Yangtze Delta, China: Taihu lake-level variation since the 1950s, response to sea-level rise and human impact

Z.Y. Chen · Z.H. Wang

Abstract Hydrological records collected from water gauge stations since the 1950s demonstrate that the Taihu lake level is rising. The average rate of the lake-level rise is 0.4–1.1 mm/year during the non-flood season, resulting directly from a rise in sea level. High rates of 3.0–5.0 mm/year of rise are even recorded during the wet season. This indicates increasing human activities such as reclamation, sluicing and embanking, which significantly hinder the expulsion of extra lake water to the coast shortly after a rainfall. Generally, the lake level of the western inlet is higher than that of the eastern outlet. However, the lake-level difference between the west and east has been diminished annually from ~10–15 cm in the 1950s to <3 cm at the present time. During non-flood seasons, the lake-level difference even appears to be reversed, indicating a retrogression of the lake flow from east to west. It is predicted that the Taihu drainage basin will lose much of its natural water-expelling ability in the next 50 years as the sea level continues to rise, and retrogression will likely occur during the flood season in the near future.

Key words Flood · Human impact · Lake-level and sea-level rise · Yangtze Delta

Introduction

The Taihu lake, a fresh water reservoir with a water surface area of 2427.80 km^2 and average water depth of ~2 m, is situated on the southern Yangtze delta plain (Fig. 1) and ranges from 60 to 100 km in distance to the coast. The lake area, agricultural breadbasket and industrial center on the eastern coast of China, is a densely populated region (600–900 people/km^2). The topography of the study area is characterized primarily by an elevation of ~2 m above mean sea level (msl, based on Wu-Shong datum plane) in the central delta plain, and by an elevation of 3–5 m on the periphery of the delta plain (Fig. 1). The lake is bounded by highlands to the west. Over the past decades, a series of geological investigations has been conducted on the delta sector; there exists abundant information relevant to sea-level fluctuation, climate change, neotectonisum, fluvial transport and anthropogenic activity (as of Neolithic migration ~7000 a BP) in the study area (Yan and Xu 1987; Yan and Hong 1988; Sun and Huang 1993; Chen and Stanley 1995; Stanley and Chen 1996). These natural processes and human impact play an important role in controlling the evolution of the Yangtze delta, and the Taihu lake origin as well.

Taihu Lake is a natural drainage basin which accommodates water levels at the time of floods through the enormous waterway system evolved on the Yangtze delta plain (Fig. 2). During the annual wet season (late March-April and July) and typhoon duration (late August-September), this saucer-like depression is frequently flooded by waters derived, to a large part, from the highlands west to the Taihu Lake and from the drainage of the delta plain. Extra fresh water at that time is typically expelled from the lake to the coast through the waterway system. During non-flood season, fresh water retreats from the waterway system to the lake to compensate for what has been extracted for agricultural purposes. At present, water levels of the waterway are controlled almost completely by sluices distributed along the lake bank and delta coast (Fig. 1). In this manner, salt water from the sea is blocked. To minimize the potential threat of floods from the western highlands, major source river courses in the western highlands have been dammed. This results in considerable fresh water being impounded. Little sediment enters the lake and accumulation rates are extremely low. Of note, the dams open at time of heavy precipitation.

Flooding is the major natural hazard in the Yangtze delta (Chen 1987, 1989; Chen and Chen 1994), and substantial damage and loss of life frequently occur during floods (Sun and Huang 1993). Threat from this hazard has apparently been increased in the past ~2000 years (Chen

