carbon (TOC), nitrate nitrogen, ammonium were investigated. Spatial trends of the physical-chemical parameters were examined to reveal the differences in different zones. The results will be better to understanding the fate, decomposition and release of odorous compounds in the lake aquatic environment.

Materials and Methods

Materials. The standard of four odor compounds DMDS, DMTS, β-cyclocitral and β-ionone (100 mg/L, methanol) were purchased from Sigma-Aldrich (Milwaukee, WI, USA), and the standard solutions were diluted with MilliQ-water. Other reagents were of analytical grade and used without further purification.

Solid phase micro-extraction (SPME) coated with stableflex DVB/CAR/PDMS fibers (50/30μm) was purchased from Sigma-Aldrich (Milwaukee, WI, USA).

Sample collection. Lake Taihu (30°55′40″–31°32′58″N, 119°52′32″–120°36′10″E), is a typical shallow eutrophic subtropical lake in China. Many serious black bloom incidents have recently occurred in Lake Taihu, especially along the northwestern bay and shorelines.

Sampling A (A-1 to A-4), B (B-1 to B-4) were collecting in the Zhushan Bay and Sampling C (C-1 to C-4) was collecting in the Gonghu Bay of Taihu Lake, where events of cyanobacterial blooms have occurred frequently in recent years. All sampling points are displayed in Fig. 1, and A-1 to A-4, B-1 to B-4, C-1 to C-4 are from lake shoreline to lake water area. Points A-1 and A-2 are in the natural reed growing area; B-1 and B-2 are located in the man-made reed area while B-3 is close to the reed area, facing the open area; C-1 is near reed area, C-2 is between Potamogeton crispus and reed area, C-3 is near Potamogeton crispus; the other points are all in the open area. The sediment and overlying water samples were collected by gravity columnar dredge. 50 mL of water was quickly separated and stored in amber glass bottles for further analysis. The sediment samples were sliced every 2 cm from top to bottom. Then about 5 g each layers of precipitate was immediately stored into amber glass bottle. Samples prepared for organic carbon and nutrients samples were saved under the dark at –20°C and 0–4°C, respectively. Odor compounds analysis were saved in the dark under 4°C and analyzed within 7 days.

Analysis of overlying water and sediment samples. Water temperature, dissolved oxygen (DO), pH and oxidation-reduction potential (ORP) were measured in situ using a HORIBA water quality monitor (HORIBA, Ltd. Kyoto Japan). Nitrate nitrogen (NO3−-N) and ammonium nitrogen (NH4+-N) were determined using an auto-analyzer (Auto-analyzer 3, SEAL, Germany). Total nitrogen (TN) was tested by UV-VIS-NIR spectrometer (Cary5000, Varian, USA). Total phosphorus (TP) was analyzed using the protocol proposed by Ruban. Samples for total organic carbon (TOC) analyses were firstly treated with 10% HCl overnight, and then analyzed with a multi N/C analyzer (HT 1300, analytikjena, Germany).

Determination of four odor compounds. The concentration of DMDS, DMTS, β-cyclocitral and β-ionone were measured by using SPME coupled with GC/MS according to previous studies.

Extraction was conducted with a DVB/CAR/PDMS (50/30 μm) for 30 min at 65°C with a stirring speed at 500 r/min. After incubation, the fiber was retracted and injected into the injector of GC-MS (Agilent 7890A GC, 5975 MSD, USA) and desorbed in splitless mode for 2 min at 250°C. The GC column was programmed from 60°C (constant temperature for 1 min) to 220°C (10°C/ min, hold constant for 5 min). The EI-MS conditions are as follows: 230°C for ion-source and 70 eV for ionizing voltage; scan range, m/z 40–350 amu; cycle time, 0.5 s. For the selection of monitoring (SIM) mode, m/z 94 and 79 for DMDS, m/z 126 and 111 for DMTS, m/z 152 and 137 for β-cyclocitral, m/z 177 and 135 for β-ionone were monitored.

