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Sediment distribution pattern mapped from the combination of objective analysis and geostatistics in the large shallow Taihu Lake, China

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Abstract: Investigation was made into sediment depth at 723 irregularly scattered measurement points which cover all the regions in Taihu Lake, China. The combination of successive correction scheme and geostatistical method was used to get all the values of recent sediment thickness at the 69 × 69 grids in the whole lake. The results showed that there is the significant difference in sediment depth between the eastern area and the western region, and most of the sediments are located in the western shore-line and northern regimes but just a little in the center and eastern parts. The notable exception is the patch between the center and Xishan Island where the maximum sediment depth is more than 4.0 m. This sediment distribution pattern is more than likely related to the current circulation pattern induced by the prevailing wind-forcing in Taihu Lake. The numerical simulation of hydrodynamics can strong support the conclusion. Sediment effects on water quality was also studied and the results showed that the concentrations of TP, TN and SS in the western part are obviously larger than those in the eastern regime, which suggested that more nutrients can be released from thicker sediment areas.

Keywords: objective analysis; geostatistics; sediment distribution; Taihu Lake

Introduction

Large amounts of contaminants such as nutrients and trace metals are transported into large lakes from inflow rivers and then absorbed onto or associated with fine-grained sediment particles (Sheng, 1979). The nutrients in recent sediment can create long-term eutrophication problems and delay water quality improvement by circulating in the sediment-water ecosystem (Varjo, 2003; Gardner, 1991; Rysgaard, 1999; Havens, 2001). With the water surface disturbed, sediment resuspension may lead to nutrient release, which results in increasing nutrient concentrations in water body and preventing recovery of the limnic ecosystem especially in shallow lakes (Bailey, 1997; Kristensen, 1992; Sondergaard, 1992). Even if there is no wind-forcing on water surface, the nutrients may diffuse statically between sediment and water with concentration gradient (Fan, 2000a; 2000b). Moreover, the suspended particluate matter (SPM) in water body may have significant influence on water column transparency, light attenuation and bio-species and their abundance associated with primary production. As a result, sediment distribution and resuspension have received much attention for better understanding of aquatic ecosystem in many areas (Grant, 1979; Lou, 1996; 2000; Guillem, 1997; Hawley, 1992; 2000).

In Taihu Lake, several investigations have been made into hydrodynamics (Qin, 1999; 2000) and its effects on algae bloom (Fan, 1998a), static nutrient release (Fan, 1998b), sediment distribution (Fan, 2000a; 2000b) and resuspension events related to surface disturbance (Zhang, 2001). There is still little knowledge about accurate recent sediment thicknesses in different region although many observations have been made in recent years. Most of the studies on sediment in the past mainly focused on depth investigation at scattered points (Fan, 2000a) and no mathematic interpolation scheme was employed to get the whole map of sediment depth in the lake. In the present study, statistical interpolation scheme was used in order to address sediment distribution pattern and the results have likelihood to provide the preliminary knowledge for the research on internal release in Taihu Lake.

1 Study area

Taihu Lake is the third largest fresh-water lake with a mean depth of 1.98 m and a surface area of 2338 km^2 in China (Pu, 1998; Sun, 1993). There is no seasonal stratification due to the vertically well-mixed water column especially during storms in summer. There are more than 100 inflow rivers and most of them are located in the west. Water volumes emptied into Taihu Lake at Dapu and Xiaomeikou can account for 80%—90% of the total inflow volume. The main three outflow stations are located in the east and the runoff there can account for 90% of the total discharge (Fig. 1). The river discharges have little influence on the current circulation in Taihu Lake (Luo, 2003).

Bottom sediments are generally cohesive, fine-sized and homogeneous spatially in the upper 10 cm in the whole lake (Qin, 2004). However, sediment characteristics change drastically at the layers deeper than 10 cm. For example, sediments become coarser, more non-cohesive, but better sorted and the water content gets less with increasing depth. In every summer, there are always algae-bloom events accompanied by sediment resuspension after storms in the north three bays (Fig. 1), which raises the problem that algae-bloom and sediment resuspension events are closely related to wind-forcing in Taihu Lake.

