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Variation of water level in Dongting Lake over a 50-year period: Implications for the impacts of anthropogenic and climatic factors

Yujie Yuan, Guangming Zeng *, Jie Liang *, Lu Huang, Shanshan Hua, Fei Li, Yuan Zhu, Haipeng Wu, Jiayu Liu, Xiaoxiao He, Yan He

College of Environmental Science and Engineering, Hunan University, Changsha 410082, PR China
Key Laboratory of Environmental Biology and Pollution Control (Hunan University), Ministry of Education, Changsha 410082, PR China

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SUMMARY

Understanding the variation regularity of water level and the potential drivers can provide insights into lake conservation and management. In this study, inter- and inner-annual variations of water level in Dongting Lake during the period of 1961–2010 were analyzed to determine whether anthropogenic or climatic factor should be responsible for the variations. The results showed that water level decreased significantly during the period of 1961–1980, while increased significantly during the period of 1981–2002 at the 5% significance level. However, the variation trend of water level after 2002 did not reach a significant level. The variation in the dry season was more obviously than that in the wet season. The date when water level was firstly below 24 m during the period of 2003–2010 appeared about 27 days earlier than usual, and the date was even advanced to mid-September in 2006. As for the duration, water level was below 24 m for about 185 days in the period of 2003–2010 and 20–30 days longer than the other two periods. In conclusion, water level might be influenced by a combination of anthropogenic and climatic factors, with rainfall probably as the main driver responsible for hydrological alteration during the period of 1961–1980 and 1981–2002 while dam construction as the main driver during the period of 2003–2010. Under the circumstance of uncontrollable climate change, effective measures for reservoir operation should be put forward to maintain the ecological integrity and ensure water release and storage capacity of aquatic ecosystems.

1. Introduction

Lakes not only provide valuable economic resources for human beings but also play important roles in regional environmental and ecological issues, such as hydrological cycle and wetland vegetation growth (Wantzen et al., 2008a). Water level, a sensitive sentinel of changes, could influence the biodiversity community patterns and functions in lake ecosystems. In recent years, the variations of water level in lakes all over the world have attracted increasing global attention from the filed of engineering design, ecological conservation and environmental management (Wantzen et al., 2008b; Wen et al. 2011; Reid et al., 2013).

Considerable researches have been performed on hydrological alterations to maintain a healthy river ecosystem (Timme et al., 2005; Russell et al., 2009; Adamowski et al., 2013; Al-Faraj and Scholz, 2014). Some of the researches focused on anthropogenic activity (McDonald et al., 2009; Ou et al., 2011; Gao et al., 2014), while other works were concerned with climatic factor (Guo et al., 2012; Song et al., 2014). Numerous studies have shown that natural and anthropogenic perturbations might be responsible for the variation of water level (Scuderi et al., 2010; Wang et al., 2011; Zeng et al., 2013a; Zeng et al., 2013b). Anthropogenic activity, such as agriculture, dam construction, reservoir operation, landscape modification, river channelization etc, would affect the lake hydrological processes and change water level (Altinbilek, 2002; Xu and Milliman, 2009; Sun et al., 2012). Dam constructions especially the large ones have been pointed out that they would bring some new challenges in hydrological regime of the global river systems (WCD, 2000; Li, 2009). Meanwhile, climatic factor as one of important inductive factors has been in hot debate for a long time. It may alter water level by precipitation, evaporation, temperature variation (Ludwig et al., 2014). Climate-induced changes may affect the fundamental ecological function and species distribution in lake ecosystems (Woodward et al., 2010; Pall et al., 2011; Holm et al., 2012). Numerous previous researches indicated that the alteration

* Corresponding author at: College of Environmental Science and Engineering, Hunan University, Changsha 410082, PR China. Tel.: +86 731 88822754; fax: +86 731 88823701.

E-mail addresses: zgming@hnu.edu.cn (G. Zeng), liangjie@hnu.edu.cn (J. Liang).