Statistical analysis. All samples were analyzed in duplicate or triplicate. In order to achieve quality control, quality control samples and standard addition samples were also analyzed simultaneously during the analysis process. The Statistical Package of the Social Science 18.0 (SPSS 18.0) was used for statistical analysis. The one-way analysis of variance (ANOVA) and correlation analysis was carried out using bivariate correlations analysis. The correlation between the nutrients and odorous compounds were developed by linear correlation analysis.

Results and Discussion

Analysis of overlying water and sediment samples. The characteristics of the sediments and overlying water can be found in Table 1. Obviously, the sediment collected in the open areas (A-3, A-4, B-3, B-4, C-3 and C-4) was more shallow than in the near-shore zones (A-1, A-2, B-1, B-2, C-1 and C-2), while the depth of water...
shows the opposite trend. And extremely low pH, DO and ORP can bee found in sites A-1, A-2, B-1, B-2, C-1 and C-2. The lower DO and ORP indicating the strong reducing conditions were formed at water-sediment interface, which might be associated with a large number of reducing bacteria23.

It has been found that excessive organic matter in water may cause hypoxia, even anoxia, in the water and surface sediments. Hypoxia and anoxia can result in black water bloom disasters in freshwater lakes4,5. Higher temperature lead to higher microorganism activity, this might consuming more oxygen in summer and further accelerates the mineralization process. The decomposition of algae and vegetation will consume a large amount of DO, which resulted in the release of a huge amount of organic matter and nutrients (Fig. 2). Feng et al. have found under the conditions of anoxic or anaerobic, organics can effectively promote the outbreaks of black bloom23. They thought that the black bloom may be originate from the co-synergistic metabolisms between organic and micro-organisms in the metabolic sediment.

The concentrations of nutrients and TOC in the sediment can be seen in Fig. 2. In the study areas, the nitrogen concentrations in the sediment range from 204.16 to 8543.68 mg/kg for TN, 1.99–132.87 mg/kg for NO\textsubscript{3}−-N and 23.97–2082.71 mg/kg for NH\textsubscript{4}+-N, with average values of 2988.91, 24.76 and 420.66 mg/kg, respectively. The phosphorus concentrations varied from 378.91 to 1561.69 mg/kg in the sediment, with an average value of 828.04 mg/kg. And the TOC concentrations varied from 3.15 g/kg to 111.03 g/kg in the sediment, with a mean value of 50.11 g/kg.

In the vertical distribution, the concentration of nutrients and TOC fluctuated with depth. The values of TN followed by A-1 (4990.91 mg/kg), A-2 (2697.25 mg/kg), A-3 (943.38 mg/kg) and A-4 (908.87 mg/kg), similar

---

**Figure 1.** Location of the sampling points in Zhushan Bay and Gonghu Bay, Taihu Lake, China. (Environmental conditions of typical sampling points can be seen in color figures). The figure is created by ArcGIS 10.2 (http://www.esri.com).
The vertical and horizontal distribution of odorants in Taihu Lake.

Distribution of odorants in overlying water and surface sediment. The spatial distribution of the four odorants in overlying water and sediments in different sampling points can be found in Fig. 3. The high contents of odorants detected in surface sediment probably due to the adsorption of sediments25.

The odorants contents in the overlying water varied from 3.29 to 78.83 ng/L for DMDS and nd to 46.88 ng/L for DMTS, with mean values of 28.01 and 16.85 μg/L, respectively. And the contents of odorants in the surface sediment varied from nd to 1003.31 ng/(g dw) for DMDS and nd to 50.93 ng/(g dw) for DMTS, with the average value of 336.71 and 15.70 ng/(g dw), respectively. The variety trends of DMDS and DMTS in the overlying water and surface sediment are similar. The correlation coefficient is 0.897 for DMDS, and the correlation coefficient is 0.849 for DMTS. Based on the Spearman correlation analysis, it was a significant correlation between overlying water and surface sediment at the level of P < 0.05. In this case, odorants present the risk of diffusion from sediment to overlying water26. Additional, the odorants detected in the water varied from 150 to 12020 ng/L for β-cyclocitral and 6.97 to 1106.96 ng/(g dw) for β-ionone, with the average values of 3194.46 and 2083.43 ng/L, respectively. And the contents of odorants in the surface sediment varied from 5.40 to 789.92 ng/(g dw) for β-cyclocitral and 6.97 to 1106.96 ng/(g dw) for β-ionone, with the average values of 196.91 and 260.03 ng/(g dw), respectively.

