

Unusual Salinity Conditions in the Yangtze Estuary in 2006: Impacts of an Extreme Drought or of the Three Gorges Dam?

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Abstract During the extreme dry year of 2006, abnormal salinity conditions in the Changjiang Estuary of the Yangtze River occurred in partial coincidence with the second impoundment phase of the TGD (Three Gorges Dam). Analysis of discharge observations in the upper reaches of the estuary and of salinity observations in the estuary as a whole reveals that in 2006 salinity was over 100 mg/l during 275 days, over 250 mg/l during 75 days and over 400 mg/l during 48 days. It is well known that this is due to extreme low discharges from the upper catchment area into the estuary. Moreover, large amounts of water consumed along the lower reaches of the Yangtze River can also aggravate the low discharges that lead to stronger saltwater intrusion in the estuary. Of the 75 days that salinity was over 250 mg/l, the low discharge was decreased further by 10 to 20% due to water consumption. The additional impact of the impoundment phase of the TGD (lasting 37 days in autumn) was noticeable only during 7 days in 2006. During that period, the relative contributions of the TGD and the water consumption in the lower reaches of the Yangtze River amounted to 70 and 30%, respectively. It may be concluded that the impact of the second impoundment phase of the TGD on salinity intrusion in the estuary was modest, while the extreme drought of 2006 was the dominant cause.

Keywords Salinity variation · Saltwater intrusion · Yangtze Estuary · TGD · Water consumption · Extreme drought

INTRODUCTION

Salinity is a key parameter describing aquatic systems in an estuarine environment (Attrill et al. 1996; Huang and Foo 2002). Understanding the salinity variation in estuaries under different forcing events, e.g. due to an extreme drought, climate change or human interventions, is important in order to manage estuarine water resources, to design water-supply systems and to protect diverse estuarine species (Savenije 1993; Liu 2004; Brockway et al. 2006; McLaughlin et al. 2007). Some researchers report that salinity in estuaries is mainly determined by estuary shape, tidal forcing, waves and river discharge (Savenije 1993; Attrill et al. 1996; Nguyen et al. 2008). Especially in alluvial estuaries the latter effect is considered dominant with discharge nonignorable large with respect to the seasonal variation of salinity. Hence, most studies focus on analysis of relationships between discharge and salinity in estuaries such as those of the Apalachicola, Mississippi, Incomati and Mekong rivers, in the Swan-Canning Estuary (Twomey and John 2005; Huang and Foo 2002; Brockway et al. 2006; Nguyen et al. 2008). It is important to quantify the relationship between discharge and salinity because long-time series of salinity in estuaries are scarce and the available discharge observations seldom reflect the actual discharge in the estuary due to water consumption in areas between the discharge observation stations and the lower estuarine reaches (Nguyen et al. 2008). Moreover, observations of salinity fluctuations in estuaries in an extreme dry year are not amply available. Such observations are particularly relevant to assess the lower boundary of freshwater discharge as a key index for estuarine environmental management and estuarine water resource allocation.

The Yangtze River, the largest river in China, is about 6,300 km long with a catchment area of 1.8×10^6 km²,

