Monitoring, environmental emergencies management and water treatment improvement of freshwater lakes in China: the Chao Lake case study

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ABSTRACT

Severe eutrophication of freshwater lakes, with the subsequent risk of algal blooms, has a critical effect on the safety of drinking water supplies in China and is one of the main environmental emergencies in the country. This paper focuses on Chao Lake, a large, shallow eutrophic lake used as a source of drinking water. The study considers the possibilities of improving the lake monitoring system and developing a SCADA system to manage the emergencies relating to water quality in order to meet the need of ensuring safe drinking water to the population of Chaohu City. The paper is presented in sub-sections that reflect the multitasking nature of the study, which focused on: (a) upgrading the monitoring system at lake and water treatment plant levels and also applying remote sensing, to develop a SCADA (*Supervisory Control And Data Acquisition*) system using *neural networks* to support prompt and effective management of emergency situations; (b) upgrading water collection and treatment technologies.

Key words | cyanobacteria bloom, drinking water treatment, early-warning system, eutrophication, neural networks, remote sensing

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doi: 10.2166/ws.2011.071

INTRODUCTION

Chao Lake (Chaohu) (Figure 1) is located in the central area of Anhui Province, on a tributary of the Yangtze River (N 31°43′10″–31°25′35″ – E 117°17′20″–117°51′05″) and is one of the five largest freshwater lakes in China. It has an area of 770 km^2 and its watershed covers 9,925 km^2 including eleven cities and towns as well as some 2,500 industrial, chemical and mining activities (e.g. phosphate mines in the North and Northwest Chaohu watershed). There is a resident population of nearly five million. The theoretical lake renewal time is 140 days. According to Liu & Qiu (2007), in 2003 50–60% industrial enterprises could not always meet national or local discharge standards. Agriculture is also an important component: cereals (rice and wheat) are grown on 6,480 km^2, mainly near the lake. Diffuse phosphorus loads are increased by erosion affecting over 50% of the Chaohu watershed, to varying degrees. In recent decades, soil erosion has been getting worse due to low forest coverage. Eutrophication has been one of the most serious problems of this lake (Xiao-e *et al.* 2008) since the 1990s and it has advanced in these decades (Dao-Gui *et al.* 2007). Cyanobacteria blooms first appeared in the early 1950s, but were still absent in the pelagic and southern zones of the lake in 1961, while in the 1980s they developed from May to November every year and throughout the lake (Dao-Gui *et al.* 2008). Due to the long and severe history of eutrophication of Chaohu, its sediments are likely to release huge internal phosphorus loads added to the external ones.

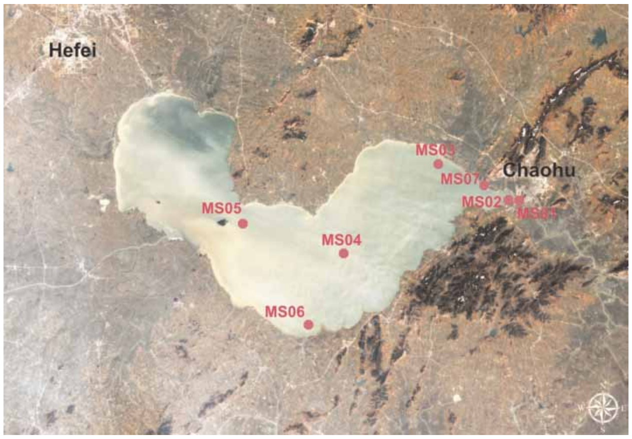

Figure 1 | Aerial view of Chaohu with the seven monitoring stations.

The lake water quality has dropped and eutrophication is badly affecting industrial and agricultural development, tourism and other activities, but especially the safety of the Chaohu City drinking water supply that comes from the lake, after treatment in two water plants.

Although full recovery of the lake is desirable but probably unfeasible, at least in the short term, this study especially focused on dealing with the need to improve the quality of the drinking water supplied to Chaohu City and on emergencies mainly relating to cyanobacterial blooms but, possibly, also to the presence of other hazardous pollutants. So, water quality was analysed by field and laboratory analyses and by remote sensing and the existing water plants were examined in order to suggest strategies to improve monitoring and water treatment and to predict alert situations.

