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Taihu Lake: Past, Present and Future*

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Abstract: *The presence of roads, farm house foundations, wells and Liangzhu period cultural relics in the bottom of Lake Taihu attest to the fact that this shallow depression was probably dry between 4 and 5 thousand years ago. This interpretation is corroborated by the sudden disappearance of algal pigments at sediment depths carbon-14 dated at 4-5 thousand years before present.*

In winter, the stronger winds are predominantly from the northeast. These winds result in a powerful counterclockwise current that transports lake sediments and has altered the very shape of the lake over the last 300 years. Winds produce a complex mixing pattern in Lake Taihu with storm induced sediment deposition occurring near the lake's center.

During approximately 240 days of the year, the wind blows across Lake Taihu with sufficient force to mix it to its bottom. As a result, this polymictic lake rarely becomes anoxic and dissolved oxygen at the mud water interface is maintained at or above $4\ mg \cdot l^{-1}$. *The consequences of this high dissolved oxygen are quite impressive as high organic loading to the lake would otherwise render its bottom waters anaerobic killing many of its natural inhabitants.*

Because suspended solids reduce (attenuate) light penetration, the major primary production takes place in the top metre of the lake (mean Secchi Transparency = 0.25 m). Suspended clays are slow to settle and wind mixing keeps fine-grained suspended solids in suspension in all but the most quiet backwaters of the lake.

In the recent past about 23 000 metric tonnes of phytoplankton were produced in Lake Taihu. This large production represents only about 5% of the total influx of organic material entering the lake. In summer and fall, cyanobacteria such as Microcystis *spp. and* Anabaena *spp. dominate most of the lake. Recently, however, mixotrophic flagellates displaced cyanobacteria as the dominant algae in parts of Lake Taihu with high bacteria and high suspended solids (e.g. Wuli and Meiliang Bay). In the future, facultative heterotrophs may come to dominate an ever larger portion of the lake waterc column.*

Keywords: *Lake Taihu, Allogenic Production, Polymictic, Suspended Solids, Light Attenuation*

1. A View to the Past

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To explain the distribution of 4 000 - 5 000 year old Liangzhu cultural relicts found at various sites in and around Lake Taihu (Fig. 1) it is possible that the basin of the lake dried up and was later refilled. According to Qu *et al.* (1997), sedimentation ceased in Lake Taihu about 5 000 years ago and resumed about a thousand years later. Underwater studies of the lake bottom revealed that rocky roads, old farm house foundations and long abandoned wells dot the bottom of this shallow water body. It is hypothesized that the lake bottom was exposed to desiccation for roughly 1 000 years for the period 4 000 to 5 000 aBP. During this time the total organic content (TOC) of the sediments dropped to their lowest levels ($30\ \mathrm{mg \cdot kg^{-1}}$, Wu *et al.* 1997). At a sediment depth of 20-25 cm the TOC increased from $30\ \mathrm{mg \cdot kg^{-1}}$ to $130\ \mathrm{mg \cdot kg^{-1}}$ indicating that the lake basin was again flooded about 4 000 aBP. Over the intervening years (0-4 000 aBP), monsoons have altered the lake's shape by creating strong currents which eroded away southern and southeastern shorelines (Zheng *et al.*, 1990). The most convincing evidence for this is the presence (under the lake's waters) of stone erosion defense perimeters (Wu and Gong, 1987; Sun and Wu, 1989 (Fig. 2)). Comparisons of figures 2 and 3 indicate how the shape of Lake Taihu has changed over the last 300 years. This change has been attributed, in part, to the erosion along the lake's southeastern margin.