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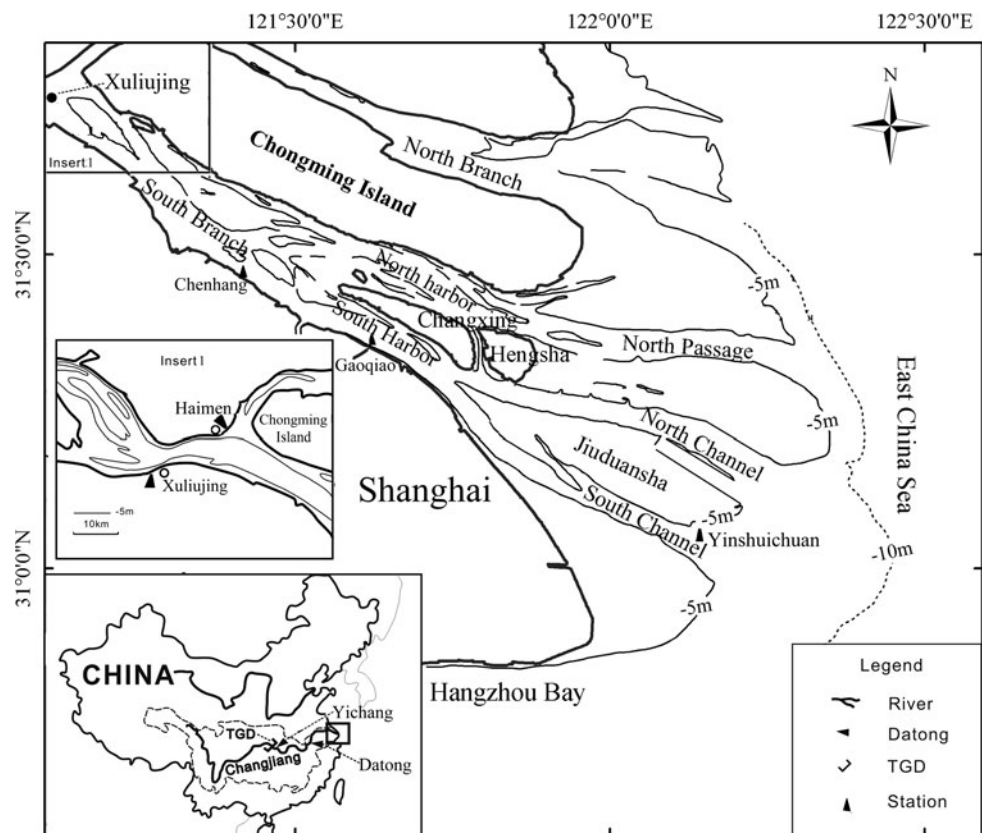
which can be divided into two parts: the upper reaches of the Changjiang River and the mid-lower reaches of the Changjiang River (MLRCR) due to the geomorphological characteristics. The MLRCR, from Yichang to Datong, has a catchment area of about $7 \times 10^6 \text{ km}^2$ with its discharge of more than 50% of the total discharge into the sea (Dai et al. 2010a). The semidiurnal tide is dominated around the river mouth with the mean tidal range of about 2.65 m. The inflow volume of flood tides varies from $13 \times 10^8 \text{ m}^3$ during neap tide in dry season to $53 \times 10^8 \text{ m}^3$ during spring tide in flood season with the average tidal discharge during flood is about $263,000 \text{ m}^3/\text{s}$ which is nine times of the annual mean river discharge (Yun 2004). Under combined influence of river fresh water discharge and tidal saline inflow, the fresh and salt water mixing in the estuary shows different types. Major time (60–70%) of a year it shows the partially mixed pattern in the estuary. In flood season, the occurrence of partially mixed pattern is more than 75 with 50% in dry season. The stratification happens when there is extreme high river discharge during neap tide (e.g. stratification in the South Passage in July 1962 with river discharge of $68,000 \text{ m}^3/\text{s}$ during neap tide). Under the combined influences of spring tide and low discharge ($7,800 \text{ m}^3/\text{s}$ in February 15–16, 1960) the well mixed pattern occurs. The salt water front in the South Branch varies in space and time under the different combination of

river discharge and tides. Normally, the salt water front is up to Gaoqiao in dry season during spring tide. However, the salt water intrusion in the North Branch of the estuary is so intense that the saline water enters the South Branch from North Branch. The upper part of the south Branch from Gaoqiao can be influenced by the salt from North Branch. Therefore, the upper limit of salt water intrusion is around Haimen to Xuliujing (Shen and Pan 2001, pp. 26–31).

Due to needs of irrigation and hydroelectric power, more than 50,000 dams have been built throughout the Yangtze's watershed since 1950 (Yang et al. 2011). Amongst these dams, Three Gorges Dam (TGD), located in the mainstream of the Yangtze River, 1,800 km upstream of the sea and 40 km upstream of the Yichang hydrological station (Fig. 1), is the world's largest dam with 185 m high (China Three Gorges Project Corporation, CTGPC, <http://www.ctgpc.com.cn>). It has been reported that TGD construction is likely to have a heavy impact on the material loads into the estuary and adjacent estuarine environment (e.g. Dai et al. 2008a; Xu and Milliman 2009; Dai et al. 2011).