Due to the gradual decomposition of cyanobacteria and vegetation, there were high odorous concentrations in some special area of Taihu Lake. And the distribution features observed in our study resemble the previous studies27. It was found that the highest DMDS contents appears at the site of C-2 in surface sediment, but not C-1. Also, the highest β-cyclocitral contents was detected in surface sediment at the site of B-3, but not B-1 or B-2. As we know, point B-3 is nearby reed area and faces the open lake area, while site C-2 is between the reed area and Potamogeton crispus. Affected by storms and hot dry weather, large number of fresh cyanobacteria gathered, and then decayed, deposited finally. Eventually, a large amount of organic and odorous matters were gradually released into overlying water and the sediments. Therefore, it might be necessary to prevent the accumulation and decomposition of cyanobacteria for lessen odor issues in Taihu Lake.

Vertical and horizontal distribution of odorants in the sediments. The vertical and horizontal distribution of the odorants in the sediments can be found in Fig. 4. The content of odorants shows a large range of...
fluctuation in sediments, from nd to 7165.25 ng/(g•dw), with the mean value of 388.04 ng/(g•dw) for DMDS, and varied from nd to 50.93 ng/(g•dw) with the mean value of 6.34 ng/(g•dw) for DMTS. The concentrations of DMDS at sites A followed by A-1 (231.28 ng/g), A-2 (130.63 ng/g), A-3 (69.94 ng/g) and A-4 (29.54 ng/g), and similar distribution characteristics can be found at site B. The highest concentration of DMDS was found at site C-2 (2150.97 ng/g). The concentrations of DMTS at sites A followed by A-1 (8.76 ng/g), A-2 (1.19 ng/g), A-3 (nd) and A-4 (nd). The highest content of DMTS was also detected at site C-2 (17.34 ng/g). It was reasonable to assume that the high-density cyanobacteria accumulated in water then gradually deposited on surface sediment.

As we know, the decomposition of the vegetation and cyanobacteria will consume large amount of DO, eventually

Figure 2. Changing trends of nutrients and TOC in the sediment from the sampling points (A, B and C) in Taihu Lake.
leading to the release of a large amount of organic matters. Volatile organic sulfur compounds in freshwater lakes are produced primarily by phytoplankton and algae. Metabolism or microbial degradation of organic matter 29,30. The anaerobic decomposition of cyanobacteria and vegetation can promote DMDS and DMTS production in point A and B. The highest production of DMDS and DMTS at section C may result from the decomposition of sulfur-containing organic compounds in dead Potamogeton and cyanobacteria, as this process generates a variety of methylated sulfides 6,30–32.

Also, the concentration of \( \beta \)-cyclocitral in sediments fluctuated from 0.11 to 5441.69 ng/(g•dw), with the mean value of 365.06 ng/(g•dw), and from 0.11 to 5441.69 ng/(g•dw) with the mean value of 259.08 ng/(g•dw) for \( \beta \)-ionone. The content of \( \beta \)-cyclocitral at sites A followed by A-1 (375.17 ng/g), A-2 (215.36 ng/g), A-3 (65.79 ng/g) and A-4 (38.68 ng/g). And at site C followed by C-2 (146.39 ng/g), C-3 (76.52 ng/g), C-4 (59.07 ng/g) and C-1 (15.55 ng/g). The highest content of \( \beta \)-cyclocitral was detected in point B-3. The concentrations of \( \beta \)-ionone at sites A followed by A-1 (486.76 ng/g), A-2 (322.15 ng/g), A-3 (76.52 ng/g) and A-4 (32.22 ng/g), and similar distribution characteristics can be found at site B and C. The highest content of \( \beta \)-ionone can be seen at site B-1 (655.45 ng/g).