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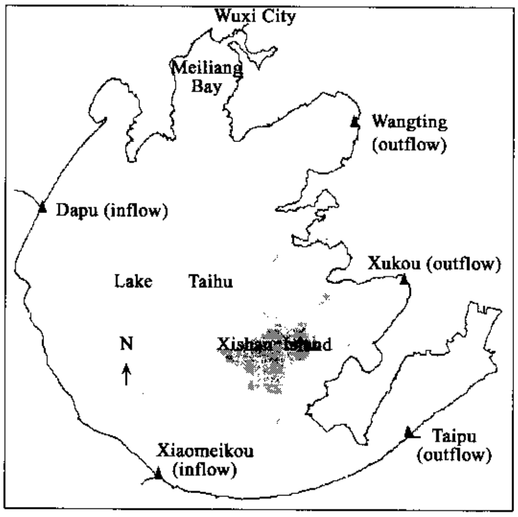

Fig.1 Taihu Lake(study area)

2 Methodologies

Interpolation scheme:

In order to obtain the values of sediment depth at the estimation grids, interpolation method has to be used. Objective analysis (OA) is a contemporary synonym for statistical estimation based on the Gauss-Markov theorem (Lynch, 2001). This theorem provides a sound basis for interpolation of irregularly spaced data and has been widely used in meteorology (Lorenc, 1981; Cressman, 1959; Fischer, 1995), oceanography (Lynch, 2001; Fischer, 1995; Molinari, 2000) and hydrology (Dunn, 1999). Successive correction analysis is one of the methods of OA schemes which has been frequently used for interpolation (Tian, 1995; Dong, 1997) and in this paper it was employed to map all the grid sediment thicknesses based on the collected data at the 723 irregularly scattered measurement points in Taihu Lake.

The successive correction scheme can be expressed as: if the measurements are indicated by D_i ($i = 1, 2, \cdots, 723$) and the estimation at point j with variable D_j, then D_j is obtained by a weighted average of the values D_i at all the measurement sites,

$$D_j = \frac{\sum_{i=1}^{n_j} D_i \alpha_i}{\sum_{i=1}^{n_j} \alpha_i}, \qquad (1)$$

where α_i is the weighting function which depends on the radius of influence R and the distance r from the estimation site to the measurement site, and n_j represents the total number of sites within a radius r smaller than or equal to the user-specified influencing radius R. α_i can be written,

$$\alpha_i = \left(\frac{R^2 - r^2}{R^2 + r^2}\right)^k \qquad r \leqslant R, \qquad (2)$$

$$\alpha_i = 0; \qquad r > R. \qquad (3)$$

In order to decide the radius of influence R, the experimental variograms were calculated based on geostatistics (Zhang, 1997),

$$F(r) = \frac{1}{2N(r)} \sum_{i=1}^{N(r)} [D(x_i) - D(x_i + r)]^2, \qquad (4)$$

where D is the sediment depth, $D(x_i)$ is the value of D at the measurement point x_i, r represents the distance lag, $N(r)$ denotes the number of pairs of measurement points separated by distance lag r (Murray, 2002; Zhang, 1997; Poon, 2000). Then the experimental variograms were fitted by an exponential model(Fig.2).

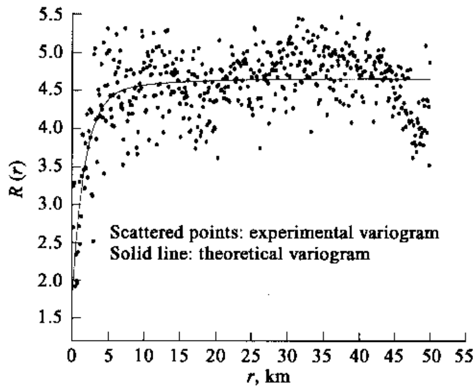

Fig.2 Variograms for sediment thickness fitted to an exponential model. A total of 650 pairs of samples were analysed with the correlation coefficient of 0.892

Fig.2 shows the range for sediment depth is about 28 km because the fitting curve slope is very small when the distance lag r is larger than the range value, which implies there is poor correlation between two sites if the distance between them is lager than it. Then the range value can be used in Eq.(2).