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of water level caused either by anthropogenic or climatic factor could result in adverse and lasting impacts on the ecosystem function, such as natural habitats loss and fragmentation (Nilsson et al., 2005; Xu and Milliman, 2009; Adamowski et al., 2013; Wang et al., 2013; Yuan et al., 2014). The variations of water level, especially the extent, frequency and duration, play important roles in affecting the ecological processes and patterns of lakes. Even small changes in water regime can lead to some irretrievable ecological results, such as dwindling of lake area, degradation of water ecosystem, and damage of biodiversity (Jöhnk et al., 2004; Fang et al., 2006; Wilcox and Nichols, 2008; Li et al., 2009; Lishawa et al., 2010; O'Farrell et al., 2011; Paillisson and Marion, 2011; Song et al., 2014).

Dongting Lake, the second largest freshwater lake in China, is directly connected with the Yangtze River. Among the dams constructed in the Yangtze River, the Three Gorges Dam (TGD) is one of the world's largest dams, which began to be built in 1994 and firstly impounded water and sediment discharge in 2003 (Xu and Milliman, 2009; Du et al., 2011). Numerous researches indicated that the impoundment of the TGD changed the hydrological regime downstream and the patterns of the lake wetlands, which in turn disturbed the ecological function of the wetlands as habitats for migratory birds (Tullos 2009; Sun et al., 2012; Wang et al., 2013). Many attentions were paid to the influence of TGD on hydrological alteration in Dongting Lake, especially in recent years (Xu and Milliman, 2009; Gao et al., 2013). According to statistics of Hunan Provincial Water Resources Department, four severe droughts occurred in Dongting Lake during 2000–2010 (in 2000, 2002, 2005 and 2006, respectively). The coincidence between occurrence of droughts and the operation of TGD has attracted much attention from all over the world. Besides, it triggered a debate whether TGD or climatic factor should be responsible for the variation (Xu and Milliman, 2009; Dai et al., 2010). However, the effects of climatic factor were neglected to some extent. Moreover, the relationship between water level variation and anthropogenic or climatic factor keeps still unclear in Dongting Lake.

Consequently, it is urgent to achieve the better understanding of the alteration of water level under the condition of anthropogenic and climatic factors. We took both anthropogenic and climatic factor into consideration in this paper, rather than single factor analysis. And it will be beneficial for providing theoretical basis and potential insight into the understanding of ecological environment changes in Dongting Lake. Specifically, the objectives of this study were (1) to reveal the inter- and inner-annual variations of water level during the period of 1961–2010; (2) to estimate the alteration in the wet and dry seasons; (3) to determine whether anthropogenic or climatic factor should be responsible for the variations.

2. Materials and methods

2.1. Study area

This study was conducted in Dongting Lake, which is situated in the middle reach of Yangtze River region (approximately 28°30′N–30°20′N, 111°40′E-113°10′E) (Ding and Li, 2011; Li et al., 2013). Dongting Lake, the second largest freshwater lake in middle China, is also one of the most important international wetlands. This region locates in the subtropical monsoon climate zone, with a wet season between July and September while a dry season between November and next February. Dongting Lake is directly connected with the Yangtze River. The water from the Yangtze River flows into the lake via the "Three Outfalls" (Songzi River,