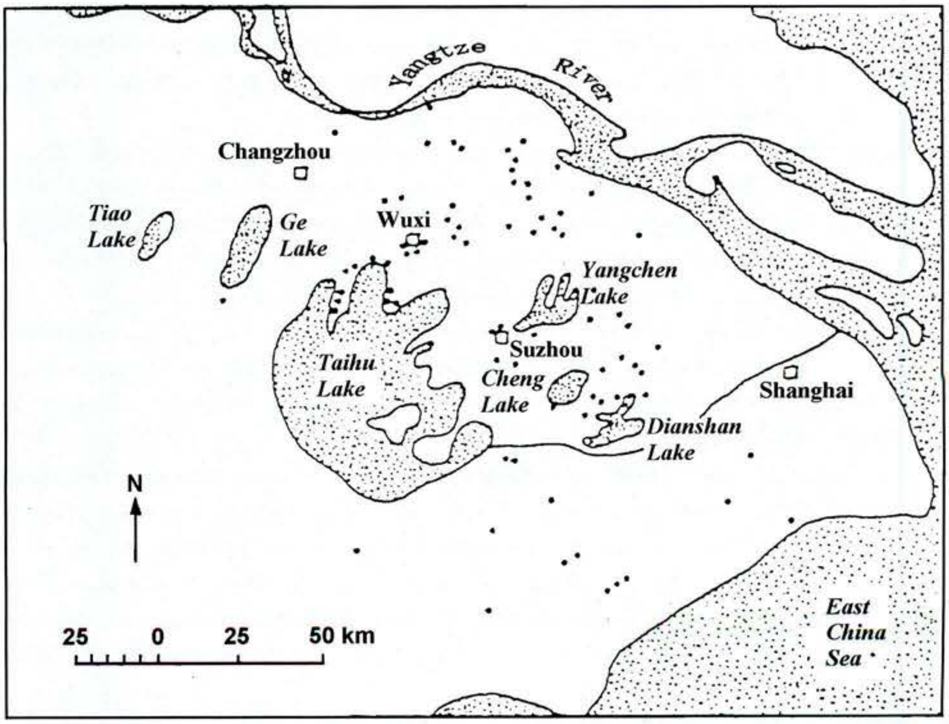

Fig. 1 The distribution of Liangzhu cultural relicts in the Lake Taihu Region (plain). Many of these relicts date back to 5 000 years before present. Modified from *Zheng et al.* (1990).

2. The Absence of Thermal Stratification and Hypoxia

During approximately 240 days of the year, the wind blows across Lake Taihu with sufficient force to mix the waters from top to bottom in open areas of the lake (Pan and Huang, 1987). As a result, severe hypoxia near the lake bottom is rare. Deeper lakes generally stratify and the organic deposition of the autogenic material which settles to their bottom produces extreme hypoxia and even anaerobic conditions. In shallow polymictic lakes like Lake Taihu, stratification does not occur or occurs for only very short periods of time. As a result, the water near the bottom of Lake Taihu does not become anoxic. In a hypothetical scenario in which Lake Taihu remained stratified for a long period of time, the more than 460 000 metric tonnes of organic matter entering the lake each year (Wu and Gong, 1987, Shi, 1962) would decay and the levels of dissolved oxygen in the bottom of the lake would fall so low that fish and invertebrates living there would perish. Fortunately, long periods of stratification do not occur in Lake Taihu and its bottom waters are well oxygenated by the wind induced mixing of the lake.