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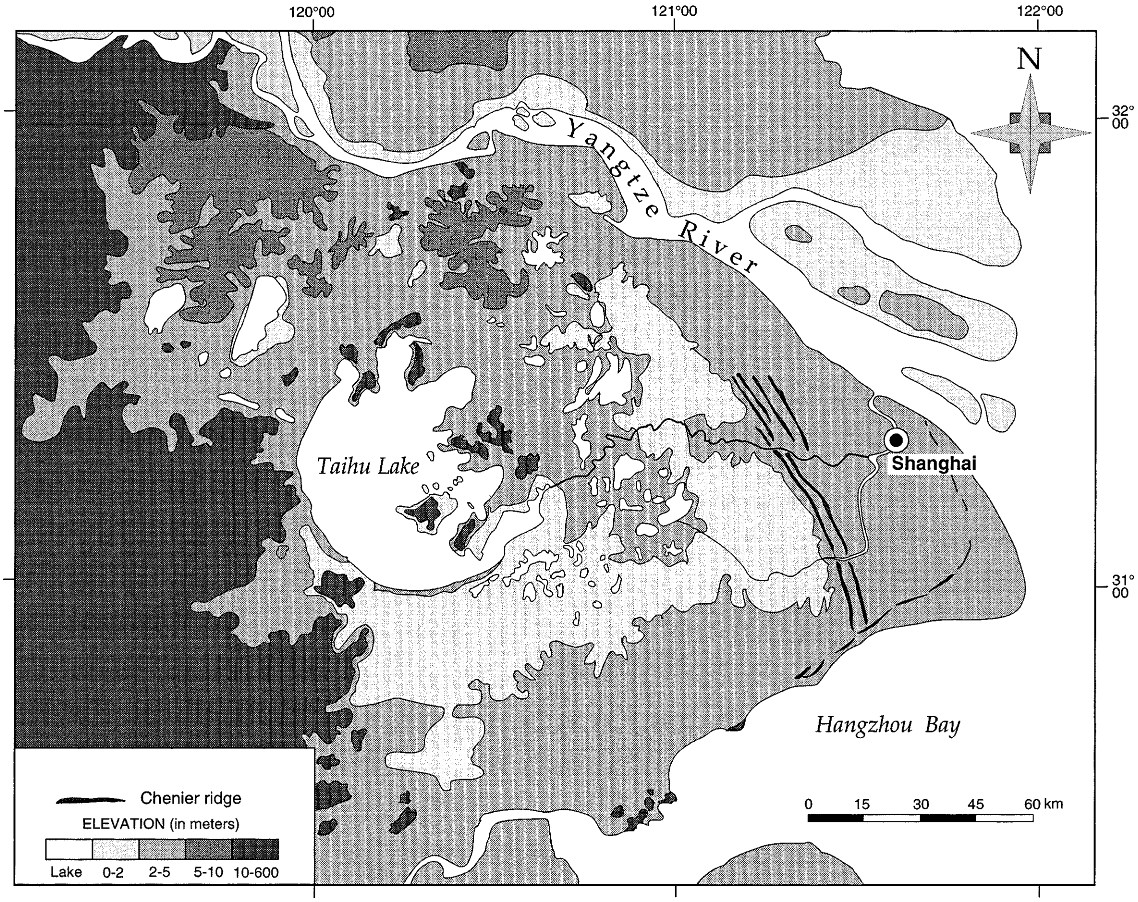

Fig. 1
The study area characterized by the large depressed Taihu Lake region in the central Yangtze delta plain

1987, 1989). Floods can now inundate most of the lake region and their duration seems longer than that of previous floods. It is our hypothesis that increased difficulty in expelling extra fresh water from the lake to the coast results from a long-term rise in sea level and growing intensity of human activities. It is thus vital to monitor lake-level fluctuations more precisely by means of record collected from hydrological gauge stations sited along the Taihu Lake, and to understand the role of intensified human impact in this major region. A raised possibility of water disaster requires that the local government take necessary steps to protect agricultural and industrial efforts in this costly region.

Observations

There are three major water inlets and three major outlets in the Taihu Lake area, each having a hydrological gauge station sited on the lake bank (Fig. 2). The water level of Taihu Lake since 1951 has been measured at the hydrological gauge stations three to four times a day. These data were grouped into a daily-mean value. The monthly-averaged data were compiled from this daily-mean value (Jiangsu Hydrological Bureau 1951–1995, unpub. data). The lake-level records of forty-five years (1951–1995) were collected on a continuous data basis from two representative gauge stations: Da-Pu-Kou inlet station situated by the western bank, and Xu-Kou outlet station by the eastern bank. In addition, also collected are the historical water level records from 1956 to 1985 at Mi-Shi-Du hydrological water gauge station, which is sited in mid-course of the Huang-pu River, the major river channel on the delta plain and connecting the lake and coast (Fig. 2). The Wu-Shong datum plane is also applied to the data from these gauge stations.

Calibration of the benchmark of ground elevation in the Yangtze delta region was carried out in 1957 and readjustment of the benchmark was thus applied to the hydrological gauge stations around the Taihu lake (Jiangsu Hydrological Bureau 1951–1995, unpub. data). Consequently, data before 1957 were modified based on this remeasurement. For the Xu-Kou station, 39 mm were added to the records from 1951–1953 and 133 mm were added to the records from 1954–1957. For the Da-Pu-Kou station, 136 mm were added to the records from 1954–1957. Records of this station from 1951–1953 were not incorporated into the present study due to discontinuity of data. Water-level records of Mi-Shi-Du gauge station were unchanged.