After the first interpolation step, the averaged value at all the measurement sites can be calculated based on the four nearest point values and bilinear interpolation method(Dong, 1997), and then all the increments can be computed at the measurement sites,

$$\Delta D_i = \bar{D}_i - D_i, \quad (i = 2, \cdots, 723). \qquad (5)$$

All the increments will be used to decide the correction value at all the estimation sites by employing the same method used in Eq.(1),

$$\Delta D_i = \frac{\sum_{i=1}^{n_j} \Delta D_i \alpha_i}{\sum_{i=1}^{n_j} \alpha_i}. \qquad (6)$$

Then the value at an estimation site can be computed,

$$D_j = D_j + \Delta D_j. \qquad (7)$$

The above procedure Eq.(1)—(3) and Eq.(5)—(7) should be repeated for four or five times according to the principle of successive correction scheme(Tian, 1995). With the initial value(28 km) of radius of influence determined, the following radiuses can be obtained with smaller and smaller user-specified values of 25, 23, 20 and 15 km in the iterative procedure. All values of the sediment depth will be obtained after the last interpolation is finished.

3 Results

A 69 × 69 grid net was used for interpolation with the resolution of 1 km in Taihu Lake. All the 723 measurement sites are uniformly distributed in the whole lake and the five radiuses of influence were set to be 28, 25, 23, 20 and 15 km based on the exponential model results (Fig. 2). With consideration on error induced by observation and calculation, all the sediment depths less than 20 cm have been set to be zero and Fig. 3 shows the results. The distribution map illustrates that there is the significant difference in sediment thickness between the western area and the eastern part in Taihu Lake. Most of the sediments are deposited in the western shore area and the northern bays with the maximum depth larger than 4 m, but most of the depths are smaller than 2 m in the eastern part. There are two special regions with very thin sediment coverage and they are located in the center of the lake and the south of Xishan Island. The notable exception is the patch between Xishan Island and the center region where the maximum sediment depth is more than 4.0 m.

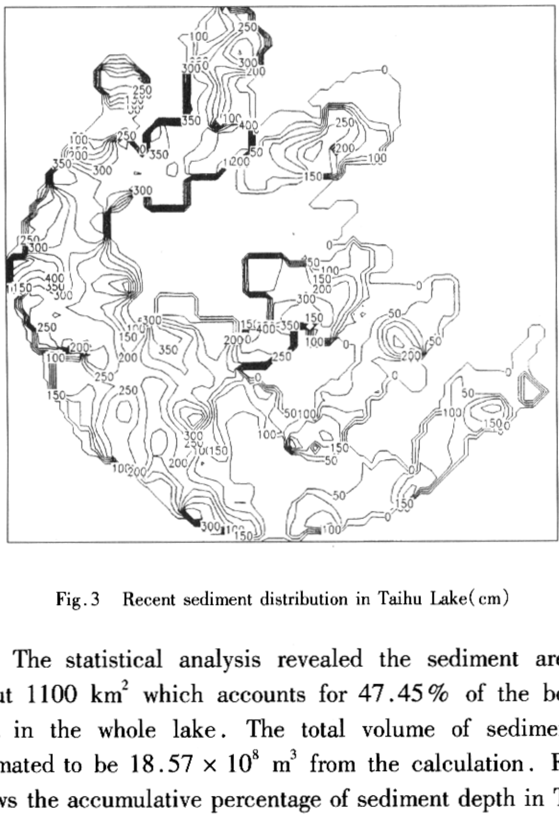

Fig.3 Recent sediment distribution in Taihu Lake (cm)

The statistical analysis revealed the sediment area is about 1100 km^2 which accounts for 47.45% of the bottom area in the whole lake. The total volume of sediment is estimated to be 18.57×10^8 m^3 from the calculation. Fig.4 shows the accumulative percentage of sediment depth in Taihu Lake. The results suggested that the sediment depth generally ranges from 0.5 m to 3.0 m and there are just a few grids where sediment depth is out of the range.