Before the 1980s, the annual discharge of the Yangtze River into the estuary was about $0.9 \times 10^{12} \text{ m}^3$ (or $28,500 \text{ m}^3/\text{s}$) (Yang et al. 2005). A significant decreasing trend of the discharge into the estuary occurred from 1985

Fig. 1 Catchment area of the Yangtze and the estuarine area with gauging stations



to 2004 due to increase in water consumption and reservoir construction (Yang et al. 2005). New records at Datong gauging station, the tidal limit of the estuary, reveal that the second lowest discharge record in history into the Yangtze Estuary occurred in 2006 (Dai et al. 2008a; Xu and Milliman 2009). It is noted that this extreme low discharge coincided with an extreme drought in 2006 and the second impoundment phase of TGD with the water level increasing from 135 to 156 m. Remarkably, the saltwater intrusion in the Yangtze Estuary showed particularly abnormal behaviour 3 months in advance of the water level rise.

Saltwater intrusion in the Yangtze Estuary could directly influence the economic development of Shanghai (the largest city in China) because the Yangtze Estuary is a vital freshwater source for Shanghai. The Yangtze Estuary, a partially mixed estuarine system, is a typical tidal estuary characterised by multi-order bifurcations, islands, and deep channels (Fig. 1) (Mao et al. 2001a, b). Under the combined effects of topography, runoff and tidal currents, the salt content and location of salt front is related to the total fresh water discharge in the Yangtze Estuary, tidal range, and winds, as maximum intrusion occurs usually during spring tide under low freshwater discharge and northwind conditions (Kong et al. 2004). With the increase in magnitude and frequency of saltwater intrusion in recent years, saltwater intrusion in the Yangtze Estuary has received wide attention (Han 1983; Han and Lu 1984; Mao et al. 2001a, b; Dai et al. 2008b; Wu and Zhu 2010). However, salinity variations in such an extreme drought year partially coinciding with the impact of the TGD have never been reported before. Therefore, the aims of this paper are (1) to analyse salinity variations in the Yangtze Estuary under extreme drought conditions; (2) to understand the causes of the saltwater intrusion in the Yangtze Estuary; (3) to establish a relationship between the freshwater discharge and salinity.

DATA AND METHODS

Monthly freshwater discharge data in the years of 1950–2005 and daily freshwater discharge in 2006 at Datong gauging station were collected from the Yangtze River Water Conservancy Committee, Ministry of Water Conservancy of China (YRWCC). Daily discharge in 2006 at Xuliujing gauging station was also provided by YRWCC. These data were collected by the Yangtze River Water Conservancy Committee (<http://www.cjh.com.cn>) (Fig. 1). Meanwhile, daily water samples collected by using glass bottles of 500 ml at 2 m below water surface at Haimen gauging station in 2006 were analysed based on

silver nitrate titration method (Fig. 1). Here, the salinity values were obtained based on chemical analyses of solutions, and thus salinity is available in mg/l. The data are from the Hydrological Bureau of Jiangsu Province (<http://www.jswater.gov.cn/>). Moreover, the monthly salinity at Yinshuichuan in the years of 1966–1984, daily salinity at Chenhang and Gaoqiao during spring-neap cycle from 8 to 29 in March, 1996 were also available from published reports (e.g. Shen and Pan 2001; Chen and Heng 2009, pp. 22–27; Yang et al. 2009, pp. 212–217).

Datong gauging station, at a distance of about 640 km from the estuary and 1,200 km downstream of the TGD (Fig. 1), is a key hydrological station that records discharge of about 95% of Yangtze River basin and represents the total freshwater input into the Yangtze estuary. However, a large amount of water of about 4,626 m³/s was consumed downstream of Datong during these years due to rapid economic development in the Yangtze delta in the recent two decades (Chen et al. 2001; Zhang et al. 2003), especially intense in the extreme drought year 2006 (Jia 2006), the actual freshwater discharge into the estuary was less than the freshwater discharge measured at Datong because of water consumption, e.g. agriculture, industry and pumping, in the downstream reach (Dai et al. 2010b). Thus, additional daily discharge data at the Xuliujing in 2006 (Fig. 1) were, collected 500 km downstream from Datong, where a new gauging station is located with discharge data available since 2005. The discharge difference between Datong and Xuliujing represents the water consumption downstream of Datong to a great degree. The reasons can be shown as follows: (1) precipitation, evaporation and groundwater discharge/redischage of the river segment between Datong and Xuliujing in the whole year remained in equilibrium, and there is no evidence indicate that these components play a meaningful role in local changes of discharges (Zhang et al. 2003); (2) the yearly freshwater supply from distributaries located at the river segment between Datong and Xuliujing is about 10% of the total consumed water (Zhang et al. 2003). In addition, Haimen gauging station is near at the first bifurcation point of the Yangtze Estuary (Fig. 1), where the salinity is determined by the intrusion of salt water through the different inlets and the freshwater discharge. The stations, Chenhang, Gaoqiao and Yinshuichuan, are respectively, at the South Branch, South Harbor and South Channel (Fig. 1).