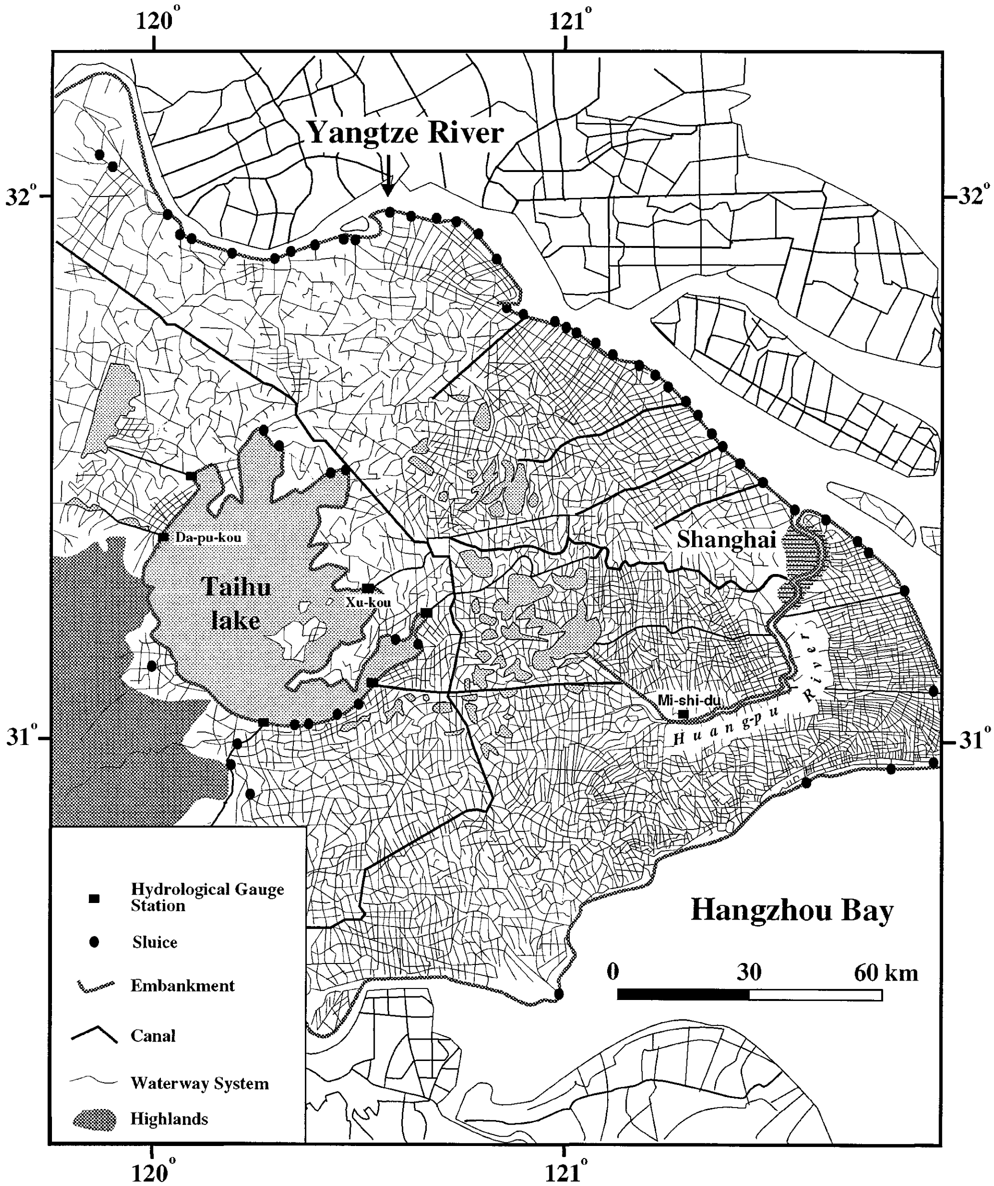

Fig. 2
Map showing the waterway system, embankments, sluices, canals and gauge stations on the southern Yangtze delta plain

Special attention has been paid to the distribution of yearly-averaged lake-level variations. The two highest levels occurred in 1954 and 1991 (Fig. 3), respectively. These two water-level highs correspond to the two major flooding events which occurred at that time (Sun and Huang 1993). They, like many similar examples recorded in Chinese historical documents during the past 500 years (Meteoritic Academy Institution of National Meteorite Bureau 1981) represent periodic events of extreme precipitation. Therefore, the established database of the present study includes a complete period of lake-level variation for the past 45 years and is thus believed to be reasonable for a study of lake-level change with time. These data are correlated with precipitation records of the most recent 45 years collected at the Shanghai Meteorite Station representative of the lake area (Nanjing Institute of Geography and Limnology 1991), and also with information on human activities affecting the lake-level fluctuation in this densely populated region (Figs. 2, 3).

