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A 200-year historical modeling of catchment nutrient changes in Taihu basin, China

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Abstract Sedimentary records provide important information for understanding changes in the history of eutrophication in Lake Taihu. In addition, the catchment nutrient model SWAT provides a powerful tool to examine eutrophic changes in a long-term context. Since it is difficult to evaluate impacts of natural eutrophic development and anthropogenic changes in catchment discharge and land use, simulation of past changes provides a mirror on processes and dynamics. Boundaries in the simulations are set to a pre-industrial time to evaluate natural-agricultural nutrient changes in Taihu Basin a 100 years ago. Total nitrogen (TN) and total phosphorus (TP) in the main channel flowing into the lake are simulated in four sub-basins for 200 model years. Results show that modeling can capture basic features of basin nutrient development, where mean TN concentration (0.12 mg l^{-1}) can be compared in broad scale to mean TN concentration (0.17 mg kg^{-1}) from Lake Taihu sedimentary cores dating back about 100 years. Spatial nutrient simulations suggest that the two major nutrient sources are from the southwestern sub-basin (48% TN and 68% TP of the basin total) and the northwestern sub-basin (18% TN and 17% TP). There are differences of $+7.3 \times 10^4$ kg TN and $+2.0 \times 10^5$ kg TP between total input and output values, simulating mean annual amounts of nutrient deposited into the lake. TN and TP concentration differences between input and output sub-basins become smaller in the second 100 years than the first 100 years, suggesting a 100 year period to reach a balance of net nutrients. Catchment nutrient modeling provides a basis to evaluate how nutrient production and balance responded to environmental changes over 200 years in Taihu Basin.

Keywords Natural-agricultural environment · TN and TP simulations · Nutrient change · Decadal-centurial time scale · Taihu Basin

Introduction

Eutrophication in Lake Taihu became a problem in the last 20 years, and anthropogenic change is a major factor (Jin et al., 1990; Huang et al., 2001; Qin et al., 2004). Nutrient release from lake bottom sediments (Qin et al., 2004) and nutrient discharge from the catchment (Xia & Yang, 2003) are two important sources leading to eutrophication, whereas nutrient source changes from

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Eutrophication of shallow lakes with special reference to Lake Taihu, China

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bottom sediments or the catchment are not only controlled by human activities on an annual-interannual timescale, but also are related to natural system changes in a decadal-century time scale (Last & Smol, 2001; Smol, 2002). Paleolimnological techniques can be used to reconstruct past water quality changes on a number of time scales using information preserved in sedimentary profiles (e.g. Ramstack et al., 2003; Rose et al., 2004; Bradbury et al., 2004). When tracking eutrophic changes using lake sediments, a number of rich-organic layers with high nitrogen content have been found in lacustrine sediments from Lake Taihu. At depths of 22, 30, 35, and 42 cm in cores from Lake Taihu (Liu et al., 2004a; b), total nitrogen contents are similar to or higher than values at 1–5 cm (1990s; Fig. 1). While examining longer sediment cores from Lake Taihu (Xue et al., 1998), nitrogen contents at two layers ^{14}C-dated to 5,930 year B.P. (i.e. Before Present) and 7,899 year B.P. were higher than those in surface sediments. The lake may have experienced natural eutrophication before industrial and urban modernization in Taihu Basin. Examining and modeling long-term changes in lake eutrophication will provide a better understanding of the trajectories of lake environmental degradation and help set realistic mitigation goals for recovery.

Taihu Basin (Fig. 2) is located in a lowland area of the Changjiang River Plains in China approximately between 29–32° N and 118–121° E and about 50–100 km from the East China Sea (Sun & Huang, 1993). Climate is warm and wet, typical of subtropical monsoon climate. The basin is covered naturally by subtropical evergreen broadleaf forest, and the lake has a high aquatic production (Huang et al., 2001). Natural soil horizons developed on parent rock are composed of loose and organic-rich fluvial-lacustrine sediments deposited in the Holocene (Sun & Huang, 1993; Wang et al., 1996). The basin is in a shallow depression in the Changjiang River Plains, and there is a seasonal water exchange between the Changjiang River and Lake Taihu. Thus these natural conditions are potentials to develop the lake eutrophication.