Although many studies have been carried out to simulate salinity in estuaries by analytical methods and numerical models (Savenije 1989; Brockway et al. 2006; Wu and Zhu 2010; Gong and Shen 2010), statistical methods have also been widely applied to salinity evaluations (Huang and Foo 2002; Marshall 2000, 2003; Frank 2005). A simple statistical model can be more effective for engineers and

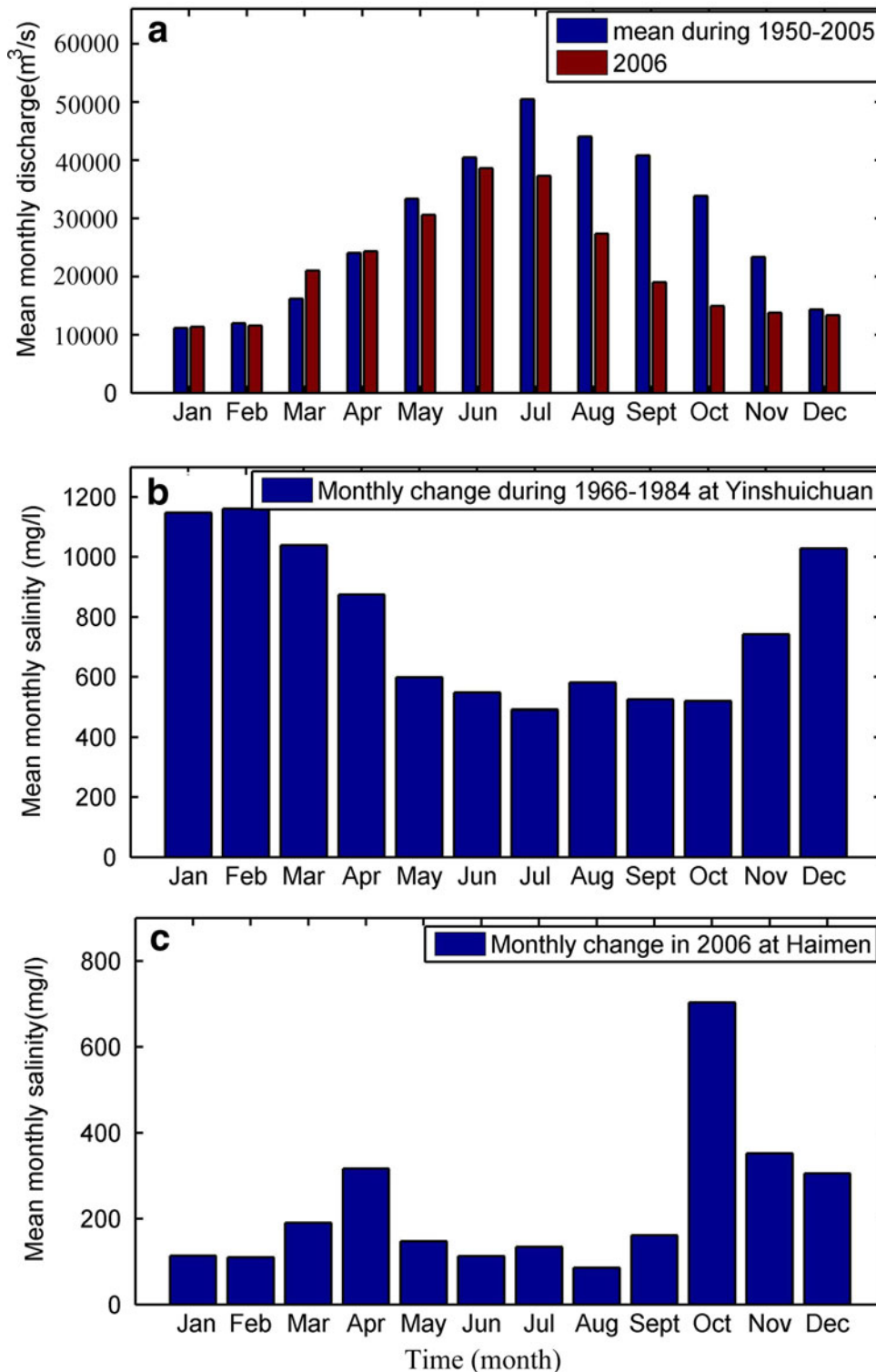
managers to make rapid preliminary estimates of salinity (Huang and Foo 2002). Hence, these data of the paper were used to study the salinity variation in the Yangtze Estuary in 2006 as a function of the actual discharge. Moreover, a simple relationship between discharge and salinity in 2006 is also derived following a frequency analysis.

