Cyanobacterial bloom management through integrated monitoring and forecasting in large shallow eutrophic Lake Taihu (China)

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6 authors, including:

Bo-Qiang Qin
Chinese Academy of Sciences

Guangwei Zhu
Chinese Academy of Sciences

Yunlin Zhang
Chinese Academy of Sciences

Guang Gao
Chinese Academy of Sciences

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Cyanobacterial bloom management through integrated monitoring and forecasting in large shallow eutrophic Lake Taihu (China)

Boqiang Qin*, Wei Li, Guangwei Zhu, Yunlin Zhang, Tingfeng Wu, Guang Gao

State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academic of Sciences, 73 East Beijing Road, Nanjing 210008, China

HIGHLIGHTS

- A large scale integrated cyanobacterial bloom monitoring is the first in practice.
- The cyanobacterial bloom formation following a storm was observed in-situ clearly.
- Integrated monitoring and forecasting increase removal efficiency of algal bloom.

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ABSTRACT

The large shallow eutrophic Lake Taihu in China has long suffered from eutrophication and toxic cyanobacterial blooms. Despite considerable efforts to divert effluents from the watershed, the cyanobacterial blooms still reoccur and persist throughout summer. To mitigate cyanobacterial bloom pollution risk, a large scale integrated monitoring and forecasting system was developed, and a series of emergency response measures were instigated based on early warning. This system has been in place for 2009–2012. With this integrated monitoring system, it was found that the detectable maximum and average cyanobacterial bloom area were similar to that before drinking water crisis, indicating that poor eutrophic status and cyanobacterial bloom had persisted without significant alleviation. It also revealed that cyanobacterial bloom would occur after the intense storm, which may be associated with the increase in buoyance of cyanobacterial colonies. Although the cyanobacterial blooms had persisted during the monitoring period, there had been a reduction in frequency and intensity of the cyanobacterial bloom induced black water agglomerates (a phenomenon of algal bloom death decay to release a large amount black dissolved organic matter), and there have been no further drinking water crises. This monitoring and response strategy can reduce the cyanobacterial bloom pollution risk, but cannot reduce eutrophication and cyanobacterial blooms, problems which will take decades to resolve.

1. Introduction

Nutrient enrichment of freshwater systems has led to a global proliferation of harmful cyanobacterial blooms [1,2], which foul water intakes [3], disrupt food webs [4], drive hypoxia [5], reduce biodiversity [6] and produce secondary metabolites that are toxic to consumers, ranging from zooplankton, shellfish, fish, cattle, and domestic pets to humans [7,8]. These impacts cause great economic loss [9], which may be exacerbated by global warming [10–12].

Many planktonic cyanobacterial species can produce cyanotoxins such as neurotoxins, hepatotoxins, cytotoxins, and irritant and gastrointestinal toxins [7,8]. The proliferations and expansions of toxic cyanobacterial blooms resulting from eutrophication threaten human health [13]. Many countries have documented the presence of toxic cyanobacterial blooms in their drinking water sources or recreational sites [14], and cyanobacterial blooms are expected to increase in the 21st century due to global warming [10,15]. Therefore, mitigating the risk of toxic cyanobacterial blooms, and reducing their negative impacts, is urgent management needs for eutrophic water bodies, especially for lakes with key roles as drinking water supply reservoirs or recreational sites [14,16].

Toxic cyanobacterial bloom issues and the potential threat for human health are more severe in China [17]. In Lake Taihu, the third largest freshwater lake in China, eutrophication has promoted cyanobacterial blooms which are mainly comprised of *Microcystis* spp. with biovolume accounting for >90% during summer time

* Corresponding author. Tel.: +86 25 86882192; fax: +86 25 57714759.
E-mail address: qinbq@niglas.ac.cn (B. Qin).

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[18,19], which have impaired drinking water supplies because of the strong odor and taste [20] and the presence of microcystin (MC) from *Microcystis* spp. [21–26]. The documented MC concentration in untreated water in Lake Taihu was 4.8–44.00 μg/L [26] which was much higher than the up limit of safe value for human being exposure (1 μg/L) recommend by WHO [13], and MCs were also present in tap water after treatment [27]; the latter may be one of the primary reason for the prevalence of liver cancer in eastern China [17,28,29]. With significant public health concerns about the water quality in this lake, it was deemed necessary to implement algal bloom monitoring, forecasting, and emergency response measures, along with best practices for cyanobacterial bloom pollution risk reduction and maintenance of safe drinking water supply.