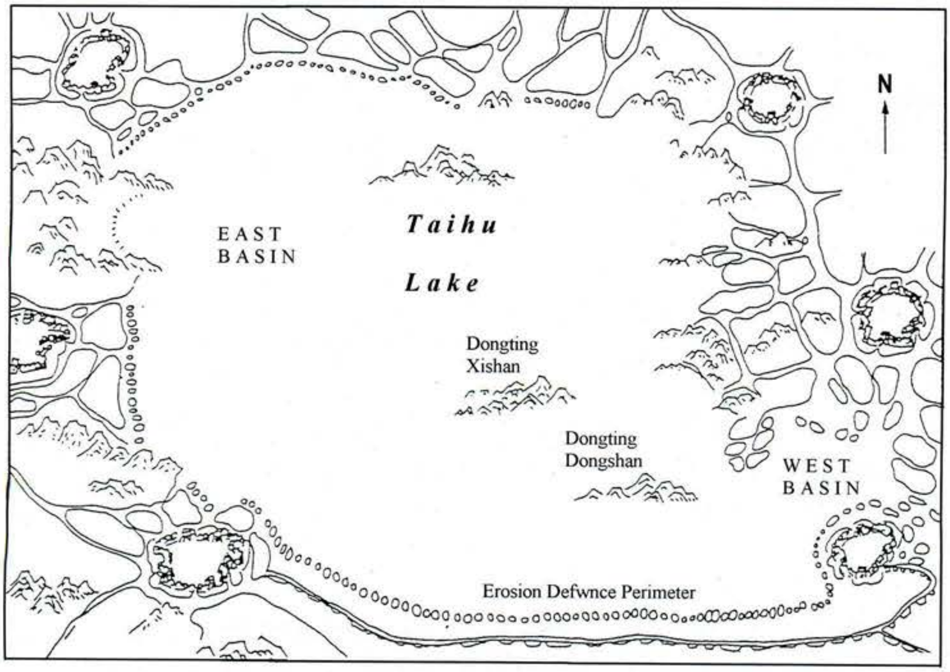

Fig 2 Lake Taihu as it was drawn in the 1700's (Qing Dynasty). Erosion defence perimeters noted in the figure are now underwater. Modified from figures by Wu and Gong (1987) and Sun and Wu (1989).

One of the most basic and important criteria determining the condition of a body of water is its concentration of dissolved oxygen just above the bottom of the lake. If dissolved oxygen concentrations fall below 3 $mg \cdot L^{-1}$ many aquatic species are eliminated. The key variables associated with dissolved oxygen are the photosynthetic production of oxygen, the reaeration rate from surface exposure to the air, tributary induced mixing and the various respiration rates associated with heterotrophy.

Shallow polymictic lakes such as Neusiedler See and Lake Taihu (Tab. 1) rarely stratify and their sediments are often resuspended by wind mixing which adds high concentrations of suspended solids (SS) to the lake water column. Primary productivity in these shallow polymictic lakes is often light limited below 0.5 - 1 m. In Lake Taihu the greatest algal biomass in Meiliang Bay occurs in the top metre (circa 100 mg·l^{-1}, Shi and Zai 1994). Below this depth, algal biomass drops to 45-50 mg·l^{-1} (ibid) where light rather than nutrients limit productivity (Dokull 1994). Algal species composition also changes with depth. The surface waters are dominated by cyanobacteria for much of the year while below 0.5 m mixotrophic microflagellates dominate the water column.

Tab. 1 Main Characteristics of some Shallow Polymictic Lakes

Lake Name	Country	Area (km^2)	Volume (km^3)	Average Depth (m)	Maximum Depth (m)	Turnover Time (a)
Neusiedler See	Austria	321	200	1.1	1.8	3
Lake Taihu	China	2 388	4 430	1.9	2.6	0.72
Biwa	Japan	616	2 700	44	104	5.5
Attersee.	Austria	46	3 944	84	170	7
Lake Superior	Canada-USA	82 100	12 100	147	406	191
Tahoe	USA	?	154	?	505	700
Baikal	Russia	?	23 000	?	1 600	?

* Lakes are arranged according to their maximum depth as this information was known for all 7 lakes.

Total phosphorus concentrations in Lake Taihu are an order of magnitude above the great majority of the OECD studied European Lakes (Dokull, 1994). Thus it is likely that light rather than phosphorus is limiting production in Lake Taihu except at the surface where light intensities are high.

3. Trophic Status Criteria for Lakes in China, North America and Europe

The criteria for the classification of lakes in China (Shu and Huang 1994) and North America and Europe (Vollenweider, 1979) according to their trophic status are quite different. **Oligotrophic** lakes in China [N.A.+Europe] have a total chlorophyll of 0.5 - 2.0 mg·kg^{-1}, [0.3-4.5 mg·kg^{-1}], a total phosphorus of 1-10 mg·kg^{-1} [3-17 mg·kg^{-1}], a total nitrogen of 20 - 100 mg·kg^{-1} [300-1600 mg·kg^{-1}] and a Secchi transparency of 3-10 m [5-25 m]. **Mesotrophic** lakes in China [N.A.+Europe] have a total chlorophyll of 4 - 10 mg·kg^{-1} [3-11 mg·kg^{-1}], a total phosphorus of 25-50 mg·kg^{-1} [10-100], a total nitrogen of 300-500 mg·kg^{-1} [300-1400] and a Secchi transparency of 1-1.5 m [1.5-8m]. **Eutrophic** lakes in China [N.A.+Europe] have a total chlorophyll of 25 - 500 mg·kg^{-1} [3-80 mg·kg^{-1}], a total phosphorus of 100-1 000 mg·kg^{-1} [16-386 mg·kg^{-1}], total nitrogen of 1 000 - 10 000 mg·kg^{-1} [400-6000 mg·kg^{-1}] and a Secchi transparency of 0.5 - 0.2 m [0.8-7 m, mean = 2.45 m]. **Hypereutrophic** lakes in China [N.A.+Europe] have a total chlorophyll of >500 mg·kg^{-1} [100-150 mg·kg^{-1}] a total phosphorus of >1 000 mg·kg^{-1} [750-1 200 mg·kg^{-1}], total nitrogen of >10 000 mg·kg^{-1} [>6 000 mg·kg^{-1}] and a Secchi transparency of <0.2 m [<0.4 m].