To understand eutrophic changes and factors controlling nutrients in Taihu Basin (e.g. Zhang et al., 2002; Qin, 2002), it must be determined if natural nutrient sources exist that can result in eutrophication. If so, what are the rates and trends of these natural changes? Long-term catchment nutrient modeling of a natural system is needed to address this question. Other issues, such as how these natural changes were different from anthropogenic effects, need to be addressed. Hydrological-based catchment models provide a powerful tool to understand these issues in processes and dynamics (Schulze, 2000; Wang et al., 2003).

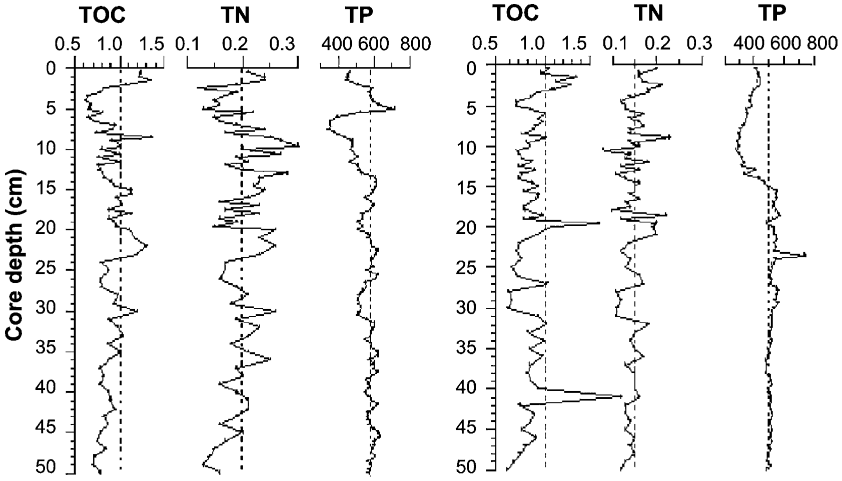


Fig. 1 Nutrient records from sedimentary cores Dls (left) and Ms (right) in Lake Taihu, which reflect higher total nitrogen concentrations (TN,%) than that in the 1990s on the surface sediments

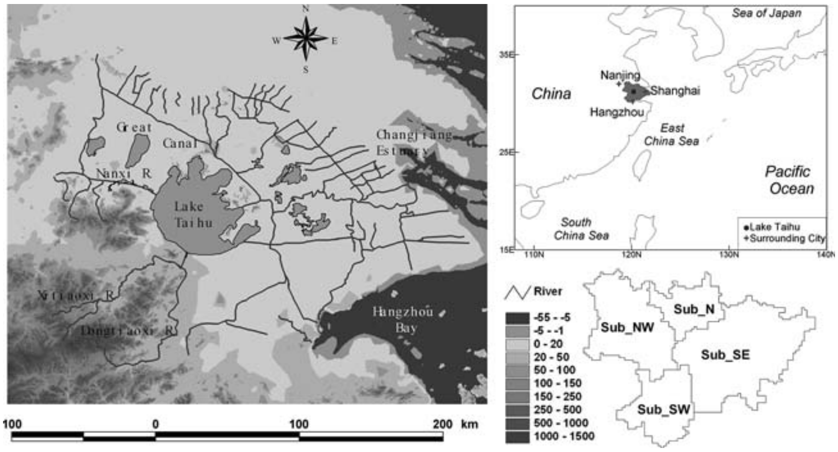


Fig. 2 Geographical location (Right upper), physical and hydrological settings (Left) and four sub-basin divisions (Right lower) of Taihu Basin