Traditional monitoring methods have relied on ship-based sampling, followed by laboratory analyses, approaches which are often time-consuming. In addition, traditional ship-borne monitoring is often limited by poor weather, thus precluding adequate spatial and temporal coverage. Cyanobacterial blooms are usually highly heterogeneous in space and time in large water bodies [30]. Subsequently, high-frequency automatic measurements have been developed [31,32], with compact sensors for detection of water quality and cyanobacterial species, using specific fluorescence finger-printers and fluorometers [33–36]. Recently, this unattended, wireless, high-frequency detection technology, combined with spatial remote sensing monitoring of cyanobacterial bloom provided a solution for monitoring highly heterogeneous cyanobacterial blooms in eutrophic water bodies [37–39]. But there are lack of large scale application and the practicability examination.

In this paper, we present a cyanobacterial bloom threat reduction strategy that combined surface cyanobacterial bloom monitoring, forecasting, alert warning and risk management measures, in eutrophic Lake Taihu. This strategy focused on delivering information for risk assessment and management response, and was a joint venture between government oriented management agencies and research institutions. The purpose of this paper is (1) to examine the capability of this integrated monitoring schema to monitor the spatio-temporal changes of surface cyanobacterial bloom, and (2) to evaluate the effectiveness of this integrated monitoring based surface cyanobacterial bloom forecasting and risk management in Lake Taihu.

2. Data and methods

2.1. Study site

Lake Taihu is a large (with area 2338 km^2), shallow (with mean depth 1.9 m) and eutrophic lake located in the delta of River Changjiang (Yangtze River) (Fig. 1) where is the most industrialized, urbanized and densely populated area in China. It has multiple functions, such as drinking water supply, flood control [40], supporting tourism and recreation [41], shipping and aquaculture [42]. The primary function is drinking water supply, with more than 10 million people relying on the lake for this resource, particularly in the cities of Shanghai, Suzhou, Wuxi, and Huzhou.

Since the reforming and opening of China in the 1980s, this lake has experienced severe eutrophication [43,44]. According to monthly monitoring conducted by Taihu laboratory for lake ecosystem research (TLLER), the total nitrogen (TN) and total phosphorus (TP) concentration increased since earlier 1990s and peaked at 2007 (Supporting information Fig. S1), which resulted in the phytoplankton proliferation and algal bloom occurrence. Long-term investigations suggested that the algal bloom mainly comprised *Microcystis* spp. which could account for 90% of total phytoplankton biovolume [18], and mostly distributed in the north stretched to

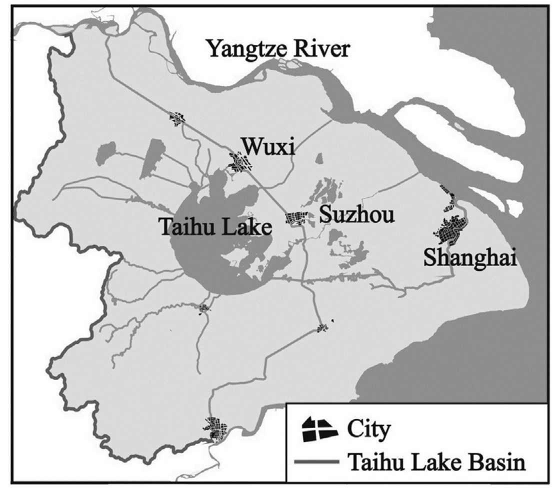

Fig. 1. Location of Lake Taihu and main cities around lake.

the northwest along shoreline (Supporting information Fig. S2). It finally resulted in a serious drinking water supply accident in late May 2007 and caused millions residents no drinking water supply for nearly a week [3,15]. This drinking water crisis became a turning-point. Since that time, the control of lake eutrophication and cyanobacterial blooms have become a priority for local governments. Many efforts have been made toward diversion of effluent in the Taihu catchment and security of drinking water supply [45]. As a part of these efforts, cyanobacterial bloom monitoring, forecasting, and drinking water supply securing have been conducted since drinking water crisis.

2.2. Water quality and cyanobacterial bloom monitoring

The monitoring comprised three different elements: (i) remote sensing image retrieval, (ii) unattended sensor detection, with wireless data transmission, and (iii) ship-borne sampling and analysis. The selection of monitoring indices depended on the feasibility and availability. In terms of monitoring data of chlorophyll and phytoplankton during 2000–2012 conducted by Taihu laboratory for lake ecosystem (TLLER), visible surface cyanobacterial bloom in Lake Taihu was defined as the Chl a concentration 20 μg/L which was equivalent to phytoplankton biovolume 5.0×10^7 cells/L (Supporting information Fig. S3). Surface cyanobacterial bloom occurrence is associated with physiological environmental parameters such as nutrients (nitrogen and phosphorus) [1,46], temperature [47,48], and light [49–51], and physical environmental conditions such as wind induced wave and current [52–54]. The physiological conditions determined cyanobacterial biomass which was a basis for bloom formation. The physical conditions determined the formation of visible surface bloom. Because *Microsystis* spp. was the overwhelming dominant species during blooming periods [18,19] and Chl a concentration was an easy and economic monitoring parameter, Chl a was selected as an indicator of the cyanobacterial bloom intensity. All above physiological and physical parameters were included in this monitoring strategy.