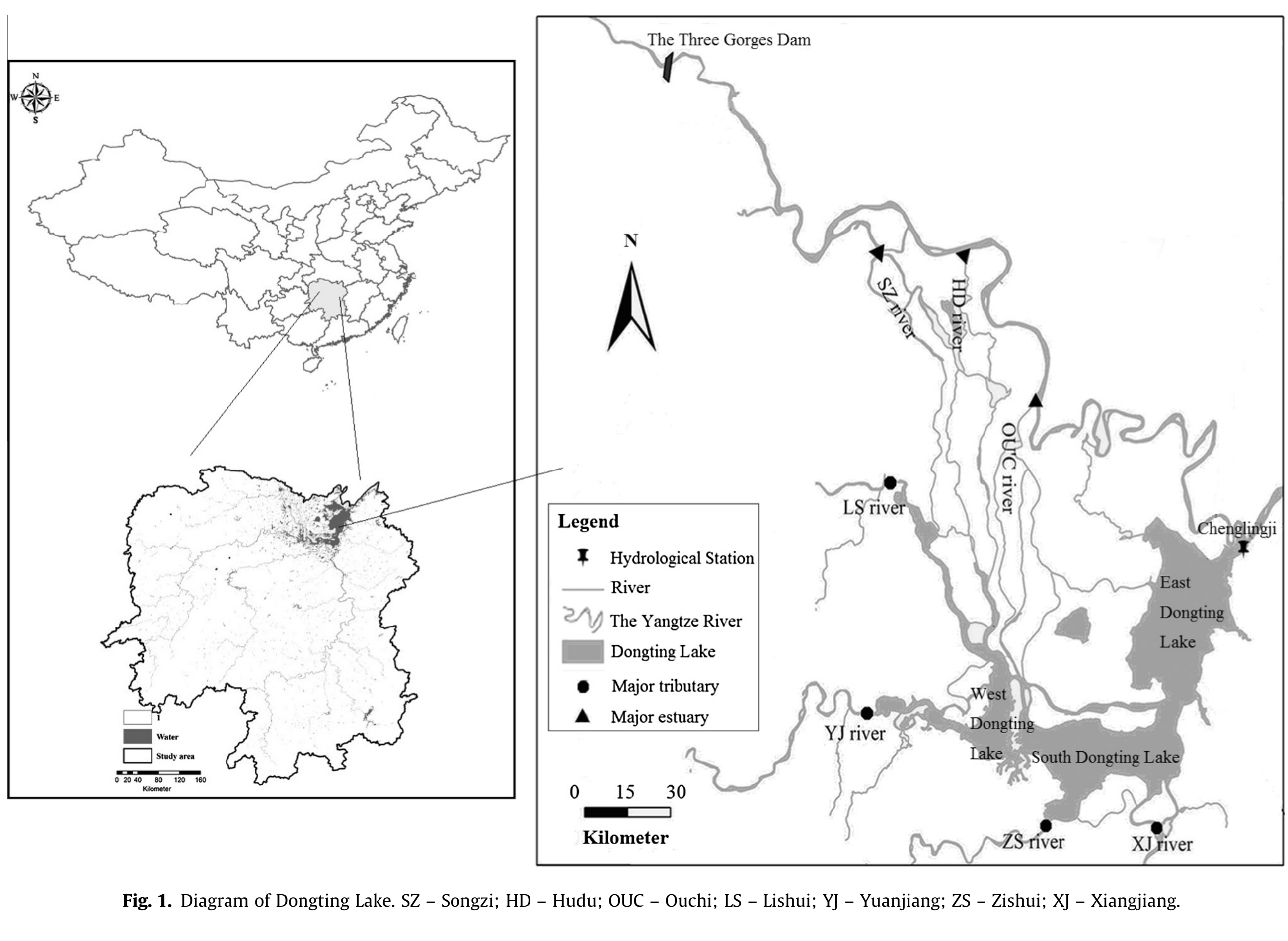

Fig. 1. Diagram of Dongting Lake. SZ – Songzi; HD – Hudu; OUC – Ouchi; LS – Lishui; YJ – Yuanjiang; ZS – Zishui; XJ – Xiangjiang.

Hudu River and Ouchi River). The lake is also fed by four other major rivers, namely Xiangjiang River, Zishui River, Yuanjiang River and Lishui River (Fig. 1). At last, the water directly drains back into Yangtze River from Chenglingji.

Dongting Lake expands to a large water surface during the wet season, while shrinks to vast mud flats and grass lands during the dry season. Along with the evolution of hydrological and morphologic characteristics, Dongting Lake was gradually divided into three parts, namely East Dongting Lake, West Dongting Lake and South Dongting Lake. And the three nature reserves wetlands were listed in the Ramsar Convention respectively in 1992, 2002 and 2002.

2.2. Data preparation

The daily water level data, ranging from 1961 to 2010, were obtained from Chenglingji Hydrological Station (a typical hydrological station in Dongting Lake). Chenglingji Hydrological Station is a monitoring station for the flood controlling activities in Dongting Lake area. Daily climatic data of Dongting Lake were acquired from China Meteorological Data Sharing Service System during the period of 1961–2010 (http://cdc.nmic.cn/home.do). We selected three representative weather stations, namely Yueyang Weather Station (representing East Dongting Lake), Changde Weather Station (representing West Dongting Lake) and Nanxian Weather Station (representing South Dongting Lake). The average rainfall of the three stations was used to represent that of the whole lake.