The odorants content showed a clearly downward trend in the sediment (<4 cm) along open area (A-3, A-4, B-4 and C-4), and the concentration are all far below that in the coastal zone. No doubt, this difference can be owing to the different environment conditions and to the accumulation of cyanobacteria. A one-way ANOVA was applied to analysis the differences among odorant compounds. We thought that high content of odorants existed in the sediments may originate from the decomposition of cyanobacteria owing to the climate and topography. As reported, influenced by prevailing winds, cyanobacteria can easily gather in the bay and western area of the Taihu Lake, especially on the shores of the Zhushan Bay, Meiliang Bay and Gonghu Bay 33. Previous studies have shown that the type of enon-wetland-dyke or intermittent-wetland-dyke wetland area will influence the drifting and aggregation of algae. Of course, the shoreline and ditch embayments will also promote the accumulation of algae.

Compared with the previous research (shown in Table 2), in water, the mean value of \( \beta \)-cyclocitral was about 6 to 28 times than the concentration in the other regions. And the content of \( \beta \)-ionone have the similar phenomenon, the mean value of \( \beta \)-ionone in water of our research was 10 to 41 times than that other regions. Simultaneously, the mean value of \( \beta \)-cyclocitral in the sediment of Zhushan Bay was about 7 to 182 times than other regions. And \( \beta \)-ionone concentration was more than 9 to 259 times than that in other regions. Surprisingly, the mean value of DMTS were lower than that in Poyanghu Lake 21.

**Correlation between C/N ratios, nutrients, TOC and odorants.** Carbon to nitrogen ratios (C/N) have been widely applied to recognize the sources of organic matter, as we know, the C/N ratios of higher plant-derived organic matter (C/N > 20) are much higher than the corresponding ratio of plankton and bacteria (6–7 and 4–5, respectively) 35,36. In the near-shore area, the C/N ratios of A-1 and A-2 were 34.63 and 39.86, followed by site C-1 (31.05), C-2 (25.08), C-3 (20.29) and B-1 (7.64), B-2 (8.01), B-3 (5.77), respectively. The values of C/N in site A, C were higher than those of site B, indicating that a large amount of bacteria and plankton gathered at point B.
The correlation between the odorous compounds and the C/N ratios in sediment are displayed in Table 3. Zuo et al. have revealed that in Xionghe Reservoir, geosmin was positively correlated with TN, TOC and chlorophyll-a in the sediment. As we know, nutrients are favor cyanobacteria blooms, and the growth of cyanobacteria was limited by nitrogen and phosphorus during the growing season. Therefore, the nutrients can regulate the production of odor compounds directly or indirectly. Figures 2 and 4 and Table 3 revealed that there were similar varying trends of odorants and nutrients (TN, NH$_4^+$-N, TP and TOC) in sediment. Yang et al. considered that the black water “agglomerate” in Taihu Lake was related to the high NH$_4^+$-N levels. In our study, both β-cyclocitral and β-ionone showed good correlations with NH$_4^+$-N. Meanwhile, DMDS and DMTS were more closely related to TOC in the sediment, while β-cyclocitral and β-ionone were more closely related to nitrogen in the sediment.

**Conclusions**

This research shows the occurrence of four odorous compounds DMDS, DMTS, β-cyclocitral and β-ionone off the bay of Taihu Lake. The results shows that odorous compounds were ubiquitous in overlying water and sediment.

The vertical distribution of nutrient, organic matters and odorous compounds in sediment reveal that there were significant differences among the different ecology environment types. Reed roots not only absorb nutrients