The SWAT (Soil and Water Assessment Tool) model is a river basin-scale model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex basins with varying soils, land use, and management conditions over long periods of time (Arnold et al., 1998; Di Luzio et al., 2002a). The model is physically based and computationally efficient, uses readily available inputs, and enables users to study long-term impacts (Di Luzio et al., 2002b). SWAT is being used extensively to assess the impact of global climate on water supply and quality (e.g. Rosenberg et al., 1999). In this study, SWAT was applied to simulate nutrient changes in Taihu Basin dating back to pre-industrial time. The model highlights the whole basin and can simulate catchment nutrients as sources and feedback. Second, climatic and geographic conditions are major controls in natural nutrient development, and the model can be driven by climate-based hydrology, topographical-based Hydrological Response Units (HRUs), and nutrients sourced from vegetation and soil coverage. Finally, natural eutrophication in a lake is a long-term process on a decade and century timescale (Smol, 2002), and SWAT is a continuous integration model capable of simulation 10^1–10^2 year timescales.

This study examines major nutrient changes in a pre-industrial time mode for Taihu Basin to identify nutrient sources from the sub-basins, estimate nutrient balance in the lake, and assess trends on a timescale of 10^1–10^2 years.

Model and experimental design

The model used in this study is the AVSWAT-2000 model (Di et al., 2002a, b), which is an ArcView graphical user interface for the SWAT model (Arnold et al., 1998). Basin topography is a basic boundary in the SWAT model. Vector-based 1:250,000 topographical maps in electronic files (National GIS Center of China, 1999) are converted using ARCINFO into a grid-based Digital Elevation Model (DEM). Grids within 28–3° N and 118–121° E were taken as the boundary of Taihu Basin, and total area was 30,246 km^2 with a maximum elevation difference of 1,266 m from the southwestern mountains to the eastern coastal plains. Four river systems in the basin constitute four sub-basins (Fig. 2). The Nanxi River and tributaries flows to the lake from the northwestern part of the basin (Sub_NW). The Tiaoxi River, with two eastern and western tributaries, discharges to the lake from the southwestern part of the basin (Sub_SW). The southeastern part of the basin is a watershed area from Lake Taihu towards the Changjiang Estuary – Hangzhou Bay (Sub_SE). The northern sub-basin connects Changjiang River and Lake Taihu by the Great Canal of China system (Sub_N).

Thus, Lake Taihu receives stream flows from Sub_SW and Sub_NW and drains to Sub_SE. Different from the other subbasins, there is seasonal water exchange between the Changjiang River and Lake Taihu in Sub_N; i.e. during Changjiang flooding, discharge is orientated from the River to the Lake, while in other seasons, water flows toward the River. Based on observations in extreme years during the 1960–1980s at Liangxihe River Station (Sun and Huang, 1993; Huang et al., 2001), the ratio of river discharge volumes to lake discharge volumes was 0.55:0.45, and the ratio of river discharge days to lake discharge days was 0.46:0.54. Thus, the ratios are approximately 1:1. Based on the estimates above, water input is from the 2.5 sub-basins, and outflow is from 1.5 sub-basins (Table 1).

Land-use in the SWAT contains vegetation coverage and agricultural, industrial, and urban land. In this study, natural and agricultural plants were set at a pre-industrial time mode. Vegetation data were sourced from a vector-based 1:1,000,000 China Vegetation Map (Hou et al., 1982), which summarizes Chinese vegetation investigations since the early 1960s. A digital map from Hou et al. (1982) at a resolution of 10 × 10 min was interpolated into the same resolution as the DEM, consistent with applications in SWAT modeling. According to the dominant plants and relative physical and biological properties (Hou et al., 1982; China Academy of Sciences, 1988) and the agricultural crop atlas (Zui et al., 1984; Bi, 1995), vegetation types in Taihu Basin consistent with the land-use types in the SWAT model setting were assigned (Table 2).