RESULTS

Discharge and Salinity Variation

Monthly mean discharges at Datong in 2006 and over the period from 1950 to 2005 are presented in Fig. 2a.

Fig. 2 Monthly discharges and salinity in different stations



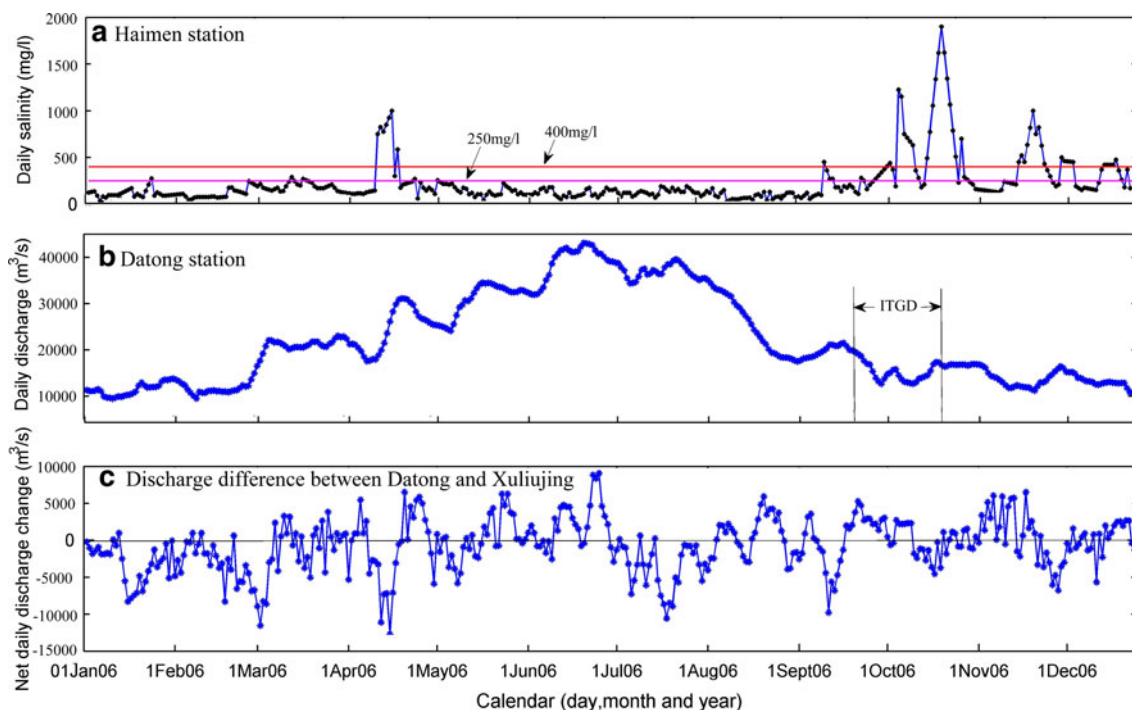


Fig. 3 Daily salinity and discharge, and daily discharge difference between Datong and Xuliujing in 2006 (Data at Datong 6 days in advance of Xuliujing, accounting for the discharge travel time between these stations (Chu and Zhai 2006))