Because the occurrence of cyanobacterial blooms in Lake Taihu was often highly heterogeneous in space. Remote sensing technology was used to solve this issue. The algal bloom signals in remote sensing images from Lake Taihu were retrieved through using a reflectance wavelength around 859 nm (band 2 of moderate-resolution imaging spectroradiometer (MODIS), which is a payload scientific instrument launched into Earth orbit by NASA. The instruments capture data in 36 spectral bands at varying spatial resolutions (250–1000 m), and image the entire Earth every 1–2 days)

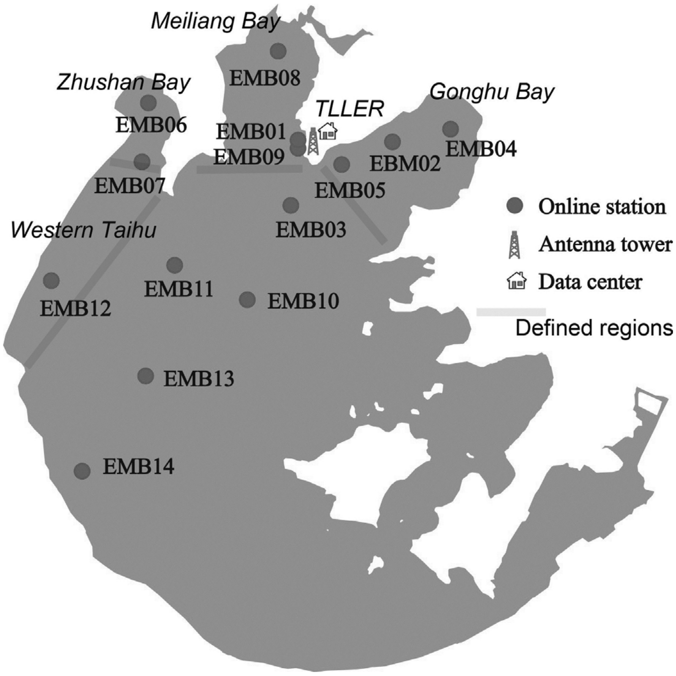

Fig. 2. Spatial distribution of 18 automatic observation and manually sampling sites and defined three regions.

[55], combined with band-ratio (859 versus 555 nm) [56], and the algal bloom was delineated with a threshold value of reflectance wavelength (859 nm or band-ratio >1). This threshold value was estimated in corresponding to Chl a concentration $\sim 10^1$ mg/L. The MODIS images with 250 m resolution data were downloaded from the NASA EOS data gateway (EDG).

In order to increase the temporal resolution so as to monitor the quick changes of cyanobacterial bloom, eighteen automatic wireless high-frequency monitoring station were deployed in the north and north–west of the lake, where the water was the most eutrophic, with high concentrations of Chl a and frequent recurrence of cyanobacterial blooms (Supporting information Fig. S2) (Fig. 2). Each station was equipped with a buoy, and sensors for water temperature (three layers from the water surface to bottom), turbidity, pH, Chl a, phycocyanin, conductivity, dissolved oxygen, and meteorological parameter sensors (air temperature, air pressure, wind speed, and direction, humidity, precipitation, solar radiation). In addition, three monitoring stations were also equipped with hydrodynamic sensors to record water current and waves (Supporting information Table S1). Every 10–30 min, these parameters were recorded and then converted to digital signals and transmitted wirelessly to the Taihu laboratory for lake ecosystem research (TLLER) based on the distributed time division multiple access (TDMA) protocol [57] (Supporting information Figs. S4–S5, Table S1).

Additional data on nitrogen, phosphorus and Chl a concentrations were available from manual monitoring, based on samples collected by ship. Sample collection and analysis were conducted twice a week (Monday and Thursday), from April until October for four years (2009–2012), for 18 sites adjacent to the automatic wireless observation sites (Fig. 2). The transparency was measured in-situ with secchi disk. Water samples from the surface and bottom were mixed and promptly transported to TLLER for analysis. Concentration of TP, TDP, TN, TDN, and Chl a were analyzed according to Chinese standard methods [58]. Specifically, TN and TP concentrations were determined by spectrophotometry after digestion with alkaline potassium persulfate [59]. Absorption coefficients at wavelengths of 210 nm were used for TN concentration calculation and absorption coefficients at wavelengths of 700 nm for TP concentration calculation were obtained by molybdenum blue method. Water samples for TDP and TDN were first filtered through GF/F fiberglass filter (Whatman, UK), and then followed the same procedures as TN and TP. Samples for Chl a were filtered by GF/C fiberglass filter (Whatman, UK), and the filters were frozen in dark under −4 °C. Chl a was calculated from spectrophotometric measurements at wavelengths of 665 nm and 750 nm after extraction in 90% hot ethanol.