Soil data were obtained from Chinese soil investigations and mapping post-1980s (Institute of Soil Science, 1986; National Soil Survey Office of China, 1993–1997). Vector-based soil data at a resolution of 1:1,000,000 (Unpublished data; ref. to Shi et al., 2002, 2003) were used in the simulation boundary. The data contain soil types and major properties, including sand, silt, and clay contents (%), organic matter content (%), pH, total nitrogen (TN mg l^{-1}), total phosphorus (TP mg l^{-1}), available phosphorus (AP mg kg^{-1}), and bulk density (g cm^{-3}). Additional soil parameters were based on documentation of regional soils in China (Institute of Soil Science, 1986; Zhang, 1998).

Climate data were sourced from observations made from 1960 to 1990 (National Meteorology Center of China, 2001). The 30-year mean monthly temperature and precipitation data were the two major climate variables for the long-term simulation. Relative climate parameters were based on the Atlas of China Climate (Lu & Gao, 1984).

The pre-industrial model was designed to simulate natural-agricultural impacts on water, sediments, and nutrients in Taihu Basin. Model results were compared to geological records from lake cores, which preserve information on decadal-centurial time scales.

Results and analysis

The experiment runs 200 model years in four sub-basins and simulates the flow of major nutrients through the main channel in the catchment, nutrients transported with water during each time step in concentrations in HRUs, and production in each sub-basin. The simulation outputs contain organic nitrogen, NO_3^-, NO_2^- and NH_4^+, organic phosphorus and mineral phosphorus. Total nitrogen (TN) is calculated as a sum of organic nitrogen, NO_3^-, NO_2^- and NH_4^+ and total phosphorus (TP) as the sum of mineral phosphorus and organic phosphorus.

Table 1 Sub-basin topography and discharge features

Subbasin	Sub_SW	Sub_NW	Sub_N	Sub_SE	Total
Area (km^2)	5254	8298	3710	12984	30246
Elevation range (m a s l.)	21–1266	2–453	1–283	0–178	–
Mean elevation (m a s l.)	180	31	11	7.8	–
Input basin	1	1	0.5	0	2.5
Output basin	0	0	0.5	1	1.5

Table 2 Dominant plants in Taihu Basin and assigned land use types in the SWAT modeling

Land use type in SWAT model	Dominant plants in Taihu Basin
Forest - Mixed	Pinus massoniana forest: Shrubby layer with *Rhododendron simsii*, *Vaccinium bracteatum*, *Loropetalum chinense* and *Eurya nitida*; *Cunninghamia lanceolata* forest
Forest - Deciduous	Deciduous oak forest: *Quercus Mongolic*, *Quercus variabilis*, *Q. Acutedentata* and *Q. glandulifera*
Forest - Evergreen	Mixed forest containing *Cyclobalanopsis*, *Castanopsis* and *Fagus*; *Phyllostachys pubescens* forest
Wetlands - Mixed	Halophytic grass and forb meadow *Aeluropus littoralis* var. *sinensis* and *Suaeda salsa*
Winter Wheat	Winter wheat, coarse grains (corn, millet, sweet potatoes), two crops annually
Rice	Summer rice, winter wheat (rapeseed), two crops annually (double cropping rice locally); Double-cropping rice followed by winter wheat (rapeseed) or green manure; Single or double-cropping rice followed by winter wheat, rapeseed, green manure annually
Potato	Potatoes, sweet potatoes, grains, soybean green upland crops annually
Water	Water

Simulation of TN and TP production from four sub-basins

The model simulates 200-year processes for nitrogen and phosphorus production for each sub-basin (Fig. 3). When annual means for each sub-basin (column diagrams in Fig. 4) are divided by sub-basin areas (pie diagrams in Fig. 4), the largest portions of TN and TP are produced in the southwestern mountain areas of Sub_SW, in which TN is 48% and TP is 68% of total production in the basin. Smaller portions of nutrients are produced in Sub_NW (18% TN and 17% TP) and Sub_N (18% TN and 10% TP). The smallest portion is generated in Sub_SE (16% TN and 5% TP).