2.3. Data analysis

Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) was used to detect the alteration of water level. MK test, a non-parametric test, requires the data to be serially independent. It has been widely used to detect significant trends in time series (Hamed, 2008). MK test is based on the statistic S defined by Eq. (1) (Kendall, 1975; Hamed, 2008):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{1}$$

where x_j and x_i represent the values at time i and j, respectively. A high positive value of S represents an increasing trend, while a low negative value indicates a decreasing trend.

It has been reported that the statistic S is approximately normally distributed when $n \geqslant 10$. The variance of S was calculated by the following formula Eq. (2) (Kendall, 1975; Hamed, 2008):

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18} \tag{2}$$

where n is the number of data points, m is the number of tied groups in the time series.

MK test was carried out in MATLAB version 7.7.0.

3. Results

3.1. Inter-annual variation of water level

The inter-annual variation and abrupt changes of water level during the period of 1961–2010 were calculated by MK test, as showed in Fig. 2. The change trend could be seen from the curve of statistic UF (Fig. 2). The positive UF indicated that the time series has an increasing trend, and the negative one indicated the opposite trend. The UF curve locating between the significance values meant the trend was significant at the 5% significance level; otherwise the trend was not significant. As shown in Fig. 2, there was a significantly decreasing trend of water level during the period of 1961–1980, while a significantly increasing trend appeared during the period of 1981–2002. However, the variation trend of water level after 2002 was not significant at the 5% significance level.

The intersection that UF and UB curve intersected was identified as the change point, indicating that the time series had a sudden change at that time. During the period of 1961–2010, there were six change points, namely 1975, 1980, 1986, 1987, 1999 and 2003 (Fig. 2). Considering the variation period, change points and real situation of Dongting Lake, we divided the time series (1961–2010) into three distinguishable periods, namely 1961–1980, 1981–2002, and 2003–2010.

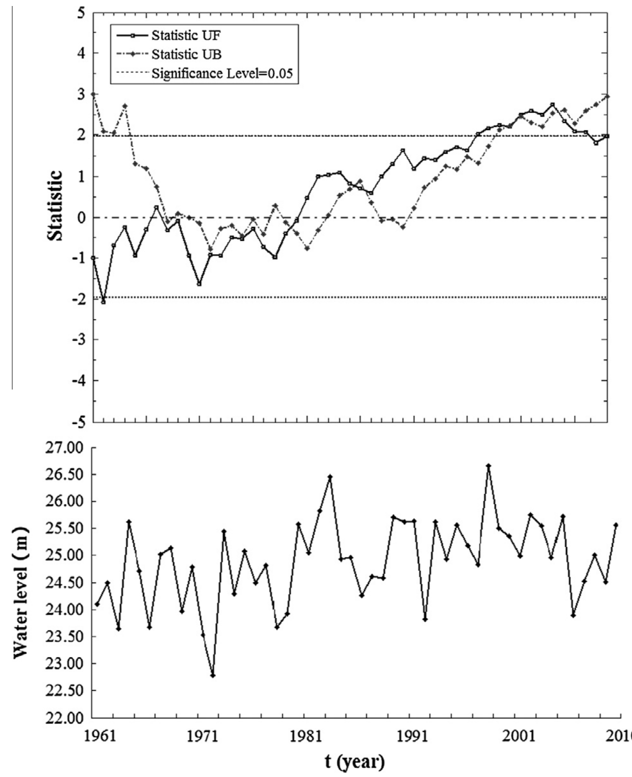

Fig. 2. Mann–Kendall test of water level in Dongting Lake. The positive UF indicates that the time series has an increasing trend, and the negative one indicates the opposite trend. If the UF and UB curve intersect between the significance values, the time series has a sudden change at that time.

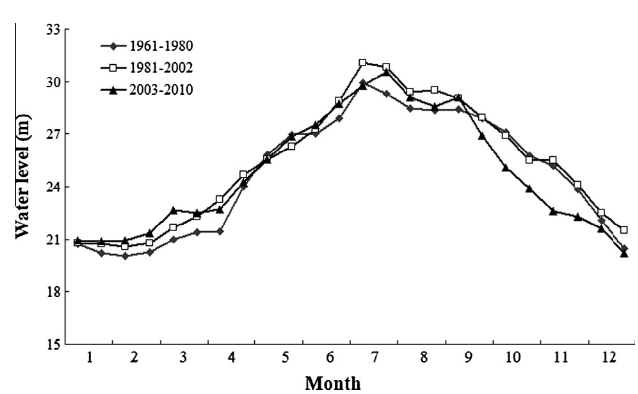

Fig. 3. Inner- annual variations of water level during the three different periods.