---

**Figure 4.** Change trend chart of four odorants in the sediment of points (A, B and C) in Taihu Lake.
| Odorants | Mean Concentrations in water | Mean Concentrations in sediment | Area | Source |
|----------|-----------------------------|---------------------------------|------|--------|
| DMDS     | 1100 ng/L                   | —                               | Gonghu Bay in Taihu Lake | Shen et al. |
|          | 27.79 ng/L                  | 388.04 ng/g                     | Taihu Lake | This study |
| DMTS     | 69.55 ng/L                  | —                               | Gonghu Bay in Taihu Lake | Chen et al. |
|          | —                           | 4 ng/g                          | Chaobu Lake | Deng et al. |
|          | —                           | 51 ng/g                         | Poyanghu Lake | Deng et al. |
|          | —                           | 3 ng/g                          | Taihu Lake | Deng et al. |
|          | 16.06 ng/L                  | 6.34 ng/g                       | Taihu Lake | This study |
| β-Cyclocitrinal | 537.61 ng/L | —                               | Gonghu Bay in Taihu Lake | Chen et al. |
|          | 115 ng/L                    | —                               | Dianchi Lake | Li et al. |
|          | —                           | 2 ng/g                          | Chaobu Lake | Deng et al. |
|          | —                           | 49 ng/g                         | Poyanghu Lake | Deng et al. |
|          | —                           | 18 ng/g                         | Taihu Lake | Deng et al. |
|          | 3209 ng/L                   | 365 ng/g                        | Taihu Lake | This study |
| β-Ionone  | 50.44 ng/L                  | —                               | Gonghu Bay in Taihu Lake | Chen et al. |
|          | 200 ng/L                    | —                               | Dianchi Lake | Li et al. |
|          | —                           | 1 ng/g                          | Chaobu Lake | Deng et al. |
|          | —                           | 259 ng/g                        | Poyanghu Lake | Deng et al. |
|          | —                           | 29 ng/g                         | Taihu Lake | Deng et al. |
|          | 2282 ng/L                   | 259 ng/g                        | Taihu Lake | This study |

Table 2. Taste and odor compounds in other areas.

| Index | TN | NH$_4^+$-N | NO$_3^-$-N | TP | TOC | C/N | DMDS | DMTS | β-cyclocitrinal | β-ionone |
|-------|----|------------|------------|----|-----|-----|------|------|-----------------|----------|
| TN    | 1  | —          | —          | —  | —   | —   | —    | —    | —               | —        |
| NH$_4^+$-N | 0.734** | 1          | —          | —  | —   | —   | —    | —    | —               | —        |
| NO$_3^-$-N | 0.569** | 0.373**    | 1          | —  | —   | —   | —    | —    | —               | —        |
| TP    | 0.605** | 0.615**    | 0.349**    | 1  | —   | —   | —    | —    | —               | —        |
| TOC   | 0.320** | 0.309*     | 0.225      | 0.218 | 1 |
| C/N   | —0.450** | —0.537**  | —0.247*    | —0.643** | 0.632** | 1 |
| DMDS  | 0.063** | —0.098*    | —0.062*    | —0.309* | 0.722** | 0.612** | 1 |
| DMTS  | 0.348** | 0.136      | 0.116      | 0.002 | 0.485** | 0.139 | 0.333** | 1 |
| β-cyclocitrinal | 0.671** | 0.502**    | 0.432**    | 0.441** | 0.261* | —0.352** | 0.109 | 0.323** | 1 |
| β-ionone | 0.492** | 0.640**    | 0.237      | 0.290* | 0.180 | —0.177 | 0.266* | 0.253* | 0.493** | 1 |

Table 3. Correlation between the available nutrients and the taste and odor compounds.

but also absorb odorous compounds, this indicating that planting reeds probably a viable method to reduce the production of odorous compounds. However, the massive degradation of dead Potamogeton crispus may increase the concentration of nutrients and odorous compounds, this indicate that the planting of submerged plants should be under suitable density.

In addition, the strong decomposition of cyanobacterial residues in typical topography under suitable climate, can release a large amount of odorous compounds and cause the malodor associated with black blooms. As the high odorous compounds detected in sediment, sediment dredging is a feasible method for the reduction of nutrients and odorous compounds originate from the sediment to the overlying water. Therefore, combination sediment dredging with preventing cyanobacteria from aggregating may be the most viable strategy to suppress odor ecological problem in eutrophic shallow lakes.