In order to provide insight into the relationship between sediment thickness and water quality, the nutrient concentrations are calculated. Table 1 shows the averaged surface concentrations of the total nitrogen (TN), total phosphate (TP) and suspended sediment (SS) during 1998—2001 in different regions of Taihu Lake. From the results, it leaved little doubt that the concentrations of TP, TN, SS in the western and northern parts are obviously higher than those in the eastern and southern regions, which suggested the sediment thickness can have impacts on the water quality via the nutrient exchanges at the sediment-water interface.

Table 1 Concentrations of TP, TN and SS in different areas of Taihu Lake during 1998—2001 (mg/L)

Parameter	TP	TN	SS
East	0.035	0.476	7.515
South	0.04	1.345	19.765
West	0.10	2.17	31.47
North	0.08	1.361	35.42

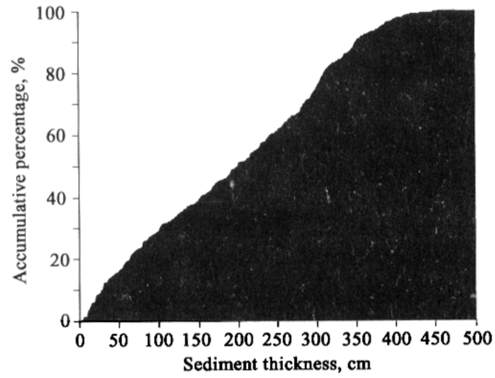

Fig.4 Accumulative percentage of sediment thickness

4 Discussion

The sediment pattern obtained from calculation demonstrated that the western and northern part are very rich in sediment and the maximum depth is more than 4.0 m, but much less sediments are deposited in the eastern and center regions. The contrast reflects the differing supply systems, the effects of storms and currents, and also the influence of control of topographical structure on the sedimentary regime (Sun, 1993).

The topographical structure was formed in depositional history and it provides the initial sediment distribution pattern. With wave effects, sediment in shallow lake can be easily resuspended by waves and then transported by currents (Luettich, 1990). In Taihu Lake, a value of 0.037 N/m^2 is estimated to be the critical shear stress for fine-grained sediment resuspension ($D_{50} = 0.017$ mm, $r_s = 1.3$ g/cm^3) by flume experiment (Qin, 2004). Thus small wave height is enough for resuspension in the shallow regions. In the areas where wind fetch is large, sediment can be also easily suspended by wind-waves. Hence the shallowness in Taihu Lake decides the close relationship between hydrodynamics and sediment resuspension.

In the western part of Taihu Lake, sediment supply is mainly from the inflow rivers although the discharges can have little influence on the lake current speed. After the sediments get into the lake, they will deposit during the transportation resulting in the sediment thickness increase in different regions. The numerical simulation provided the direct evidence for the conclusion because there is always strong along-shore current with prevailing wind-forcing in Taihu Lake (Luo, 2003). As a result of water movement, the sediment deposits along the west shore and the process makes the present pattern possible. The discharge from Wuxi City also greatly contributes to rich sediment in Meiliang Bay and the convergent zone induced by predominant wind (Luo, 2003) raises the possibility that the sediment coverage can get thicker and thicker in this region.

The sediment distribution pattern can also reflect the nutrients exchange between sediment and water column in Taihu Lake. It is very obvious that the concentrations of TP, TN and SS in the eastern region are much smaller than that in the western part (Table 1), which suggested the sediment thickness can significant impact on water quality in the lake. Although the current circulation will redistribute the sediments resuspended by waves, there is still static nutrient release from the bottom sediment. Fan *et al*. (Fan, 1998b) revealed the averaged release rate of NH_4^+-N, DTP and DCOD are 158.2, 2.05 and 27.8 mg/($m^2 \cdot d$) respectively and the static nutrients release should be paid much attention in the pollution and eutrophication control in Taihu Lake. There will be greater nutrient release with wind effects (Qin, 2004) because a large amount of sediment can be suspended and the organic matter such as P and N are more than likely to be released from the overlying water with proper condition (Wainrignt, 1997; Kleeberg, 1997; Hu, 2001; Lohrer, 2003).

The mapped sediment distribution pattern will be very beneficial to aquatic environmental analysis and also to better understanding the discrepancy of water quality among the different regions. It is also very useful in controlling lake eutrophication and developing policy especially in controlling external loading in order to reduce internal loading in Taihu Lake.

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