METHODS

Assessment of lake water quality

Data collection and analysis

Lake monitoring is carried out in seven stations (Figure 1) in the eastern part. In six of these, sampling is manual and analyses are carried out at the laboratory according to Standard Methods (APHA, AWWA & WEF 1998). One station (MS07) is provided with an automatic sampler and analyser (Aqualab system), and analyses are performed every four hours. The monitored parameters are: pH, conductivity, temperature, dissolved Oxygen, TOC, COD, BOD_5, NH_3-N, NO_3^-, NO_2, total P, total hardness, Cl^-, SO_4^{2-}, Cr^{6+}, Cd, Pb, Cu, Zn, Phenols, LAS, chlorophyll *a* (chl-*a*), Permanganate Index, faecal coliforms, algal density, toxins, turbidity. The data were processed by PCA (Principal Component Analysis) and evaluated according to OECD criteria (OECD 1982; Cardoso *et al.* 2007), Trophic State Index (Carlson & Simpson 1996) and Morpho-Edaphic Indices (Cardoso *et al.* 2007). The reported evaluations are based on a 3-year series of data (2008, 2009 and 2010).

Remote sensing

When water is polluted by optically active substances, their presence can be observed by optical remote sensing, viewing larger water areas with greater temporal coverage than point measurements. Since the 1980s, satellite remote sensing has provided the opportunity for synoptic and multi-temporal viewing of water quality; it gives information on spatial-temporal variability of bio-optical parameters such as chl-*a*, transparency or even total phosphorus (Lindell *et al.* 1999). Recent developments in water quality algorithms have mainly been driven by the advent of MODIS and MERIS satellite sensors and their specific capacities for resolving inland and coastal waters (Peters *et al.* 2005; Reinart & Reinhold 2008; Odermatt *et al.* 2010). In this study, 35 MERIS images (time-series: May 2004–December 2008), radiometrically corrected with radiative transfer code 6S (Kotchenova *et al.* 2006), were used to evaluate algal blooms and classify water quality into five classes. The classes were defined according to the retrieved MERIS reflectance and to increasing values of chl-*a* concentrations, the latter determined by means of a semi-analytical model for turbid productive waters (Gitelson *et al.* 2007). The water reflectance of the worst water class also indicates the presence of cyanobacteria-dominated algal blooms (Lin *et al.* 2003; Le *et al.* 2011). The two-year analysis of (2007–2008) daily surface temperature products provided by MODIS pointed out their relationship with algal blooms. Besides water quality parameters, remote sensing allows the investigation of land cover dynamics and evolution; depending on the extent of target areas, a wide variety of satellite instruments are available for describing land cover according to the catchment scale. In this study, the analysis of land use/cover change at the catchment scale was performed with a historical dataset comprising four Landsat scenes acquired between 1989 and 2003. From pre-processed data, the detection of two main land cover features strongly related to water consumption and degradation in the area (i.e. urbanized and aquaculture areas) was carried out using a supervised decision tree approach.

Evaluation of drinking water treatment technologies

The study mainly focused on: (a) evaluation of possible water intake strategies, to reduce the amount of influent Total Suspended Solids (including algae) and (b) feasibility of different options for upgrading the two Chaohu water treatment plants (DWTPs). As to *water intakes*, three solutions were evaluated: bank filtration, levee filtration and HRFs (Horizontal Roughing Filters) (Dastanaie *et al.* 2007) in technical and economical terms. The *upgrading* of the two DWTPs, displaying different layouts and treatments, was considered on the basis of priority level interventions and subsequent upgrades including the optimization of the existing units – namely filtration and disinfection – and a thorough review of DWTP hydraulics.

RESULTS AND DISCUSSION

Lake water quality

The evaluation of analytical data according to TSI (Trophic State Index) (Carlson & Simpson 1996) and OECD criteria (OECD 1982) led to defining the state of Chaohu as between eutrophic and hypertrophic. Table 1 shows average, minimum and maximum total phosphorus concentrations for all the monitoring stations. In spite of the large area of the lake, the variations among stations are limited, as shown by the low standard error. The highest values are always found in station 5 (Zhongmiao), directly affected by input from Hefei city.

Figure 2 shows TSI over 50 (threshold for eutrophy) in all the manual monitoring stations.