3.2. Inner-annual variation of water level

The inner-annual variations of water level during the above three different periods were shown in Fig. 3. The results showed that the differences of water level were not obvious during the period of 1961–1980 and the period of 1981–2002 except water level in July and August. Meanwhile, water level in July and August during the period of 1981–2002 was respectively 3.34–5.18% higher than that during 1961–1980 and 0.95–4.26% higher than that during 2003–2010. However, water level from September to December during the period of 2003–2010 was obviously the least during the three different periods. Compared with the other two periods, water level from September to December decreased about 0.45–2.94 m during the period of 2003–2010. Moreover, water level decreased respectively by 1.23–10.28% in comparison with that during 1961–1980 and 3.72–11.52% that during 1981–2002 (Fig. 3). Specifically, water level decreased almost 1–2 m and even higher than 3 m at some point in 2006.

Table 1
The date and duration when water level below 24 m.

Year	Date (when water level firstly ⩽ 24 m)	Duration (when water level ⩽ 24 m) (d)
1961	12/6	125
1962	10/31	151
1963	11/5	161
1964	11/27	139
1965	11/21	158
1966	11/10	164
1967	11/7	145
1968	11/17	129
1969	11/18	164
1970	11/7	143
1971	11/5	145
1972	11/4	161
1973	11/6	153
1974	11/1	173
1975	11/31	139
1976	11/25	145
1977	11/22	139
1978	10/14	160
1979	11/6	168
1980	11/18	151
1961–1980	11/14	151
1981	11/23	135
1982	12/20	137
1983	11/26	142
1984	11/4	157
1985	11/18	147
1986	11/9	165
1987	11/30	158
1988	11/12	133
1989	11/30	120
1990	11/30	110
1991	11/5	146
1992	10/18	158
1993	12/6	151
1994	11/7	154
1995	11/9	159
1996	11/25	148
1997	11/4	153
1998	11/7	121
1999	12/4	140
2000	11/24	140
2001	11/21	134
2002	11/25	148
1981–2002	11/16	143
2003	10/28	171
2004	11/4	181
2005	11/7	169
2006	9/11	214
2007	10/21	212
2008	10/22	175
2009	10/3	184
2010	11/4	172
2003–2010	10/20	185

3.3. Alterations in the wet and dry season

The water discharge period of TDG was usually in June or July, while water storage period is in September or October. The sudden discharge or impound of water would influence the alteration of water level in the wet season and the dry season. As seen in Fig. 3, water level did not change much in the wet season. Nevertheless, water level variation in the dry season was more obviously than that in the wet season.

In order to explore the deep understanding of variation in dry season, we compared the date when water level was firstly below 24 m and the duration when water level was below 24 m during the period between 1961 and 2010 (Table 1). The period was mainly divided into three intervals: (1) 1961–1980, as a reference; (2) 1981–2002, earlier period preparation and construction of TGD before water impounding; and (3) 2003–2010, the years since the impoundment of TGD. The result showed that the average date when water level was firstly below 24 m was put forward early especially during the period of 2003–2010. Compare to the reference interval, the starting time of dry season during the period of 1981–2002 did not change much, however, the date during the period of 2003–2010 appeared about 27 days earlier. Moreover, the most remarkable change appeared in 2006 and the date was advanced to mid-September. As for the duration, water level was below 24 m for about 185 days during the period of 2003–2010. The time was 20–30 days longer than the other periods. By coincidence, the longest duration (214 d) appeared in 2006.

4. Discussion

4.1. Alterations of water level in Dongting Lake from 1961 to 2010

Water level is one of the most important ecological factors for maintaining the function and the health of the lakes (Coops et al., 2003). As the second largest freshwater lake and directly connected with Yangtze River in China, hydrological alterations in Dongting Lake have attracted a lot of attentions (Tullos, 2009; Wang et al., 2011; Ou et al., 2012; Sun et al., 2012). Ou et al. (2012) analyzed the variation character of water level in Dongting Lake in typical years and drew a conclusion that water level was just slightly lower than the usual level with the same inflow but heightened a sort under the water-storage dispatch. However, slightly different conclusions were gotten in our study. We found that a significantly increasing trend appeared during the period of 1990–2002 and water level decreased slightly after 2003 especially during the water storage period.