According to the above criteria, Lake Taihu (total phosphorus concentrations of 40-800 mg·kg^{-1}) would be classed as slightly eutrophic by Shu and Huang (1994) and as extremely eutrophic by Vollenweider (1979). Xuanwu Lake in Nanjing, China with a total chlorophyll of 80.5 ppm, a total phosphorus of 87 ppm, total nitrogen of 500 ppm and a Secchi transparency of 0.22 m. would be mildly eutrophic (Shu and Huang ,1994) or hypereutrophic (Vollenweider,1979) depending on which set of criteria are adopted. Tahoe lake with a Secchi Disc transparency of 25 m would be off scale (Shu and Huang,1994) or oligotrophic (Vollenweider,1979). To avoid this kind of confusion in the classification of lakes based on trophic status, a set of trophic criteria for world lakes should be developed so that all lakes can be classified according to their trophic status using similar criteria.

4. Mixotrophy in Lake Taihu

In Lake Taihu, tributary discharges into the lake at the beginning of the rainy season have a profound impact on high BOD and high bacterial biomass (Cai *et al.*,1994). Under these conditions phagotrophs and facultative phagotrophs are able to out-compete obligate autotrophs. A similar situation was observed in Lake Kinneret, a eutrophic lake in northern Israel (Paran *et al.*, 1994). When bacterial densities reached their highest densities, phagotrophic flagellates formed the dominant assemblage in the lake (Paran *et al.*, 1994).

The topography of the land around Lake Taihu is quite flat and because the majority of the lake inlets stop flowing during winter, the dry season, these tributaries serve as sedimentation basins for domestic and industrial wastes which enter them throughout the dry season. When the first heavy rains occur in the spring, large quantities of decaying organic material from these tributaries are flushed into Lake Taihu. This drastically reduces dissolved oxygen levels in large portions of the lake until wind mixing can aerate and oxidize these decomposing wastes (Cai *et al.* 1994). Approximately 200 inlet rivers or streams annually discharge approximately 5.2 km^3 (range = 3.6 - 9.1 km^3) of water into the lake (Shi,1962, Pu *et al.*,1987).

In general, the larger the lake and the less sheltered the lake from wind action, the less likely that it will stratify thermally. Phytoplankton which pass below the photic zone cease photosynthesis until they re-enter the photic zone (Talling,1965). In the more eutrophic portions of Lake Taihu, the Secchi transparency is rarely more than 0.3 m. The photic zone is generally less than a metre deep. Phytoplankton passing below this 1 m depth receive insufficient light for photosynthesis. Mixotrophic phagotrophs are at a definite advantage under these conditions because they can consume organic matter in the absence of light. It is not surprising, therefore, that in the more eutrophic sections of Lake Taihu (*e.g.*, Meiliang Bay) as in Xuanwu Lake in Nanjing, mixotrophic algae are able to out-compete cyanobacteria. Mixotrophy is the ability to use either dissolved or particulate organics in the absence of light. Facultative heterotrophy is the ability to use either sunlight or organic matter as an energy source. Some euglenoids, dinoflagellates, cryptomonads and chrysomonads use both light and organic matter for energy. Individuals referred to as facultative phagotrophs (Lewin,1962) use particulate organic matter while those referred to as osmotrophs use dissolved organic matter. Mixotrophs were initially considered to be osmotrophs (Lewin,1962) but recent authors such as (Fenchel,1987 and Paran *et al.*,1994) consider mixotrophs capable of ingesting bacterial cells.