To estimate the natural P concentration and load, Morpho Edaphic Indices have been applied (Cardoso *et al.* 2007):

$$\mathrm{MEI_{cond}}: \mathrm{Conductivity}\ (\mu\mathrm{S/m})/\mathrm{Average\ Depth}\ (\mathrm{m})$$
$$\mathrm{Log\,P} = 0.75 + 0.27 * (\pm 0.11) \log \mathrm{MEI_{cond}}$$

Table 1 | Total phosphorus in Chaohu: averages, minimum, maximum, standard deviation and standard error (based on one year monthly analyses)

	Average (g/m³)	Minimum (g/m³)	Maximum (g/m³)
Average	0.117	0.024	0.270
Standard deviation	0.019	0.007	0.041
Standard error	0.161	0.303	0.152

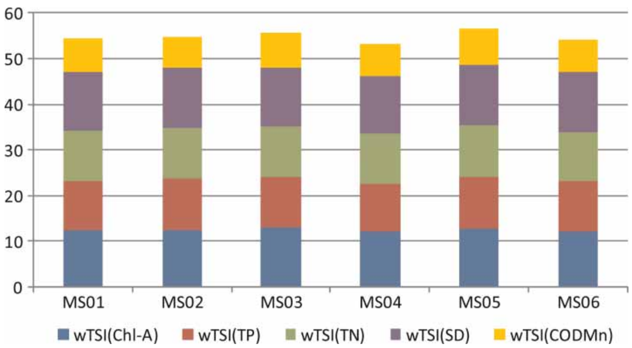

Figure 2 | TSI based on annual average chl-*a*, total P and total N concentration, transparency (Secchi disk) and Permanganate Index in the six manual monitoring stations.

$$\mathrm{MEI_{alk}}: \text{Alkalinity}\ (\mathrm{mg\ CaCO_3/L})/\text{Average Depth}\ (\mathrm{m})$$
$$\mathrm{Log\,P} = 1.48 + 0.33 * (\pm 0.09)\ \log \mathrm{MEI_{alk}}$$

Based on 2.89 m depth, 29.3 mS/m conductivity and 120 mg $CaCO_3$/L alkalinity (average values), the natural P concentration would be 0.102 g/m^3 (0.073 ÷ 0.142) and 0.067 g/m^3 (0.024 ÷ 0.0185), respectively. Such values are comparable to the measured ones, which means that the overall phosphorus loads are not much different to natural loads and the non point source loads in particular are very important.

PCA shows that chl-*a* concentration is strictly related to the main indicators of domestic pollution, such as NH_4-N, total P, anionic surfactants (LAS) and faecal coliforms and also confirms the importance of P loads from domestic sources.

A first attempt to analyse the collected data by means of neural networks was made by running the program using a regression methodology (to discover discrepancies in the data that can mean irregular behaviour of the monitoring instruments) and time series methodology (Bertani *et al.* 2006), in order to forecast the increase of chl-*a* before it occurs, thus allowing countermeasures to be put in place before the water quality worsens too much.

The results obtained are satisfactory, as shown in Figure 3.

The analysis of time series MERIS maps shows the worst water quality conditions mostly in the north-western part of the lake (Figures 3(a) and (b)), concurring with the results of chemical analyses. The frequency of worst quality classes is 35% in the north-western basin, 1% in the lake centre and 5% in the eastern part, facing Chaohu City. The worst quality status occurs from May to July (Figures 4(c) and (d)). Multi-sensor analysis between MERIS and MODIS indicates a positive correlation between surface temperature and phytoplankton ($r = 0.91$), but this relation is faulty ($r = 0.1$) when cyanobacteria blooms are detected by the worst water quality class.

The analysis of Landsat data highlights the enormous growth of Hefei city in the north-western area and the spreading of aquaculture facilities (Figure 5) as important sources of impact on the lake water quality.