About half of the nitrogen production comes from Sub_SW, which relates to high biome productions of evergreen forests over the areas (Huang et al., 2001). The model also simulated a

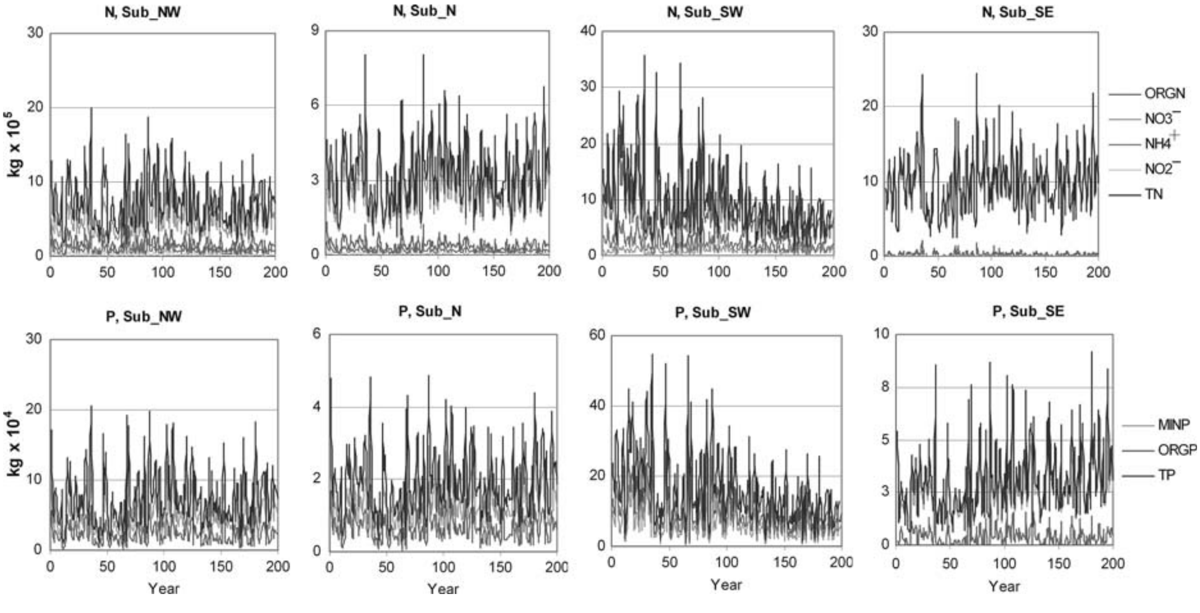


Fig. 3 Annual nitrogen and phosphorus production (kg) simulated from four sub-basins in Taihu Basin, where total nitrogen (TN) as a sum of organic nitrogen (ORGN), NO$_3^-$, NO$_2^-$ and NH$_4^+$, total phosphorus (TP) a sum of mineral phosphorus (MINP) and organic phosphorus (ORGP)

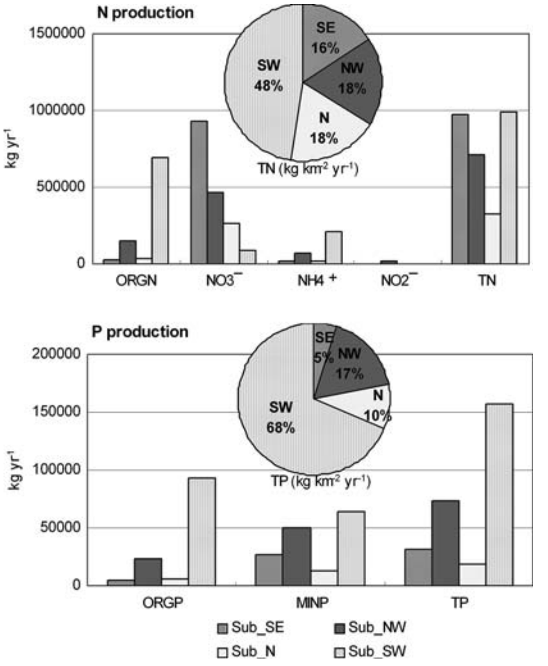


Fig. 4 Distribution simulations of TN and TP in the Lake Taihu sub-basins. Nutrient codes as in Fig. 3

high phosphorus production (–67%) for this area, reflecting strong weathering and erosion of limestone and metamorphic bedrock/outcroppings in the sub-basin. Additionally, relatively steep slopes in this mountain area (mean 2.0%) result in a high capability of discharge and transportation. Lower nutrient production was simulated in Sub_SE, which is an output area for Lake Taihu. Although nutrients discharge to coastal areas, there is small slope (mean < 0.1%), which often slacks water flows and favors nutrient deposition into the lake.