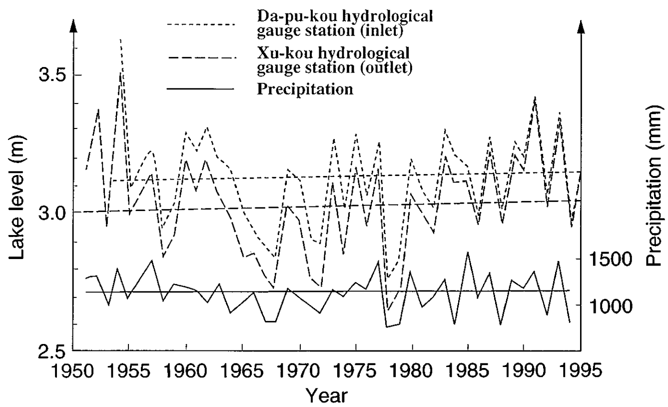

Fig. 3
Records of yearly-averaged lake-level values and annual precipitation during the past 45 years. Of note, the rising trend of lake level and the diminishing lake-level difference with time

Data analyses and result

To examine lake-level variation, a time series database was established using daily- and monthly-averaged lake-level records from the two representative hydrological gauge stations cited above for a period of recent 45 years. A statistical model of time series analysis was applied to investigate the trend of lake-level fluctuation, and thus, the monthly rates of the past 45 years were obtained (Table 1). The statistically-treated time-series records indicate that these rates of Taihu Lake level are variable (Table 1). Rates in most months are positive, ranging from 0.02 to 5.42 mm/year. Of special note, a few negative rates varied from –0.59 to –2.50 mm/year occured in dry seasons (May, June and October at the Da-pu-kou station; June at the Xu-kou station; Table 1).
Maximum rates in lake-level fluctuation are apparently related to flood seasons. At both Da-Pu-Kou inlet and Xu-Kou outlet stations, rates approach 4.65 mm/year and 5.42 mm/year in April, respectively. In contrast, minimum rates occur in a dry season, for example, –1.72 to –2.50 mm/yr in May and June at Da-Pu-Kou inlet station and –0.49 mm/year in June at Xu-Kou outlet station. In addition, rates from November, December, and January representative of a typical dry season in the study area are selected and averaged to 0.40 mm/year and 1.10 mm/year at Da-Pu-Kou inlet and Xu-Kou outlet stations (Table 1), respectively. The gross precipitation of these three months is only ~3–5% in proportion to the annual amount that is ~1200 mm/year on average.
Statistical analysis reveals an uneven altered trend of the lake-level difference through time between the two gauge stations. From historical lake-level records, it is found that the western lake level is generally higher than that of the eastern. This water difference potential enables the expelling of extra fresh water in the lake to the coast via the eastern outlet. However, this study shows that the range of this lake-level difference has diminished gradually on a yearly-averaged basis from ~10–15 cm in the 1950s to <3 cm at the present time (Fig. 3). It is even found that the value of lake-level difference appears to be negative after the mid-1980s during non-flood seasons (Fig. 4).
It is likely that precipitation in the study area may influence lake-level variation. To demonstrate this, a database of annual precipitation during the past 45 years was determined and the distribution of precipitation through time was plotted (Fig. 3) to compare to the lake-level variation. Moreover, the total lake area reclaimed from the 1950s to 1980s is estimated to be ~160 km^2, which mostly occurs along the eastern lake margin and is ~6.7% of the entire lake surface area. Reclamation was made primarily in the 1960s (42%) and 1970's (~51%), in comparison to only 5.8% in 1950s (Nanjing Institute of Geography and Limonology 1991). The rate has been greatly reduced (~0.7%) since the mid- 1980's. Furthermore, 14 major sluices around the Taihu Lake bank and 43 along the Yangtze coast were counted (Fig. 2) indicating human activity from another respect.