References

1. Diaz, R. J. & Rosenberg, R. Spreading dead zones and consequences for marine ecosystems. Science 321, 926–929 (2008).
2. Paerl, H. W. et al. Controlling harmful cyanobacterial blooms in a hypertrophic lake (Lake Taihu, China): The need for a dual nutrient (N & P) management strategy. Water Research 45, 1973–1983 (2011).
3. Rabalais, N. N., Turner, R. E. & Wiseman, W. J. Gulf of Mexico hypoxia, aka “the dead zone”. Annual Review of Ecology and Systematics 33, 235–263 (2002).
4. Stahl, J. B. Black water and 2 peculiar types of stratification in an organically loaded strip-mine lake. Water Research 5, 467–471 (1979).
5. Yang, M. et al. Taihu Lake not to blame for Wuxi’s woes. Science 319, 158 (2008).
6. Lu, X., Fan, C., Shang, J., Deng, J. & Yin, H. Headspace solid-phase microextraction for the determination of volatile sulfur compounds in odorous hyper-eutrophic freshwater lakes using gas chromatography with flame photometric detection. Microchemical Journal 104, 26–32 (2012).
7. Peter, A., Köster, O., Schildknecht, A. & Von Gunten, U. Occurrence of dissolved and particle-bound taste and odor compounds in Swiss lake waters. Water Research 43, 2191–2200 (2009).
8. Jiang, Y., Cheng, B., Liu, M. & Nie, Y. Spatial and temporal variations of taste and odor compounds in surface water, overlying water and sediment of the Western Lake Chaohu, China. *Bulletin of Environmental Contamination and Toxicology* **96**, 1–6 (2015).

9. Chen, J. et al. A systematic study on spatial and seasonal patterns of eight taste and odor compounds with relation to various biotic and abiotic parameters in Donghu Bay of Lake Taihu, China. *Science of the Total Environment* **409**, 314–325 (2010).

10. Lin, T. et al. Effect of chlorination on the cell integrity of two noxious cyanobacteria and their releases of odorants. *Journal of Water Supply: Research and Technology: AQUA* **58**, 539–551 (2009).

11. Jüttner, F. Dynamics of the volatile organic substances associated with cyanobacteria and algae in a eutrophic shallow lake. *Applied and Environmental Microbiology* **47**, 814–820 (1984).

12. Wang, G., Li, X., Fang, Y. & Huang, R. Analysis on the formation condition of the algae induced odorous black water agglomerate. *Saudi Journal of Biological Sciences* **21**, 597–604 (2014).

13. Graham, J. L., Loftin, K. A., Meyer, M. T. & Ziegler, A. C. Cyanotoxin mixtures and taste-and-odor compounds in cyanobacterial blooms from the Midwestern United States. *Environmental Science & Technology* **44**, 7361–7368 (2010).

14. Westerhoff, P., Rodriguez-Hernandez, M., Baker, L. & Sommerfeld, M. Seasonal occurrence and degradation of 2-methylisoborneol in water supply reservoirs. *Water Research* **39**, 4899–4912 (2005).

15. Zuo, Y. et al. Contribution of Streptomyces in sediment to earthy odor in the overlying water in Xionghe Reservoir, China. *Water Research* **44**, 6085–6094 (2010).

16. Shang, G. P. & Shang, J. C. Spatial and temporal variations of eutrophication in Western Chaohu Lake, China. *Environmental Monitoring and Assessment* **130**, 99–109 (2007).

17. Jiang, Y., Xie, P. & Nie, Y. Concentration and bioaccumulation of cyanobacterial bioactive and odorous metabolites occurred in a large, shallow Chinese Lake. *Bulletin of Environmental Contamination and Toxicology* **93**, 643–648 (2014).

18. Liu, X. S., Shi, C. F., Huang, H. Y. & Wang, C. X. Spatial distributions of β-cyclocitral and β-ionone in the sediment and overlying water of the west shore of Taihu Lake. *Science of the Total Environment* **579**, 430–438 (2017).

19. Ravez, A. & Avnimelech, Y. Total nitrogen analysis in water, soil and plant material with persulphate oxidation. *Water Research* **13**, 911–912 (1979).

20. Ruban, V. et al. Harmonized protocol and certified reference material for the determination of extractable contents of phosphorus in freshwater sediments—A synthesis of recent works. *Presentsia journal of analytical chemistry* **370**, 224–228 (2001).

21. Deng, X., Liang, G., Chen, J., Qi, M. & Xie, P. Simultaneous determination of eug, Liqiong G. odors in natural water body using automatic purge and trap coupled to gas chromatography with mass spectrometry. *Journal of Chromatography A* **1218**, 3791–3798 (2011).