Annual and areal means of TN and TP production are plotted in Fig. 5. Total TN input from the 2.5 sub-basins to the lake is 1.86×10^5 kg, and total TN from 1.5 output sub-basins is 1.14×10^5 kg. This indicates that there is net deposition of 7.3×10^4 kg TN to the lake. Annual TP mean is 2.39×10^5 kg in 2.5 input sub-basins and 0.41×10^5 kg in 1.5 output sub-basins. TP difference between input and output is 1.99×10^5 kg, suggesting that there is TP deposition in the lake each year.

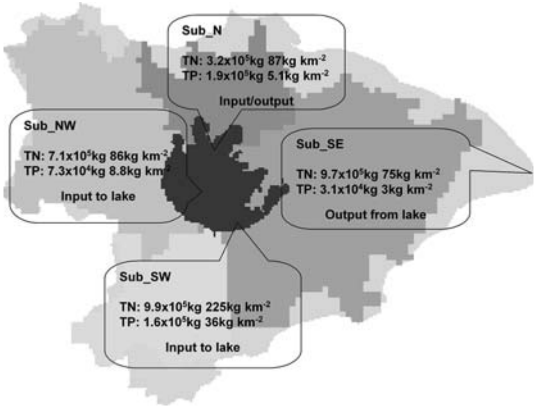


Fig. 5 Simulations of TN and TP annual means (kg) and the annual area means (kg km^{-2}) in four sub-basins

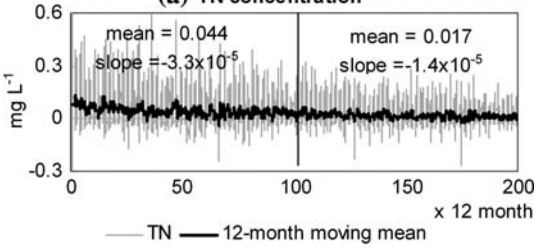
Analysis of catchment-sourced lake eutrophication

To examine lake eutrophication changes, the nutrient balance was evaluated by calculating nutrient differences between input sub-basins and output sub-basins. TN and TP concentrations used are weighted averages of all HRUs within the sub-basins.

The 200-year simulations show that annual TN concentration changes are characteristic of 12-month cycles (Fig. 6a). In the first 100 years, mean TN concentration difference was 0.044 mg l^{-1}, suggesting a positive deposition in the lake. In the second 100 years, the mean difference decreases to 0.017 mg l^{-1}, reflecting positive nitrogen deposition but at a lower rate than the first 100 years. Slopes for the trends are -3.3×10^{-5} in the first 100 years and -1.4×10^{-5} in the second 100 years (Fig. 6a), indicating that TN change stabilized after the first 100 years.

TP concentration simulations show phosphorus deposition in the lake (Fig. 6b). The TP difference in the first 100 years (+0.012 mg l^{-1}) is higher than the second 100 years (+0.008 mg l^{-1}), indicating a declining trend in phosphorus deposition. The slope for the first 100 years (-5.0×10^{-6}) was steeper than the second 100 years (slope -2.4×10^{-6}), suggesting that phosphorus concentration changes are small in the lake.