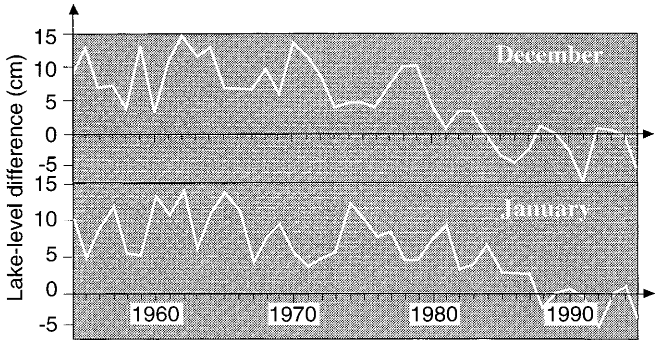

Fig. 4
The plot showing the reduced lake-level differences and the negative values in December and January since the mid-1980s

Discussion

The fluctuation of Taihu Lake level can be directly caused by several major factors, e.g., sea-level variation, land subsidence, precipitation and anthropogenic activity. Subsidence due to tectonic lowering and unconsolidated sediment compaction in the delta area can lead to a rise in water level (Flemming and Webb 1986; Emery and others 1988; Pirazzoli 1991; Stanley and Warne 1993; Chen and Stanley 1998). However, from our previous study, it is found that Taihu Lake is positioned on the upper delta plain sector where the Holocene sediment sequences are only 1–3-m thick, and the subsidence due to tectonic lowering and sediment compaction is subtle (Stanley and Chen 1993; Chen and Stanley 1993, 1995; Stanley and Chen 1996). Thus, this status of land motion does not ex-

Table 1
Monthly-averaged rates (in mm/year) of lake-level variation of the two hydrological gauge stations, and averaged rates (in mm/year) of the dry season, during the past 45 years

Hydrological gauge station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Averaged rate of typical dry season (Nov + Dec + Jan)
Da-Pu-Kou	1.12	0.26	2.22	4.65	−1.72	−2.50	3.11	1.25	3.40	−0.51	0.07	0.02	0.40
Xu-Kou	1.32	1.28	3.53	5.42	0.55	−0.49	4.06	2.99	4.15	0.36	1.19	0.77	1.10

plain the rise of Taihu Lake level, especially to the extent measured over the past 45 years.

Precipitation is the major factor in the fluctuation of the lake level, particularly during the flood season. It is of note that the annual precipitation of the study area has been generally between ~1000–1300 mm/year for the past 45 years (Fig. 3), rainfall in flood season which is ~80% in proportion to annual precipitation (Nanjing Institute of Geography and Limnology 1991) obviously vibrates the lake level. The overall phenomena of lake-level rise based on yearly-averaged data from the 1950s to the 1990s has apparently resulted from the oscillation of precipitation in the study area (Fig. 3). However, when the precipitation of the typical dry season (November, December and January) is separated from that of the annual ones, it is still found that the lake level during this time period has risen with different rates ranging from 0.02–1.12 mm/year in the western lake, and 0.77–1.32 mm/year in the eastern lake (Fig. 5). The authors believe that this result reflects the situation of rise in sea-level along the East China sea (Chen and Stanley 1998).

In fact, Taihu Lake level and its origin are closely associated with sea-level fluctuation. The previous study of the Yangtze delta evolution provides a better understanding of how the sea level has oscillated the lake level since mid-Holocene.

Prior to ~7000 a BP, when the global sea level was 7–12 m lower than at present (Morner 1976; Lighty and others 1982; Chen and Stanley 1998), the Taihu Lake area was subaerially exposed (Yan and Hong 1988; Stanley and Chen 1996). Sea level did not reach the former delta plain where Taihu Lake is located until ~6000 a BP, and then continued to rise to 1–3 m below the present msl at ~5000 to 3000 a BP. This brought about a rise in ground water in the study area (presently <0.5–1.0 m below present ground surface). Deceleration of sea-level rise by mid-Holocene time (Stanley and Warne 1994) induced fluvial sediments to accumulate along the periphery of the delta plain. Sediment accumulation has aggraded, in terms of topographic rise, at an equal rate as sea-level rise. Continued aggradation along the periphery of the delta eventually altered the central delta plain into a large saucer-like depression, the Taihu reservoir, which has become filled by rising ground water in response to sea-level rise (Stanley and Chen 1996) and precipitation. This depression thus serves as a reservoir to accommodate the water from the drainage of the delta plain and runoff from the western highlands.