22. Ma, K., Zhang, J. N., Zhao, M. & He, Y. J. Accurate analysis of trace earthy-musty odorants in water by headspace solid phase microextraction gas chromatography-mass spectrometry. *Journal of separation science* **35**, 1494–1502 (2012).

23. Peng, Z., Fan, C., Huang, W. & Ding, S. Microorganisms and typical organic matter responsible for lacustrine "black bloom". *Science of the Total Environment* **470**, 1–8 (2014).

24. Gu, X. Z., Zhang, L., Bo, X. & Fan, C. X. Characteristics of sediments and pore water in Lake Nansi wetland. *Environmental Science** **31**, 939–945 (2010).

25. Huang, W., Young, T. M., Schlautman, M. A., Yu, H. & Weber, W. J. A distributed reactivity model for sorption by soils and sediments. 9. General isotherm nonlinearity and applicability of the dual reactive domain model. *Environmental Science & Technology* **31**, 1703–1710 (1997).

26. Guttman, L. & Rijn, J. V. 2-Methylisoborneol and geosmin uptake by organic sludge derived from a recirculating aquaculture system. *Water Research* **43**, 474–480 (2009).

27. Li, L., Fan, N., Qian, J. & Zhang, X. et al. Annual dynamics and origins of the odorous compounds in the pilot experimental water of the west shore of Taihu Lake. *Fresenius' journal of analytical chemistry* **579**, 430–438 (2017).

28. Qi, M. et al. Development of models for predicting the predominant taste and odor compounds in Taihu Lake, China. *Plos one* **7**, e51976 (2012).

29. Song, L. R., Li, L., Chen, W. & Gan, N. Q. Progress on the off-flavours and secondary metabolites of algae in the aquaculture environment. *Acta Hydrobiologica Sinica* **28**, 434–439 (2004).

30. Hu, H. Y., Mylon, S. E. & Benoit, G. Volatile organic sulfur compounds in a stratified lake. *Chemosphere* **67**, 911–919 (2007).

31. Pedersso, P. et al. Harmonized protocol and certified reference material for the determination of extractable contents of phosphorus in freshwater sediments—A synthesis of recent works. *Presentsia journal of analytical chemistry* **370**, 224–228 (2001).

32. Hedges, J. L., Kell, R. G. & Benner, R. What happens to terrestrial organic matter in the ocean? *Organic geochemistry* **27**, 195–212 (1997).

33. Andreadis, M. G. The ocean as a source of atmospheric sulfur compounds. *The role of air-sea exchange in geochemical cycling* **185**, 331–362 (1986).

34. Gineburg, B. et al. DMS formation by dimethylsulfinopropionate route in freshwater. *Environmental science & technology* **32**, 2130–2136 (1998).

35. Sun, Y., He, J., Lu, C. W., Liu, E. D. & Shen, L. L. The Simulation Research of Ammonium Nitrogen Release from the Surface Sediments of the Dazhai Lake. *Journal of Agro-Environment Science* **7**, 28–36 (2009).

36. Boatman, C. D. & Murray, J. W. Modeling exchangeable NH4+ adsorption in marine sediments: Process and controls of adsorption. *Limnology and Oceanography* **27**, 99–110 (1982).

37. Shen, Q. S., Shao, S. G., Wang, Z. D. & Fan, C. X. Simulation of black bloom in Moon Bay of Lake Taihu and physical and chemical responses of water and sediment. *Advances in Water Science* **22**, 710–719 (2011).

Acknowledgements

This research was supported by the National Natural Science Foundation of China (No. 41573061, No. 41273082, No. 4773077), Research Projects of Water Environment Comprehensive Management in Taihu Lake of Jiangsu Province (No. TH2014402) and the National Science Foundation of the Higher Education Institutions of Jiangsu Province, China (No. 15KJB610007).

Author Contributions

Heyong Huang wrote the main manuscript text. Heyong Huang, Xiansheng Liu and Guoxiang Wang designed and conducted the experiments and collected and analyzed the data. Heyong Huang, Ruiming Han, Xiaoguang Xu, Jine Liu and Guoxiang Wang contributed to analyzing the data and writing and editing the manuscript. All of the authors reviewed the manuscript.
Additional Information

Competing Interests: The authors declare no competing interests.

Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2018