2.3. Surface cyanobacterial bloom forecast

Cyanobacterial bloom occurrence prediction model included three key factors: (i) algal biomass indicated as chlorophyll a concentration, (ii) wind-induced turbulence, indicated by wind velocity; and (iii) precipitation which may diminish cyanobacteria via irradiance [60]. Algal blooms would occur with high algal biomass (>20 μg/L), low wind velocity (<3.1 m/s [61]), and low or absence of precipitation. The probability of cyanobacterial bloom occurrence was a product of the probabilities of chlorophyll a concentration, the wind strength (Beaufort scale), and precipitation (Supporting information Table S2). The phytoplankton biomass (indicated as Chl a concentration) in predictive model was calculated by summing the algae growth, death and settling rate during the predictive period [62]. The input for the algal biomass prediction model included initial algal biomass (Chl a), temperature (measured by automatic and high frequency monitoring sensor), light (measured manually from the transparency), P and N concentration (measured by manually monitoring). These input data were gridded with interpolation or extrapolation based on reciprocal of distance [62]. Forecasting of algal blooms in space was achieved by running phytoplankton biomass predictive model coupled a three dimensional hydrodynamic model. This hydrodynamic model employed an unstructured triangular mesh in the horizontal to represent the complex geometry and σ-coordinate in the vertical to represent the irregular bottom topography, and energy conserving using the finite volume method [62]. Because Lake Taihu is very shallow, the vertical computational domain was divided into five layers and the algal biomass (indicated as Chl a concentration) at surface layer would determine the visible cyanobacterial bloom. Thus, the future algal biomass (Chl a) spatial distribution was predicted using initial conditions from monitored data and driving input from the weather forecast. The algal biomass (Chl a) prediction model was run twice a week (every Monday and Thursday). The input of every run was updated from monitored data, thus avoiding an accumulation of simulation deviation. According to the predicted Chl a concentration at each cell, along with the probability of wind intensity and precipitation from weather forecast, the probability of cyanobacterial bloom occurrence in future three days could be calculated and the forecast report was produced (Supporting information Fig. S6).

The cyanobacterial bloom prediction results were evaluated using the following three days observation data either from remote sensing image or automatic high-frequency measurement, or ship-based sampling data, depending on the availability. Three most concerned regions were defined to evaluate the forecast precision, i.e., Meiliang Bay Gonghu Bay and Western Taihu (Fig. 2). If one grid cell in the defined region had cyanobacterial occurrence probability greater than 0.5, and the observation, either from remote sensing image or automatic monitoring or manual observation, showed the cyanobacterial bloom occurred in the defined region, it meant cyanobacterial bloom occurrence forecast success, and vice versa. The forecast precision for specific region was obtained by counting the total number of days in which cyanobacterial bloom were predicted correctly and divided by the total forecasted days.