Sea-level rise in association with delta progradation have reduced the gradient of the main Yangtze River channel and its waterway system on the delta plain since the mid-Holocene (presently between 1:5000 to 1:120000). Many outlets of tidal channels linking the lake and coast have

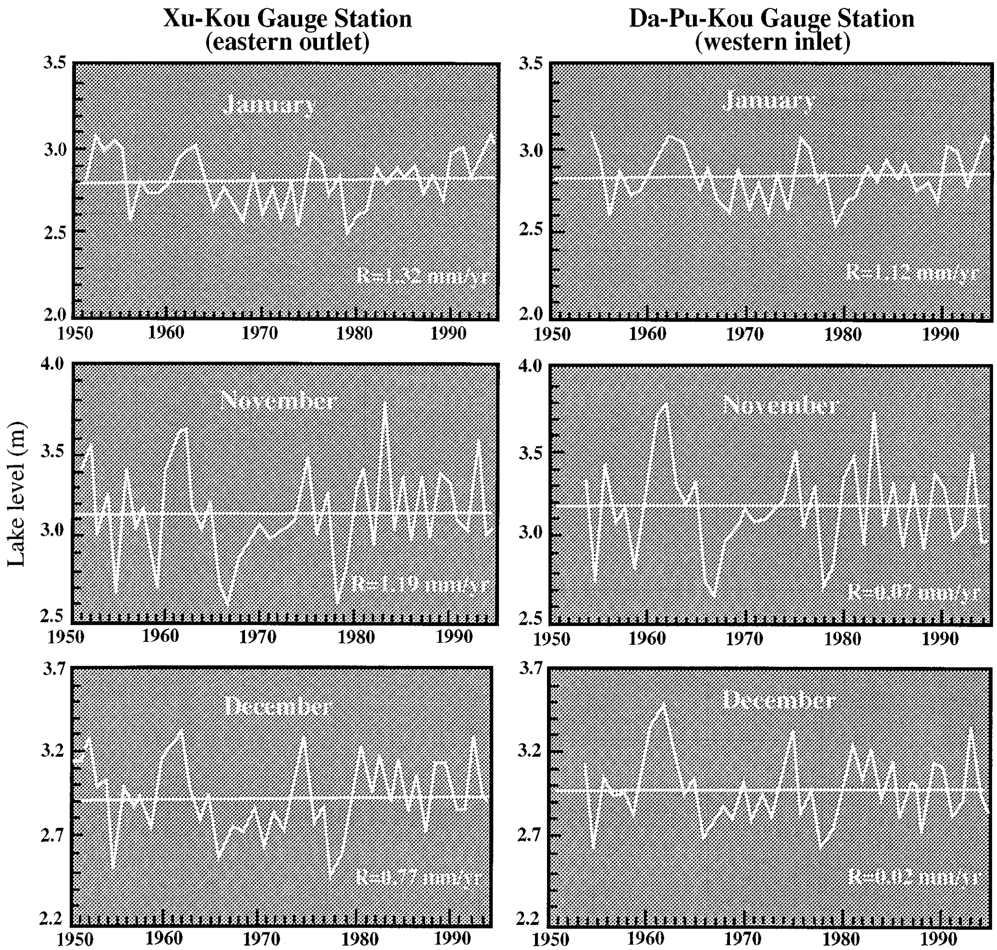

Fig. 5
Records of monthly-averaged lake-level values of the dry season (November, December and January) during the past 45 years. Of note, the rising trend of lake level with time, affected by sea-level rise (discussed in text)

narrowed, and as a consequence, it has been increasingly difficult for extra fresh water in the lake to be expelled to the coast. The situation has now become worse, primarily during wet season. Attention is called to climate-related devastation which occurred in 1954 and 1991 (lasting briefly) when almost half of the southern delta plain was inundated and many people lost their lives. The occurrence of flooding events in the lake area have apparently increased since 2000 a BP(Chen 1987, 1989). To prevent potential inundation and minimize damage from floods, embanking along Taihu Lake levee has been completed since 1950s . Of note, the top elevation of the embankment has been increased from 7.0 m in the 1960s to 7.5 m in the 1980s, and will possibly be >8.0 m in the near future.

The authors conclude that recent lake-level rise indicated by water-level record of the non-flood season is due to sea-level fluctuation. An average rate of 1.1 mm/year (Table 1) in the eastern lake reasonably records the trend of the sea-level rise along the Yangtze estuary. This value is further supported by a study of sea-level rise, in light of tidal-level records collected at tidal gauge stations situated along the Yangtze estuary during the past ~70 years. Examination of these records reveals an average rate of 1.0–2.0 mm/year of sea-level rise in the Yangtze estuary, based on mean- and high-tidal level (Chen 1991), respectively. In addition, the possibility of lake-water expulsion to the coast is calculated on the condition of sea-level rise to different elevations above msl (Yang and Shi 1995). The ability to expel water would be reduced by 40% if the sea level rose by 0.5 m, and by >80% if sea level rose by 1.0 m. Taihu drainage basin would not be able to expel it if sea level rose by 1.50 m. Thus, Taihu Lake's position will become precarious in the next century if the sea level continues to rise.