Figure 2b and c shows the monthly mean salinity at Haimen (represent the salt front) and the monthly mean salinity at Yinshuichuan (represent the mixing area), respectively. We can find that from April to July onwards the discharges in the dry years are significantly lower. It can be seen from Fig. 2b and c that mean salinity in the Yangtze Estuary in 2006 and over 1966–1984 show a seasonal characteristic, which agrees with the seasonal variation of the discharge at Datong. The salinity in the flood season (May to October) is found to be lower than in the dry season. Some anomalies, however, occurred. An obvious difference is that salinity values in October 2006 were the highest of the whole year in comparison with those during 1966–1984 (Fig. 2b, c).

Figure 3 shows the daily values of salinity at Haimen, daily discharge at Datong and daily net discharge through Xuliujing cross section in 2006. We can find that salinity at Haimen keep constant with the increasing of river discharge in the first three month of 2006. However, the salinity was so high, more than 1,000 mg/l (salinity of 2‰), in April that it is different from usual expectation and observation. An extreme high salinity value of 450 mg/l is found on September 15, 2006, as such high salinity had never been observed in flood season (Fig. 3a, b). It is also remarkable that the largest value (1,621 mg/l) occurred on October 27 in 2006 with the largest monthly mean salinity occurring in October, which also differs from common

sense with a relatively high salinity occurring in November and December (Tan and Wang 2004). These anomalies will be discussed later in more detail.

In addition, salt water intrusion is the same as the usual in the Yangtze Estuary in 2006, which leads the longitudinal salinity distribution increases downstream (Figs. 2, 4). However, saltwater could also intrude from the North Branch into the South Branch during the spring tide in dry season, which would be related to the high salinity values at the intersection region of the South Branch and North Branch (e.g. Haimen station). Then, high salinity values dropped and moved seaward during the neap tide, which will lead Yangtze Estuary into a partially mixed estuarine system (Xue et al. 2009).

Saltwater Intrusion Thresholds

When the salinity level in the Yangtze Estuary is over 100 mg/l, saltwater intrusion is assumed to occur (Chinese living drinking water and water source standard (CJ3020-93)). Based on this definition, we observe that saltwater intrusion occurred during 285 days in the estuary in 2006. This is the highest recorded occurrence with the second highest of 236 days measured at Wusong station in the other historically dry year, 1978. Two other salinity limits, i.e. 250 and 400 mg/l, are of even greater importance than the limit of 100 mg/l. The limit of 250 mg/l is the limit for

Fig. 4 Salinity change of over bi-monthly and yearly intervals (a Yearly salinity change during 1966–1984 at Yinshuichuan (revised from Chen and Heng 2009); b Daily salinity at Chenhang and Gaoqiao during neap-spring cycle on 8–29, March, 1996 (Mao et al. 2000)