The change of water level would have great effects on the ecosystem of lakes, including turning some floodplain wetland area into terrestrial ecosystem or water body temporarily even permanently (Zhang et al., 2006). Along with the rise of water level, the study area was covered with water in wet season. Nevertheless, water level withdrew below 24 m in dry season, resulting in a large area of floodplain. This flood buffer area provided sufficient resources for the vegetation communities. Due to the variation of water level, the ecological niche of vegetation would change, such as the vegetation area extended outward or reduced slowly. Especially, when water level was higher than usual in autumn, the long flood time could affect the vegetation growth. Therefore, to some extent, a further study should be carried out to explore the specific influences of hydrological alteration on ecological systems.

4.2. Impacts of anthropogenic activity on the alterations of water level

Anthropogenic activity, such as dam construction, reservoir operation, landscape modification, river channelization, may affect the alterations of water level. Dam construction is particularly prominent in the Yangtze River basin. Many dams, such as the High Aswan Dam of the Nile River, the dams on the Lancang River, and the dams in the middle and lower reaches of Yangtze River and Yellow River, have turned out to bring adverse effects on the ecological environment of rivers, especially the hydrological regimes of downstream areas (Moussa et al., 2001; Yang et al., 2008; Zhao et al., 2012). More than 50,000 dams have been constructed in the Yangtze River (Fuggle et al., 2000; Yang et al., 2011; Sun et al., 2012). Among those dams, TGD are well known (New and Xie, 2008; Yi et al., 2010; Liang et al., 2014).

Due to the special relationship between Dongting Lake and Yangtze River, many experts suggested that dams or floodgates should be built at the inlet or outlet of Dongting Lake to cope with the irregular variations of the water level. However, it is in a fierce debate, especially after the running of the TGD (Li, 2009). After the occurrence of greatest flood over the past more than 100 years in 1998, the government implemented a policy, namely the Return Land to Lake Program, to construct some embankments to prevent flooding (Li et al., 2007). Certainly, dams may play an important role in maintaining the ecological water of the lakes.

In order to determine the impacts of anthropogenic activity on the alterations of water level, we reveal the inter- and inner-annual variations of water level during the period of 1961–2010. From the initial operation of TGD to 2010, the Three Gorges Reservoir went through six impoundments, namely June 2003, September 2006, September 2007, September 2008, September 2009 and September 2010. The results revealed that water level (during the period of 2003–2010) decreased obviously especially in the dry season during and after the water storage period. However, the change of water level was not obvious during the water discharge period (usually in April or May). As seen in Fig. 2, a sudden change point of water level happened to be in 2003, which was synchronized with the operating time of TGD. Moreover, the date when water level was firstly below 24 m during the period of 2003–2010 appeared about 27 days earlier than that during the period 1961–1980 and 1981–2002. The duration (when water level was below 24 m) in 2003–2010 interval was about 20–30 days longer than the other two periods. All of these results indicated that dam construction might be a main factor that should be responsible for the seasonal alteration of water level in Dongting Lake especially during and after the water storage period in dry season. However, whether the river-lake connectivity is accelerated under the condition of the hydraulic engineering construction needs further study.

4.3. Impacts of climatic factor on the alterations of water level

Meanwhile, climatic factor as one of important inductive factors has been in hot debate for a long time. It may alter hydrological regime by precipitation, evaporation, temperature variation (Woodward et al. 2010; Green et al. 2013). Climate-induced changes, including alteration in the magnitude of water recharge and river flow regimes, may affect the fundamental ecological function and species distribution in wetlands ecosystem (Pall et al. 2011).

In recent years, too much attention was paid to the influence of dam construction on hydrological alteration in Dongting Lake, especially after the impoundment of TGD. However, the effects of climatic factor were neglected to some extent. Variation of annual rainfall in Dongting Lake during the period of 1961–2010 was shown in Fig. 4. The annual rainfall fluctuated greatly during the period of 1961–1980 with an average rainfall of 1288.09 mm y^{-1}. While the annual rainfall increased significantly during the period of 1981–2002 with an average rainfall of 1422.827 mm y^{-1}. Moreover, the annual rainfall remained relatively stable during the period of 2003–2010 with an average rainfall of 1328.031 mm y^{-1}. Coincidentally, water level decreased significantly during the period of 1961–1980, while increased significantly during the period of 1981–1999.