During the past half century, reclamations have been conducted around the Taihu Lake to meet the pressure from the increasing population in the Yangtze delta region, and have slightly reduced the capacity of lake-water storage. Sluicing at openings of a series of channels connecting the lake and coast was primarily completed during that time (Chen 1992). Originally, there exist 84 major channels to the east of the lake. Because of the embanking and sluicing, the number of channels has been largely decreased, with >40 channels having been silted, >35 sluiced, and the only major one, the Huangpu River (Fig. 2) connecting the lake and coast, via Shanghai, remaining open. As a result, there has been a decrease in the natural exchange of waters between the lake and waterway system on the delta plain, and a delay in expulsion of lake water to the coast shortly after rainfall events. The authors believe that the relatively high rates of the lake-level rise (~3–5 mm/year) during the wet season, and a diminished average water-level difference between the eastern and western lake with time, result primarily from the combined effects of anthropogenic alteration and sea-level rise.

A few negative rates (–0.25 to –0.5 mm/year, Table 1) occurring in the non-flood season in May, June and October can be caused by human and natural effects. Intensive damming along major river courses in the western highlands and water-pumping irrigation obviously decrease the lake water during the non-flood season (Sun and Huang 1993). In addition, evaporation in the summer in the lake area is another critical factor in temporarily degrading the lake level (Nanjing Institute of Geography and Limnology 1991).

Negative water-level differences occur in non-flood season to indicate an inverted relationship between the western and eastern lake levels. This implies a retrogression of lake flow from east (outlet) to west (inlet) during non-flood season, when lake level typically remains low and, in some instances, even lower than sea level (Chen 1991). Salt water can intrude along the large, non-sluiced Huangpu River channel (Fig. 2), to as far as >100-km inland from the present coast (Chen and Chen 1994). Time-series treated water-level records collected from the Mi-shi-du water gauge station (Fig. 2) indicate a rise of water level, with a rate of 2.10 mm/year (Fig. 6). Recently, a maximum water level of >4 m above msl in this station was recorded, obviously due to the rise of sea level (Chen 1991).

Increased water level on the waterway system to the east of the lake affected by sea-level rise plays a "barrier effect" to keep the lake from smoothly expelling water to the coast. This also explains why the negative value of lake-level differences occurs during the non-flood season, when lake level generally remains low. The authors thus postulate that retrogression of the lake water may occur during the flood season in the near future.

Summary

1. Variations of the Taihu Lake-level records collected from the two hydrological gauge stations during the past 45 years provide a means to detail information on sea-level rise and anthropogenic activity on the Yangtze delta plain.

2. The present study verifies that Taihu Lake level is rising, based on time-series analysis of the past 45 years'

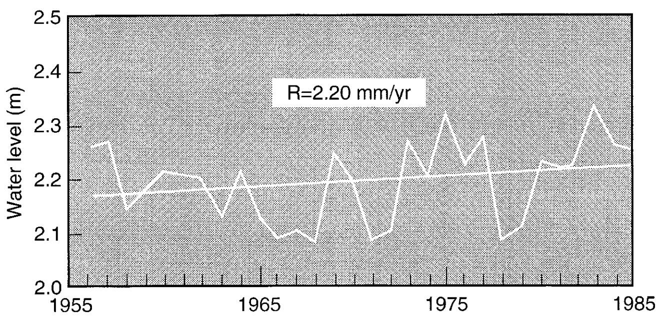

Fig. 6
Records of yearly-averaged water-level values from Mi-Shi-Du hydrological gauge station (1956–1985), indicating a rise in water level