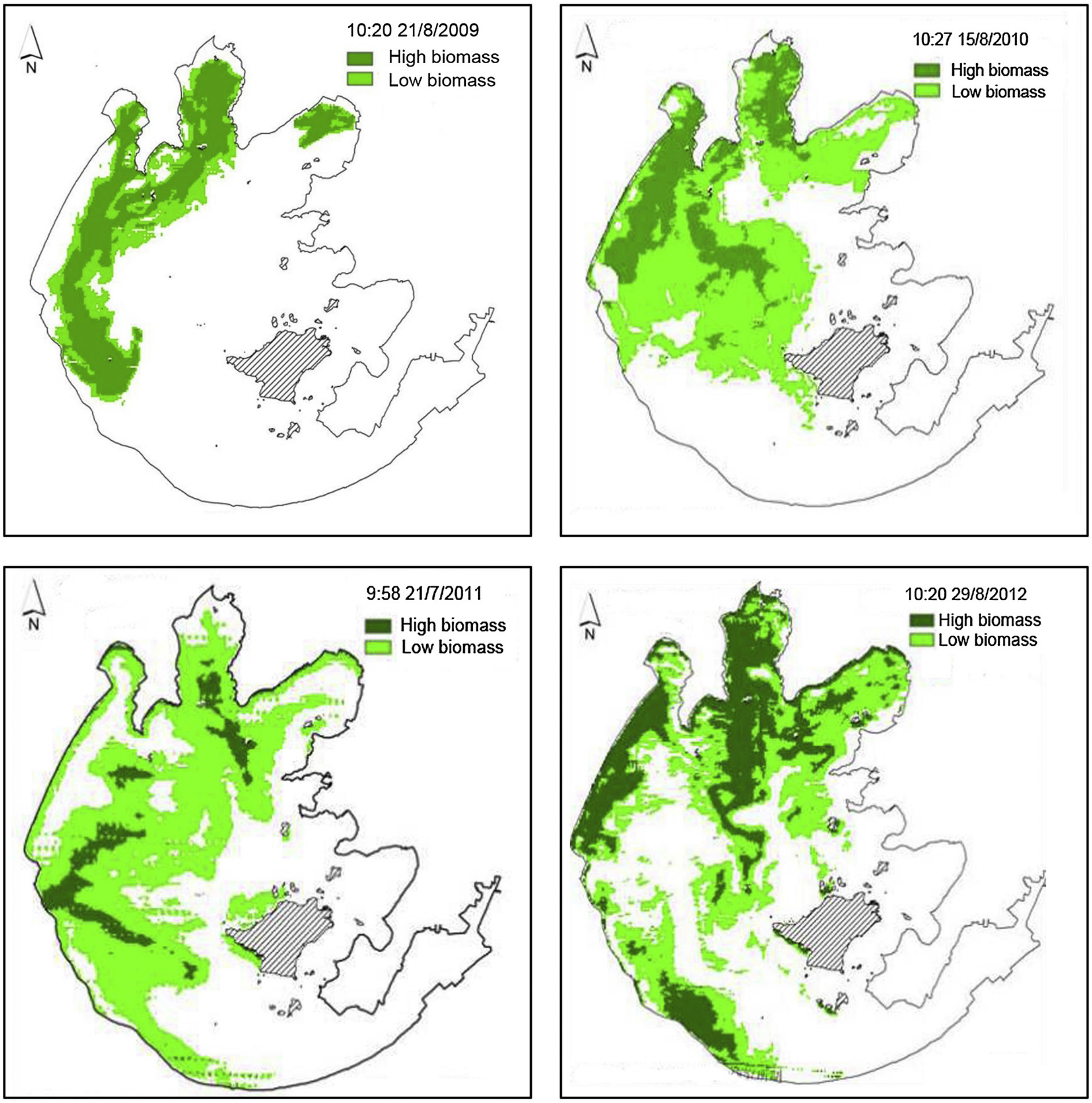

Fig. 3. Annual maximum cyanobacterial bloom area in Lake Taihu in 2009 (top-left), 2010 (top-right), 2011 (bottom-left), and 2012 (bottom-right).

3. Results

3.1. Surface cyanobacterial bloom monitoring

The monitoring of cyanobacterial blooms in Lake Taihu initiated in 2008. For the monitoring data continuity, the period from April 2009 to October 2012 was selected for implementation of this study.

During the warmer months from April to October in the four consecutive years of monitoring (2009–2012), there were a total of 258 images from which cyanobacterial bloom could be retrieved. Of these, 217 images showed cyanobacterial bloom reflectance signals, and the maximum area of cyanobacterial blooms were 524.2 km^2, 982.8 km^2, 997.5 km^2, and 991.4 km^2 (Fig. 3), and the mean areas were 154.3 km^2, 191.6 km^2, 242.8 km^2, and 191.1 km^2 for 2009–2012, respectively, which suggested that Lake Taihu continued to suffer from severe eutrophication, and that surface cyanobacterial blooms recurred without significant alleviation.

In August 2009, remote sensing and wireless automatic online observation showed that the cyanobacterial bloom dynamics following the passage of a typhoon over Lake Taihu. Typhoon Morakot passed Lake Taihu during August 11–13, 2009, with wind velocity peaking around 8.7 m/s at 17:00 August 11, 2009 (Fig. 4a). Water current measurement showed that before early morning of August 12, the vertical flow velocity had bi-direction movement (up and down), and after that time, there was uniform upward movement near surface layer (Fig. 4b). Interestingly, around the peak typhoon, the fluorescence-measured Chl a concentrations at the surface and bottom were destratified and fully mixed, while the surface Chl a concentration increased and bottom Chl a concentration decreased in the post-typhoon period. Correspondingly, the satellite image showed that there were several small sections of bloom with total area 92.3 km^2 in the center of lake at 10:27 am when the wind strength was at beginning of decline (Fig. 4c); one day later the bloom area had expanded to 467.6 km^2 (Fig. 4d). These data from August 11–13, 2009 showed that cyanobacterial bloom formation