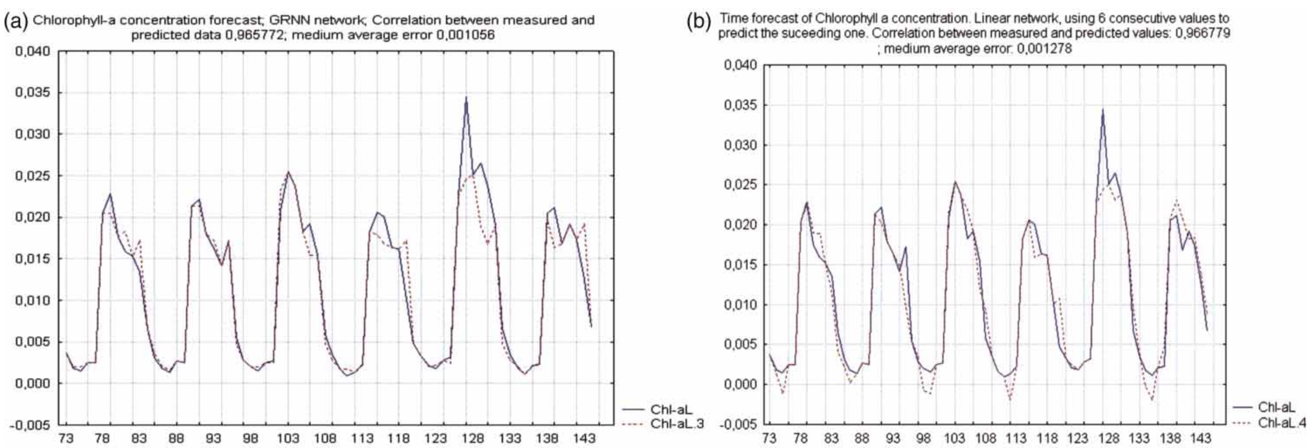

Figure 3 | Results of neural networks application in regression mode (a) and time series mode (b), to predict chl-*a* concentration as a function of all the parameters monitored in the automatic station from 2008 to 2010.

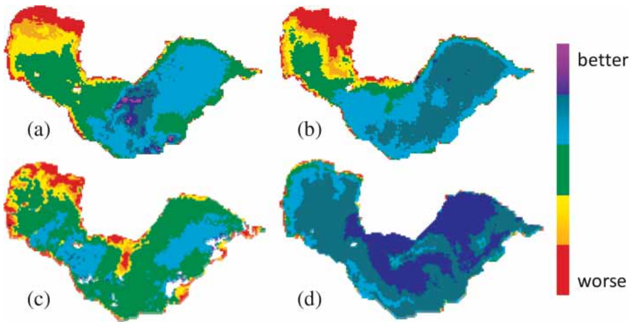

Figure 4 | Example of MERIS-derived maps of water quality (a) 31 May 2006; (b) 11 April 2007; (c) 03 July 2008; (d) 06 December 2008. From purple (better) to red (worse) the water quality decreases.

Evaluation of drinking water treatment technologies

Hydraulics

Both plants are hydraulically oversized in many of their treatment units; only filtration complies with the standard data range, but the insufficient bed depth and the improper media characteristics lead to poor overall efficiency. We also highly recommend interconnecting treatment lines and using flow-partition devices.

Water intake

The eutrophic situation in Chaohu suggests upgrading the water taken from the lake. Bank filtration or, alternatively, horizontal roughing filters (HRFs) should be considered and HRFs may be the easiest (and the least expensive) option (Wiese & Nützmann 2009). As suggested by remote sensing analyses, further benefits could derive from the displacement of the withdrawing station site.

Pre-treatment

If the water intake system cannot be modified, a bar-screening step, followed by micro-straining (20–65 μm) should be considered. The current *pre-chlorination* step must be dismantled, as the presence of NOM and the production of toxic DBPs through their reactions with chlorine are very probable.

Coagulation

Both plants must be equipped with mechanically stirred flash-mixing tanks (operating at high G values) to improve the destabilization process.

Flocculation

HRT of the present hydraulic slow-mixing step is too high; better and more flexible results can be attained (after a regular coagulation) with mechanical stirrers.

Sedimentation

Present sedimentation tanks are oversized (if both tanks are in operation) and their size has to be reconsidered together with flocculation tanks.

Filtration

A strong upgrade is needed in both DWTPs, especially for the filtering media (deeper filter bed, larger and more uniform grain size) and filter regulation to obtain an automatic filter backwashing sequence.