lake-level records. The monthly-averaged rates of lake-level rise in the non-flood season (November, December and January) is 0.4 mm/year (in western Da-Pu-Kou inlet station) and 1.1 mm/year (in eastern Xu-kou outlet station), implying a lake-level rise in direct response to sea-level fluctuation. Of note, the eastern lake level is more influenced by sea-level oscillation than that of the western.
3. Also recorded are high rates (3–5 mm/year) of lake-level rise during flood seasons, which interpret accelerated anthropogenic modification of the delta plain, including reclamation, sluicing and embanking. These processes hinder substantially the expulsion of excess lake water to the coast shortly after rainfall events. Moreover, a few negative rates of –2.5 to –0.5 mm/year occur in non-flood season, suggesting a correlation with damming along the major river courses in the western highlands, water-pumping irrigation and evaporation in summer; these may lower the lake level.
4. Lake levels are usually high in the west, and low in the east. However, the yearly-averaged lake-level difference has diminished annually from ~10–15 cm in the 1950s to <3 cm at the present time, and the difference even appears negative in non-flood season after the mid-1980s. This hydrological characteristic hints retrogression of lake flow from east to west during a non-flood season, indicating a reduced ability of lake expulsion.
5. On the basis of the above observations, it is predicted that retrogression of lake flow will even occur during flood season in the near future as sea level further rises and the Taihu Lake will greatly weaken its ability of expulsion in the next 50 years.

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References

Chen JQ (1987) The heavy flood and drought of Taihu basin from the Southern-Song Dynasty and the possibility of their reoccurrence in the near future. Geogr Res 6:44–52 (in Chinese with English summary)
Chen JQ (1989) A preliminary research on the regularity and factors of changes of flood and drought in Taihu Lake basin since the Southern Song Dynasty. Sci Geogr Sin 9:25–33 (in Chinese with English summary)
Chen JQ (1992) The applicability of research on flood-drought tendency – an analysis on disastrous flood of Taihu basin in June-July. Acta Geogr Sin 47:1–5 (in Chinese with English Summary)
Chen X (1991) Sea-level changes since the early 1920's from the long records of two tidal gauges in Shanghai, China. J Coastal Res 7:787–799
Chen X and Chen J (1994) On the flood disasters and the water conservancy works in the Taihu Lake Plain, and their future development. J Lake Sci 6:364–374 (in Chinese with English Summary)
Chen Z and Stanley DJ (1993) Yangtze delta, eastern China: 2. Late Quaternary subsidence and deformation. Mar Geol 112:12–21
Chen Z, Stanley DJ (1995) Quaternary subsidence and river channel migration in the Yangtze Delta Plain, eastern China. J Coastal Res 11:233–258
Chen Z, Stanley DJ (1998) Rising sea level on eastern China's Yangtze Delta. J Coastal Res 14:360–366
Emery O, Aubrey DG, Goldsmith V (1988) Coastal neo-tectonics of the Mediterranean from tide-gauge records. Mar Geol 81:41–52
Flemming NC, Webb CO (1986) Tectonic and eustatic coastal changes during the last 10,000 years derived from archaeological data. Z Geomorph N F Suppl Bd 62:1–29
Lighty TG, Macintyre IG, Stuckenrath R (1982) *Acropora palmata* reef framework: a reliable indicator of sea level in the western Atlantic for the past 10000 years. Coral Reefs 1:125–250
Meteoritic Science Institution of National Meteorite Bureau (1981) Atlas of Chinese flood and drought distribution during past 500 years. Map Publish House, Beijing (in Chinese)
Morner NA (1976) Eustatic changes during the last 8000 years in view of radiocarbon calibration and information from the Kattegutt region and other northwestern coastal areas. Paleogeogr, paleoclim, paleoeco 19:63–85
Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences and Taihu Basin Management Bureau Ministry of Water Resources (1991) Atlas of natural resources of the Taihu basin. Science Press, Beijing (in Chinese and English)
Pirazzoli P (1991) World atlas of Holocene sea-level changes. (Elsevier Oceanogr Ser 58) Elsevier, Amsterdam
Stanley DJ, Chen Z (1993) Yangtze delta, eastern China: 1. Geometry and subsidence of Holocene depocenter. Mar Geol 112:1–11
Stanley DJ, Chen Z (1996) Neolithic settlement distributions as a function of sea-level controlled topography in the Yangtze delta, China. Geology 24:1083–1086
Stanley DJ, Warne GD (1993) Nile delta: recent geological evolution and human impact. Science 260:628–634
Stanley DJ, Warne AG (1994) Worldwide initiation of Holocene marine deltas by deceleration of sea-level rise. Science 265:228–231
Sun SC, Huang Y (1993) Taihu Lake. Ocean Press, Beijing (in Chinese)
Yan QS, Hong SX (1988) Issues of the Holocene transgression on the southern plain of the Changjiang Delta. Acta Ocean Sin 7:578–590
Yan QS, Xu SY (1987) Recent Yangtze delta deposits. East China Normal University Press, Shanghai (in Chinese with English summary)
Yang GS, Shi YF (1995) Advances in relative sea level rise and its impacts in the coast of China. Adv Earth Scie 10:475–482 (in Chinese with English summary)