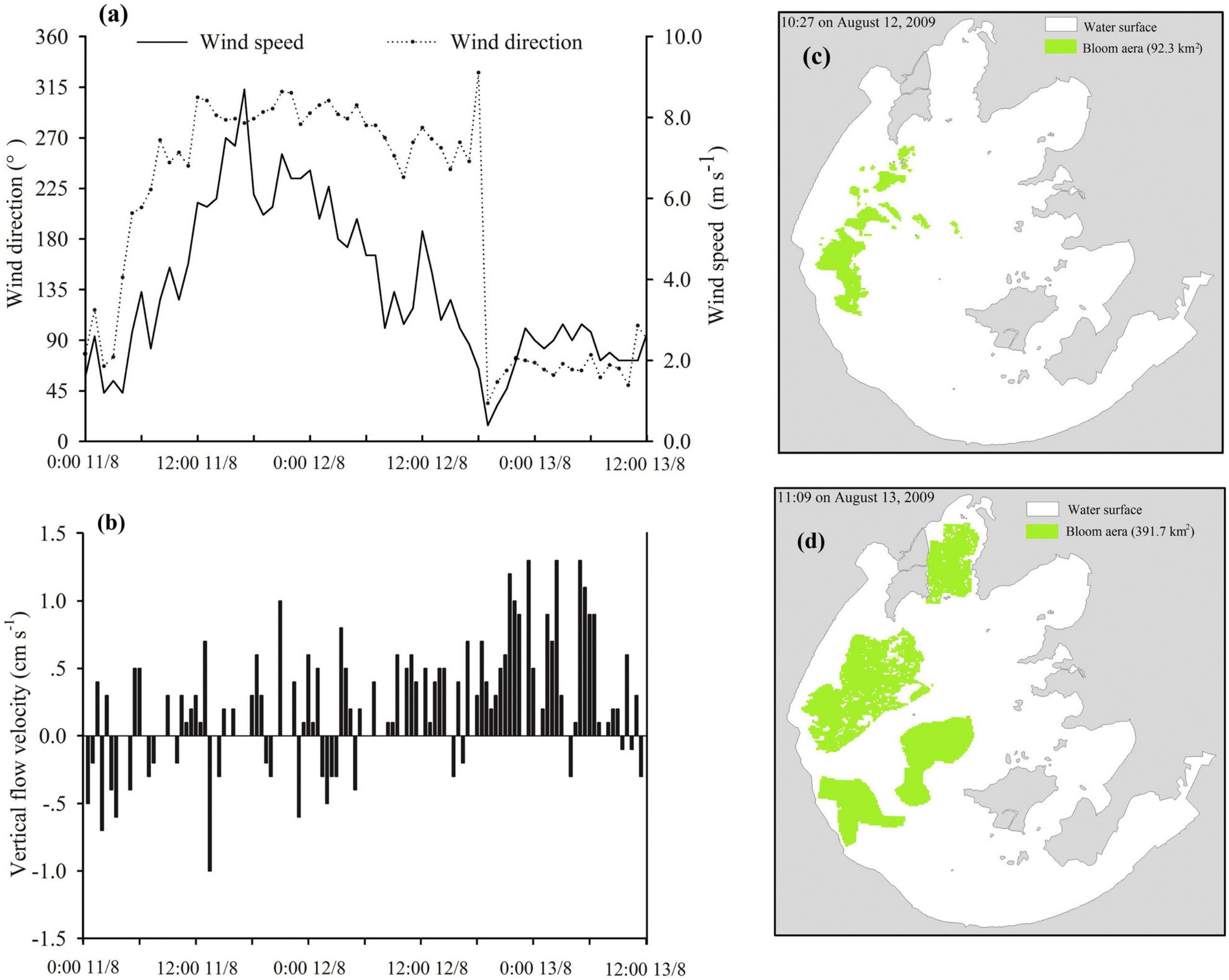

Fig. 4. Formation of the cyanobacterial bloom during typhoon Morakot in August 2009. (a) The wind speed and direction, (b) vertical flow velocity of cyanobacterial particles, and (c and d) satellite images of the cyanobacterial blooms after the peak of the typhoon at 10:27 am (top-right) and 12: 48 am (bottom-right), on August 13.

in the short period after the peak of the typhoon was determined by hydrodynamic conditions.

3.2. Forecasting surface cyanobacterial bloom

During the four consecutive summers of monitoring, the model predicted the cyanobacterial bloom outbreaks and accumulation at the surface as 141, 150, 138, and 102 days in 2009–2012, respectively. The prediction precision was evaluated by comparing chlorophyll a concentration from model output with data from satellite images, automatic monitoring parameters or boat survey data in the subsequent three days. The mean forecast precision was $82.2 \pm 11.7\%$ (Table 1). In addition, the satellite images were used to evaluate forecasted spatial distribution of cyanobacterial bloom. An example of this assessment was the comparison of cyanobacterial bloom model prediction against the retrieved algal bloom imagery from the satellite on July 31 2009 (Supporting information Fig. S7). Visible comparison suggested that the forecasted spatial pattern of cyanobacterial bloom matched the images very well. The good agreement between prediction and observation of algal blooms provided confidence that the data acquisition and management system in Lake Taihu can be used as an alert tool for subsequent risk management.