(a) TN concentration



(b) TP concentration

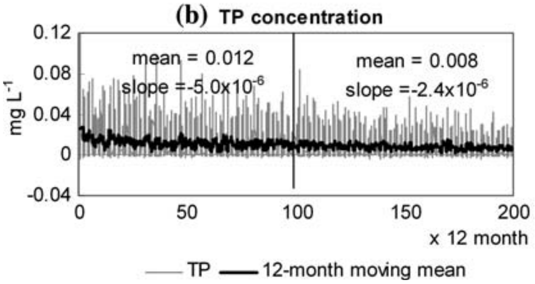


Fig. 6 Monthly differences of TN and TP concentration with the 12-month moving means between input and output sub-basins in Taihu Basin

Discussion and conclusions

Comparison with nutrient records from lake sediment cores allows evaluation of the simulations when the area was agricultural before modern industrial development in Taihu Basin. Two sediment cores provided TN concentrations dating back 100 years (Liu et al., 2004a; Fig. 1). Core Dls was taken from the southern part and Core Ms from the northern part of Lake Taihu. TN concentrations at core depth of 20–40 cm are 0.14–0.19 mg kg^{-1} (Liu et al., 2004b), where sediment samples were ^{210}Pb- and ^{137}Cs-dated to before 1900 AD (Liu et al., 2004a). 200-year means show TN concentrations between 0.09 and 0.18 mg l^{-1} (Fig. 7). Geochemical nitrogen values from lake sediments may be subjected to post-depositional mobility (Smol, 2000). Diatom-inferred nutrients, together with geochemical data, may be used for historical eutrophication studies in the future.

The simulation mean (0.12 mg l^{-1}) and sub-basin means (0.09–0.18 mg l^{-1}) are significantly lower than the data mean (0.17 mg kg^{-1}) and two cores (0.14–0.19 mg kg^{-1}) with 95% confidence interval in T-test. Nitrogen from sediment cores would respond to both catchment sources and lake water production. However, the present modeling is focused on nutrient production in the catchment and transport to the lake. Thus, the nitrogen concentration simulation should be lower than in the cores. Modeling may adequately simulate basin nutrients for pre-industrial times.

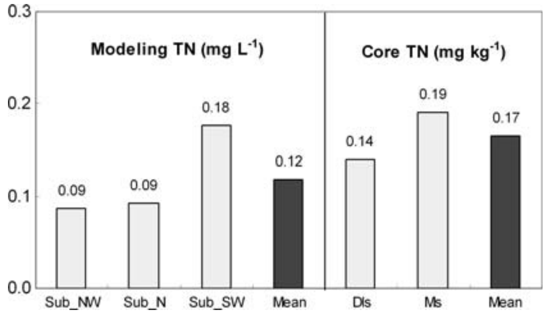


Fig. 7 Modeling TN means for a 100 year ago and measured TN from sediment records in Lake Taihu. Modeling TN concentrations (mg l^{-1}) for the lake water are tentatively compared to concentrations from sediment deposits (mg kg^{-1})

In summary, the present simulation may capture major factors of lake eutrophication over a 200-year history. Analysis of spatial nutrient distributions suggests that the major source (48% TN and 68% TP) comes from the southwestern sub-basin. Due to a gentle slope in the eastern plains of Taihu Basin, the smallest portion of nutrient input (16% TN and 5% TP), from the southeastern sub-basin, cannot be fully discharged to the lake. There is a net annual nutrient deposition of 7.3×10^4 kg TN and 1.99×10^5 kg TP to the lake. Time series analysis for the 200-year simulation suggests that nitrogen and phosphorus deposition has decreased over the last 100 years.

Catchment nutrient modeling provides a basis to evaluate nutrient production and balance response to environmental changes for the last 200 years in Taihu Basin. There is considerable uncertainty about the direction of future nutrient changes in Lake Taihu due to anthropogenic changes. The accuracy of model-based predictions of future eutrophication cannot be evaluated, but the models used to generate such predictions can be tested by simulating the past and comparing these simulations with sediment records. This effort, along with future investigations, e.g. using regional climate modeling (Zheng et al., 2003) and fossil pollen-based vegetation reconstructions (Yu et al., 2000), would provide more credibility for modeling the future.

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