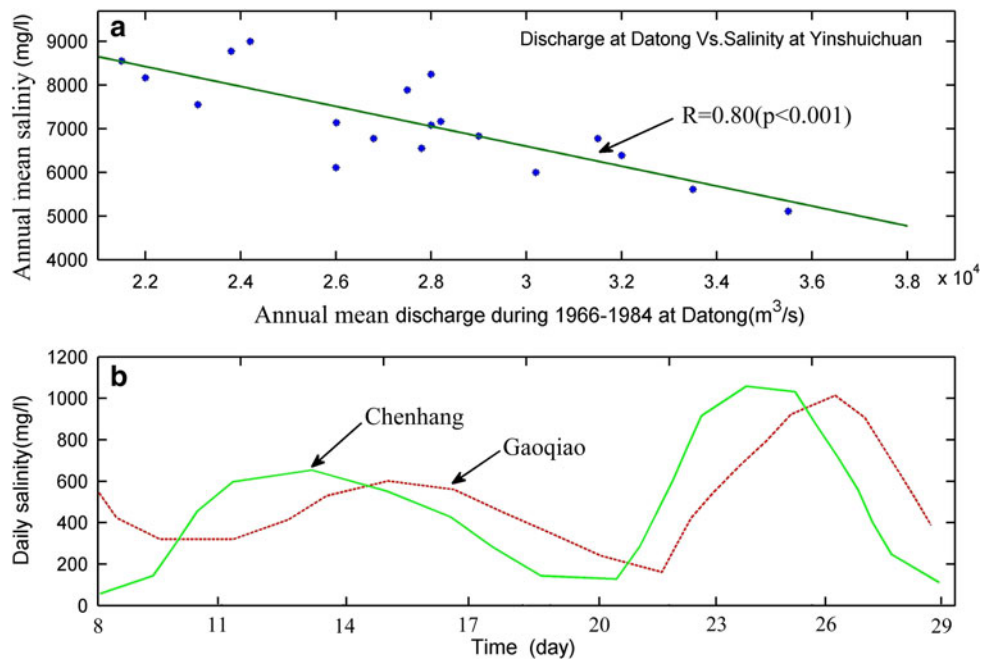


Table 1 Duration of salinity over 250 mg/l in 2006 at Haimen station of the Yangtze Estuary

Starting time Calendar (Lunar)	Duration period (day)	Maximum salinity (mg/l)	Dis1 (m ³ /s)	Dis2 (m ³ /s)	Net water loss (m ³ /s)
3.17 (1.8)	3	270	21117	17500	3617
4.12 (2.25)	8	1000	20440	17100	3340
9.15 (8.5)	4	450	18375	19600	-1225
10.3 (8.23)	7	406	18625	16200	2425
10.11 (9.1)	8	1225	13720	11500	2220
10.21 (9.11)	11	1621	12650	14000	-1350
11.2 (9.23)	3	700	16620	15300	1320
11.22 (10.13)	12	816	12320	10900	1430
12.7 (10.17)	5	500	14625	14150	475
12.21 (11.12)	8	475	13200	12000	1200

Dis1 Discharge at Datong 7 days earlier than salinity intrusion occurring at Haimen

Dis2 Discharge at Xuliujing when salinity intrusion occurring at Haimen

Spring tides occur on day 1, 16, 17 and 30 of each lunar month

drinking water quality, and the limit of 400 mg/l is the critical quality limit used in water for industry and agriculture (Chinese living drinking water and water source standard (CJ3020-93)). During 75 days salinities were over 250 mg/l in the estuary in 2006 with 60% of these events occurring in October and December. The occurrence of salinity over 400 mg/l in 2006 was 48 days, of which 40% occurred in October. During these days, the salinity was so high that there was no water available of suitable quality for drinking water, industry or agriculture in the Yangtze Estuary.

Usually, saltwater intrusion occurs from December to April of next year in the Yangtze Estuary when discharges

are low (Mao and Shen 1994; Zhu et al. 2004) such as saltwater intrusion like in the normal year of 2003–2004 (Table 1). However, in 2006, 10 intense saltwater intrusion events occurred in the Yangtze Estuary with a salinity value of over 250 mg/l (Table 2). The earliest intense saltwater intrusion occurred on September 15 with a maximum salinity of 450 mg/l, when saltwater intrusion occurred 3 months in advance compared to normal years. It is also interesting that seven intense saltwater intrusion events had the duration over 5 days with six of these occurring in the autumn and winter of 2006. Moreover, three of these happened to occur during the impact period of TGD. Thus, the dominant features of the intense

Table 2 Duration of salinity over 250 mg/l from September 2003 to April 2004 at Chenhang station in the Yangtze Estuary

Starting time Calendar (Lunar)	2003.11.27 (11.4)	2003.12.28 (12.6)	2004.1.28 (1.7)	2004.2.13 (1.23)	2004.2.23 (2.4)	2004.3.10 (2.20)	2004.3.23 (2.3)
Duration period ^a (day)	5	4	5	5	9	7	8
Dis1 (m ³ /s)	10600	10240	9490	9600	8350	15300	14900

^a Data from Zhu et al. 2004

Dis1 Discharge at Datong 7 days earlier than salinity intrusion occurring at Haimen

saltwater intrusion events in the Yangtze Estuary in the extreme drought year 2006 can be summarised as: historically abnormal with more frequent, longer lasting and earlier occurring events of intense saltwater intrusion.