3.3. Risk management for cyanobacterial bloom

The aim of the extensive monitoring and forecasting system was to provide early warning of cyanobacterial bloom issues to government and water authorities via generation of forecasts and their distribution to Lake Taihu management agencies. To interpret this forecast data and use it for risk management, three levels of cyanobacterial bloom events were defined based on the historical observations:

Level 1: Cyanobacterial bloom area was greater than 60% of the lake area (i.e., 1403 km^2), or a *Microcystis* spp. biomass higher than 8×10^8 cells/L, or cyanobacterial bloom caused intrusion of black water agglomerate within the 2500 m distance of the main intake of drinking water.

Level 2: Cyanobacterial bloom area was greater than 40% of the lake area (i.e., 935 km^2), or the *Microcystis* spp. biomass was higher than 5×10^8 cells/L and less than 8×10^8 cells/L, or the cyanobacterial bloom caused intrusion of black water agglomerate within the 5000 m distance of the main intake for drinking water.

Level 3: Cyanobacterial bloom area was greater than 10% of lake area (i.e., 267 km^2), or the *Microcystis* spp. biomass was higher than 3×10^8 cells/L and less than 5×10^8 cells/L.

The different levels of cyanobacterial bloom events were accorded different counter measures to reduce the risk of pollution. These emergency responses included water diversion for flushing,

Table 1
Precision of forecasts for algal bloom occurrences in three areas of Lake Taihu during 2009–2012.

Years	Areas	Nr. offorecasts	Nr. of days covered by forecast	Days nr. of algal bloom can be detected	Days nr. of algal bloom correctly forecast	Accuracy(%)
2009	Meiliang Bay	47	141	30	26	86.7
	Gonghu Bay	47	141	15	10	86.7
	Western Taihu	47	141	–	–	–
2010	Meiliang Bay	50	150	38	31	81.5
	Gonghu Bay	50	150	28	24	85.7
	Western Taihu	50	150	–	–	–
2011	Meiliang Bay	46	138	–	–	–
	Gonghu Bay	46	138	–	–	–
	Western Taihu	46	138	–	–	–
2012	Meiliang Bay	34	102	31	26	83.9
	Gonghu Bay	34	102	14	8	57.1
	Western Taihu	34	102	50	47	94.0
MeanValues						82.2 ± 11.7

Table 2
Collection of cyanobacterial biomass, and frequency and area of black water agglomerates during 2009–2012.[a,b,c]

Year	Collected cyanobacterial scum (water content around 95%) Ton	Frequency of algal bloom induced black water agglomerate	Summed area of algal bloom induced black water agglomerate Km^2
2009	600,000	11	5.4
2010	650,000	4	6.6
2011	970,000	6	12.6
2012	1,250,000	12	4.8

[a] Data was provided by Water Resource Department of Jiangsu Province.
[b] Black water agglomerate originated from decomposition of accumulated cyanobacterial blooms. The number of black water agglomerate events was based on regular visible survey, and the area was measured with delineated area of black water agglomerate.
[c] Collected cyanobacterial blooms were weighed, and the water content was estimated from subsamples.

algal bloom collection and removal, drinking water securing, etc. For drinking water securing, the emergency measures included increase frequency of monitoring of water quality and MCs, transfer of water from other alternative treatment plants, setting up of barriers 500 m around the inlet to the drinking water plant, and floating coffer dams 500–1500 m from the inlet to the drinking water plant and preparation of potassium permanganate oxidation and powdered activated carbon adsorption for removing volatile sulfide chemicals and dimethyl trisulfide and cyanotoxin.

During the four-year implementation phase (2009–2012) of this directed cyanobacterial bloom monitoring and forecasting system, the government agencies collected and removed the following amounts of blooms: 600,000 tons (2009), 650,000 tons (2010), 970,000 tons (2011), and 1250,000 tons (2012) (Table 2); the water content of the blooms was around 95%. The cyanobacterial blooms caused black water agglomerate events, which although they increased in frequency in 2012, the total extent of black water agglomerate was reduced to 4.8 km^2 (Table 2). During 2009–2012, there was no drinking water contamination, even though the nutrient concentrations were similar to those before implementation of the monitoring and response program (Supporting information S1).

4. Discussion

Cyanobacterial bloom was an outcome of eutrophication which resulted from nitrogen (N) and phosphorus (P) over-enrichment from increasing anthropogenic activities such as industrial waste disposal, domestic sewage discharge and farmland irrigation [63,64]. Thus, removal of N and P from the effluents was a principal option for eutrophication control [65,66]. However, some aspects of this strategy would be difficult to implement, e.g., control of non-point source pollution from agriculture production, which might need strict soil management, managed fertilizer application, or soil ameliorations at the catchment scale [67]. The most recent example was Lake Erie, USA, which had recently been experiencing severe cyanobacterial blooms [68].