Recent samples taken from Lake Taihu Meiliang Bay indicate that mixotrophic algae (microflagellates) are replacing *Microcystis* and other cyanobacteria in areas of the lake where large amounts of bacteria and particulate organic matter is released. This is illustrated in Figure 3 at sites impacted by effluents released from Wuxi (circa 3 million people). It appears that in areas of Lake Taihu where light rather than nutrients is a major limiting factor, mixotrophic microflagellates are capable of out-competing autotrophic algae. Particulate organic matter and inorganic suspended clays are so abundant in the northern enclosed bays of the lake (*e.g.* Meiliang Bay near Wuxi, Fig. 3) that Secchi transparency is only 0.2 - 0.3 m. Such areas are dominated by facultative microflagellates. This occurs in portions of Lake Taihu where low Secchi transparencies associated with high suspended solids result in obligate autotrophs being frequently mixed to depths below the photic zone. Under these conditions, phytoplankton is likely to be light limited. Evidence of phagotrophy was observed in the samples taken by the first author from the stippled area in Fig. 3 but more work is needed to confirm how general these observations are for Lake Taihu.

The replacement of cyanobacteria by facultative phagotrophs is a relatively rare event in natural lakes because bacterial densities in most lakes fall below the threshold levels described by Fenchel (1987) for facultative phagotrophs to predominate ($0.5 - 1.5 \times 10^6$ cells ml^{-1}). Below this concentration, ($<0.5 \times 10^6$ cells $\cdot ml^{-1}$) grazing is energetically unfavorable and above 1.5×10^6cells ml^{-1} obligate phagotrophs are able to out-compete facultative phagotrophs (ibid). In Lake Taihu, facultative phagotrophs were relatively common in the stippled areas in the northern portions of the lake (Fig.3) while colourless microflagellates (obligate phagotrophs) were relatively rare in these same areas. This indicates that the ability to switch from heterotrophy to autotrophy is critical in out-competing both the obligate heterotrophs and the obligate phototrophs in sections of Lake Taihu indicated by the stippled pattern (Fig.3).

Over the last 20 years, major changes in species composition of the Lake Taihu phytoplankton assemblage have occurred with biodiversity declining and a few cyanobacteria forming the dominant base of the lake autotrophic food web (Shi and Zai, 1994). In the last eight years since the first author has visited Lake Taihu, these cyanobacteria have been displaced by facultative microflagellates in sections of the lake receiving waste waters from the city of Wushi (*e.g.* Meiliang Bay). It is likely that if nutrient and bacterial inputs to the lake are not greatly reduced, facultative autotrophs will dominate more and more of the lake waters over the next five to ten years.