Besides rainfall, temperature is also a useful indicator of climatic factor. Sang et al. (2013) investigated the spatial and temporal variability of temperature in the Yangtze River Basin during 1961–2010 and the result reflected that the temperature showed upward trends after the 1980s in Dongting Lake. Seen from the coherence of rainfall, temperature alteration and water level alteration, we drew a conclusion that climatic factor (exactly rainfall) might be a main factor responsible for hydrological alteration especially during the period of 1961–1980 and 1981–2002 (Figs. 2 and 4). During the past years, flood (especially in the 1998) and drought (especially in 2006) have become big issues in Dongting Lake (Sun et al., 2012). Due to the occurrence of extreme climate events, inter- and inner-annual variations of water level were significant. For instance, water level decreased almost 1–2 m in 2006 by comparison with the normal years and the date when entering the dry season was advanced to mid-September.

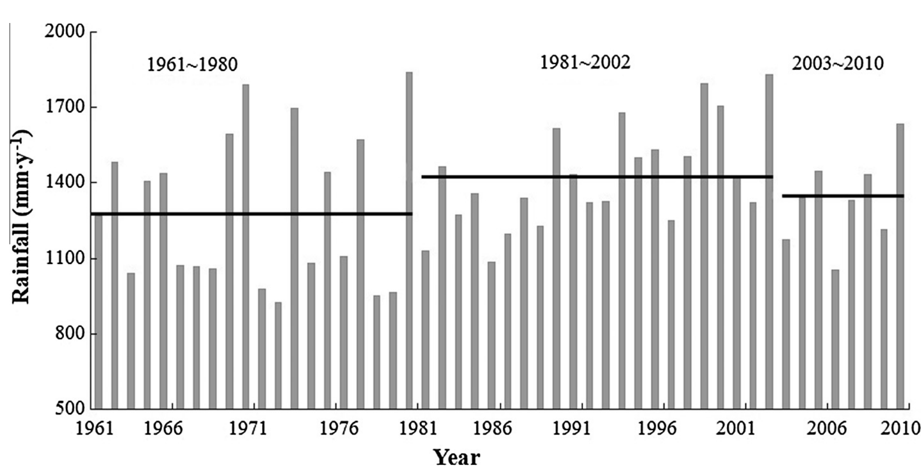

Fig. 4. Variation of annual rainfall in Dongting Lake during the period of 1961–2010. The solid lines represented the average rainfall of the three different periods.

5. Conclusions

In this study, inter- and inner-annual variations of water level in Dongting Lake over a 50-year period from 1961 to 2010 were analyzed to evaluate the potential impacts of anthropogenic and climatic factors. The time series was divided into three distinguishable periods, namely 1961–1980, 1981–2002, and 2003–2010.

The results showed that water level decreased significantly during the period of 1961–1980, while increased significantly during the period of 1981–2002 at the 5% significance level. The variation in the dry season was more obviously than that in the wet season. The date when water level was firstly below 24 m during the period of 2003–2010 appeared about 27 days earlier than usual, and the date was even advanced to mid-September in 2006. As for the duration, water level was below 24 m for about 185 days in the period of 2003–2010 and 20–30 days longer than the other two periods. In conclusion, water level might be influenced by a combination of anthropogenic and climatic factors, with climatic factor (exactly rainfall) as the main driver responsible for hydrological alteration during the period of 1961–1980 and 1981–2002 while anthropogenic activity (exactly dam construction) as the main driver during the period of 2003–2010.

Understanding the variation regularity of water level and the potential drivers can provide insights into lake conservation and management. Keeping water at a proper level is important for lake ecosystems. Under the circumstance of uncontrollable climatic factor, effective measures for reservoir operation should be put forward to maintain the ecological integrity and ensure water release and storage capacity of aquatic ecosystems. Quantitative analysis of the impacts of anthropogenic and climatic factors on hydrological regimes is needed in the further study.

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