Watershed scale effluent diversion might be more difficult in China. As the world's largest developing country and rapid economic development in past three decades, China has faced severe environmental pollution, and about 80% of its freshwater lakes were facing eutrophication [69]. The gross domestic production (GDP) oriented economic development strategy made the environmental protection and pollution control policies weakly implemented. Since, the drinking water crisis in May 2007, although massive financial and human resources have been invested in pollutant diversion and ecological restoration in Lake Taihu [45], these investments were compensation for debts of economic development, such as closing down or relocation of small pollutant–producing chemical enterprises and constructing wastewater collection pipeline system and treatment plants. However, the great amount of and widely diffusive distribution of effluents in watershed couldn't be diverted completed in short period [70]. Our observations of water quality and cyanobacterial bloom during 2009–2012 confirmed that the eutrophication severity of Lake Taihu has not been alleviated since 2007 compared with the maximum extent of algal blooms before 2007 (Table 1 and Fig. 3) [44].

With integrated monitoring approach, it was first time to clearly see in-situ the surface cyanobacterial bloom formation after a strong storm. Satellite image data showed that the surface cyanobacterial bloom area expanded from 92.3 km^2 at 10:27 am, August 12, to 391.7 km^2 at 11:09am, August 13, 2009 (Fig. 3). Deployed ADCP monitoring data showed that suspended particles in the upper layer (most comprise of organic matter such as algal colonies) moved upward to water surface following the strong storm, indicated that surface cyanobacterial bloom formation was a redistribution of cyanobacterial colonies after a full mixture in water column. This cyanobacterial colonies movement to water surface was attributed to the buoyance, which was a physical process driven by floatation rather than by the *Microcystis*'s gas vesicles adjustment [71]. It was speculated that physical aggregation through collision during the turbulent period increase the colonies buoyance resulted in the colonies moving upward and floating at water surface (Yang et al., in preparation), since the observed vertical moving velocity was as large as 1 cm/s (Fig. 3). This monitoring outcome further confirmed that amount of cyanobacterial colonies (or biomass) was the basis of bloom formation, the vertical entrainment intensity determined the accumulation rate at surface and extent of visible cyanobacterial bloom.

The precision of forecasting depended on the spatial and temporal scale of monitoring [30,72]. During the four consecutive year from 2009 to 2012, there were a total of 177 reports of cyanobacterial bloom occurrence and location forecast, which covered 531 days (each report forecast the cyanobacterial bloom in following three days). But in these forecasted days, only about 15% were detectable with cyanobacterial bloom occurrence. With comparison between the forecasted algal bloom distribution against satellite image data or automatic high-frequency sensor data or manual sampling and analyzing data, the mean forecast accuracy was $82.2 \pm 11.7\%$, which meant that these predictions were highly in accordance with observations. This may be attributable to the low spatial resolution of model simulation (the minimum grid length was 500 m) and observations (MODIS image pixel resolution was >250 m, distance between automatic observation and manual sampling sites >5 km). Only large area of cyanobacterial bloom occurrence could be observed and predicted, which would increase the agreement degree between observations and forecasts.

With the cyanobacterial bloom occurrence forecast, the manual collection efficiency and total amount of algal scum increased from the 600,000 tons in 2009 to 1250,000 tons in 2012, which reduced the algal induced black water agglomerate areas in 2012. Removal of the cyanobacterial scum from the lake system could reduce not only the risk for drinking water supply, but also the nitrogen and phosphorus load. In addition, removal of cyanobacterial scum could reduce the source for microbial decomposition and degradation, which would break anoxia-driven "vicious cycle" [73] and reduce the recurrence frequency of cyanobacterial bloom.

The cyanobacterial bloom monitoring and forecasting approach was a temporary measure for securing drinking water supply; it cannot replace external effluent diversion. Even though the levels of TN and TP were no longer increasing annually, these nutrients were still present all year, at levels sufficient for algal bloom recurrence [36], especially in the northern part of the lake which still receiving wastewater from the catchment. Reduction of N and P from the watershed was still the most appropriate and sustainable long term measure for restoration of Lake Taihu. However, to date, endeavors have focused on the point source of wastewater diversion in the Lake Taihu Basin, and only part of wastewater from industry and domestic sewage has been diverted. There are still no effective measures for the widely distributed, large amount, non-point pollution from agriculture production and rural residents. The cyanobacterial bloom issue would sustain and recur in a period.

This integrated monitoring system was an exploration. The cost of construction and maintenance was quite high for this large and heterogeneous lake. The key for successful application is the spatial resolution of monitoring sites and more available and reliable chemical and biological sensors. In order to increase the spatial monitoring resolution and unattended chemical and biological monitoring parameters, more wireless high frequency automatic monitoring stations and reliable water chemical and biological detective sensors would be needed for this large lake in the future.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhazmat.2015.01.047.

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