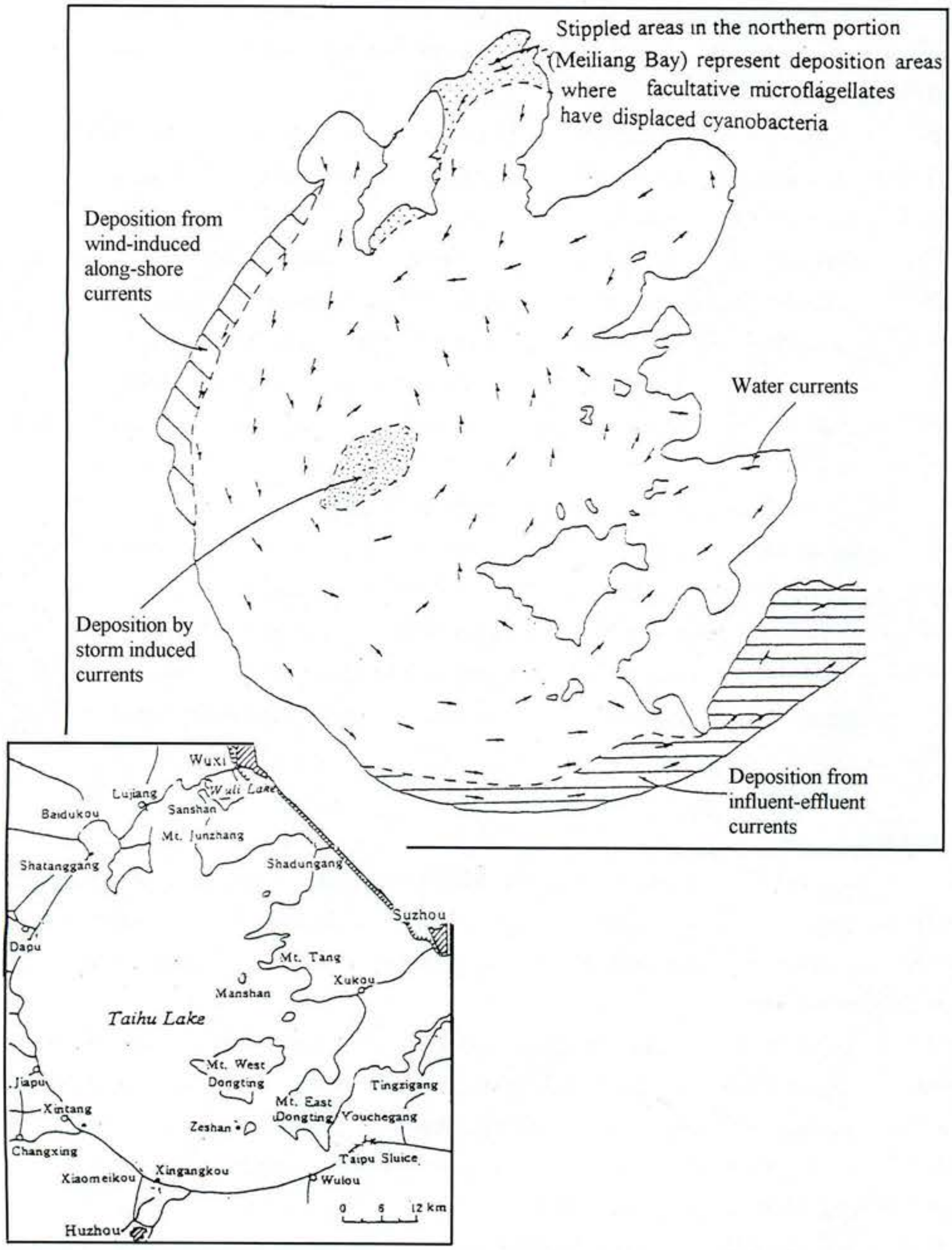

Fig. 3 Lake Taihu as it exists today with currents and major deposition regions depicted to represent winter monsoon conditions. Stippled areas in the northern portion of the lake (Meiliang Bay) represent deposition areas where (over the last five years) facultative microflagellates have displaced cyanobacteria as the dominant members of the plankton community. Modified from *Zheng et al.* (1990). Inset depicts the major cities of Wuxi and Suzhou and smaller towns along the shores of Lake Taihu.

5. Conclusions

1. The presence of roads, farm house foundations, wells and Liangzhu period cultural relics in the bottom of Lake Taihu attest to the fact that this shallow depression was probably dry between 4 and 5 thousand years ago.

2. The 460 thousand metric tonnes of organic matter which enter Lake Taihu and/or are produced in the lake each year do not accumulate in its bottom as revealed by multiple cores taken from the lake bottom in 1989.

3. The polymictic character of Lake Taihu protects it from long periods of hypoxia that would destroy many of its benthic species if the lakes' waters stratified for extended periods of time. However, if wind mixing failed following heavy spring rains, Lake Taihu would partially stratify and the huge organic loading from its watershed plus the tonnes of phytoplankton produced in its surface waters would eventually die and sink to the bottoms to decompose making the bottom of the lake anaerobic.

4. The replacement of obligate autotrophs in portions of Lake Taihu with high suspended solids and large inputs of dissolved and particulate matter was noted. Facultative heterotrophs, primarily chrysomonads and cryptomonads, were more abundant than either the obligate autotrophs or the obligate heterotrophs. This condition is only rarely observed in natural lakes and is likely related to low transparency, frequent wind mixing which transports autotrophs to depths where they are unable to carry out photosynthesis and high bacterial densities of 0.5 - 1.5 $\times 10^6$ cells·ml^{-1}.

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