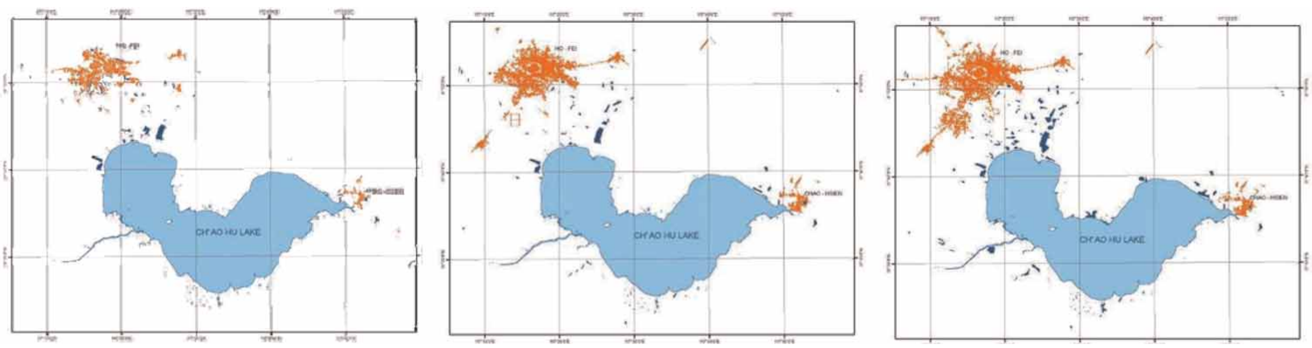

Figure 5 | Landsat-derived maps of urban areas (in orange/dark grey) and aquacultures (in blue/light grey). From left to right: the situation in 1989, 1995 and 2003.

Disinfection

Chlorine can be used as the main disinfectant (although the residual Chlorine-meter and effective doses have to be optimized), but the use of ozone or UV rays has to be considered if (especially for UV) water transmittance is high enough.

Extra treatments (algal blooms)

In the case of bank filtration or HRFs, the specific treatments currently performed can be abandoned (pre-chlorination must be abandoned in any case). The injection of PAC (powdered activated carbon) could cut micro-pollutant concentrations.

Suggestions for further treatment

Adsorption on GAC (granular activated carbon) is strongly recommended.

CONCLUSIONS

To improve monitoring, the study suggests installing two more automated stations for sampling and analyses, to automatically and continuously monitor toxicity, to measure oxygen at the water sediment interface, to include the analysis of ortho-phosphate P and to determine chl-*a* by fluorescence.

Remote sensing may offer an important source of information for monitoring water quality in Chaohu and to follow the evolution of algal blooms.

The chief indications for water treatment consist of the adoption of HRFs at intakes, of suggesting specific options for upgrading the existing plant processes and of provision for further treatments.

A neural network based SCADA can be implemented to face emergencies. Thus a series of pre-alert thresholds is defined for some significant parameters (correlated with chl-*a* on the basis of PCA) as reported in Table 2. The reference values are defined according to the trends observed in the three years of monitoring.

Table 2 | Proposal of reference values to define pre-alert conditions for toxicity in Chaohu

Parameter	Value
Ratio chl-*a* concentration/baseline chl-*a* concentration	5
Chl-*a* concentration	10 μg/L
Ratio P-PO_4/TP at the surface	<0.5
pH at the surface	≥ 8
Toxicity	25–50%

Two levels are required: for the most severe hazard, the treatment plants should be stopped and water supplied from other sources. Less severe situations could be held as a pre-alert. For both alert levels, toxicity (continuously monitored) should be the prevailing parameter. The pre-alert is defined at 25% reduction of bioluminescence in *Vibrio fischeri* test, whatever the temperature, or at values over/under the reference value for only one of the listed parameters when the temperature is between 18 and 25 °C. The values of the remaining indicators are not likely to vary simultaneously and, in particular, only some of them become critical at the same time. So, a first level of pre-alert is established when one of the indicators reaches the critical level, while a second level corresponds to critical values for all indicators.

When pre-alert occurs, further analyses are needed. If the critical parameter is toxicity, chemical analyses should be performed on the basis of a survey of the possible input or concentration increase of toxic substances. If the value of even only one of the other indicators is over (or under) the indicated thresholds, the algal groups and their proportion need to be determined.

Such indications will be effective as long as all the other pre-requisites established by Chinese laws are respected. The immediate priority is to improve the quality of drinking water, but the real solution to the problem is the adoption of a strategy to recover the overall conditions of the lake. This will require improved coordination of the various local and government public institutions and private stakeholders, therefore making proper and updated data and information management infrastructures accessible.

ACKNOWLEDGEMENTS

This research was developed in the framework of the Sino-Italian Cooperation Program for Environmental Protection and with the full support of the Chaohu Environmental Protection Bureau. MERIS data was derived from the ESA AO-553 MELINOS Project. ASTER data were kindly provided by Luigi Boschetti. We acknowledge Paolo Villa for processing Landsat data.

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First received 6 January 2011; accepted in revised form 12 July 2011