DISCUSSION

Salinity Variation

It can be seen from Fig. 4 that during normal years salinity values are primarily varying inversely with the discharge (Chen and Heng 2009; Mao et al. 2001a, b), while secondary variations are due to the neap-spring tidal cycles (Yang et al. 2009) (Fig. 4). Salinity and duration of intense saltwater intrusion events in the Yangtze Estuary are indeed stronger during spring tides than those during neap periods (Mao and Shen 1994). However, the most intense periods of saltwater intrusion in 2006 were not coinciding with the occurrence of spring tides (Table 2). The data in Table 1 also confirm that a low discharge at Datong causes high salinity in the estuary, and vice versa. Indeed, salinity and discharge synchronously measured at Haimen and Datong in 2006 indicates a negative relationship between the daily discharge at Datong and the salinity at Haimen (Supplementary Fig. 1). Thus, although salinity change in the Yangtze Estuary could be influenced by various factors, the salinity was mainly controlled by the freshwater discharge from the upstream regions in 2006, in agreement with previous studies of other dry years (Han 1983; Mao et al. 2001a, b).

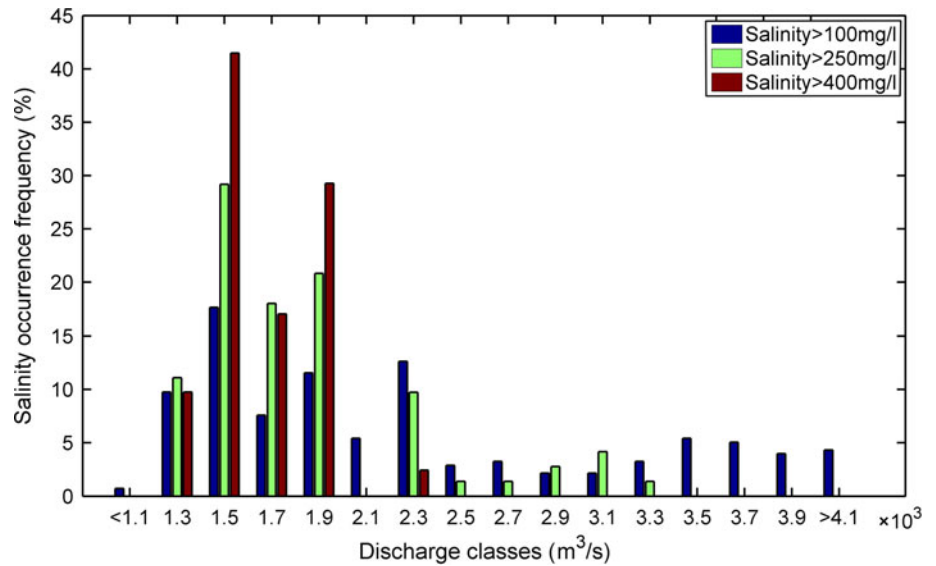
Water consumption along the Yangtze basin just upstream of the estuarine area in 2006 was more intense than that during normal years (Jia 2006). If a large amount of freshwater is extracted in the upstream reach, it effectively decreases the discharge and promotes a more intensity of saltwater intrusion in the Yangtze Estuary. Figure 3c shows the discharge difference between Datong and Xuliujing, where a positive difference is an indication of the dominance of freshwater extraction over additional run-off. Although the discharge difference between Datong and Xuliujing was negative at the beginning of the intense saltwater intrusion occurring on September 15, the

discharge difference became positive soon afterwards. The intense saltwater intrusion starting on October 21 was similar to the one on September 15. In addition, it can be observed from Fig. 3c that the difference of daily discharge between Datong and Xuliujing was positive and increased from March to April, which implies a decreasing discharge into the estuary in the same period. The decrease of the discharge in this period was due to fresh water extraction for rice farming in spring in the lower reaches of the Yangtze. Although freshwater discharge from Datong was large, relative high salinity in the estuary with intense saltwater intrusion occurred in the Yangtze Estuary in the spring of 2006. The high salinity and saltwater intrusions in the winter of 2006 can also be ascribed to water consumption. From Table 2, we show that the discharge difference between Datong and Xuliujing is about 1,000 m³/s when saltwater started to intrude. Based on Fig. 3c, we can quantify that the water consumption was about 1,800 m³/s in the winter. Hence, water consumption along the Yangtze basin between the Datong and Xuliujing contributes importantly to the high salinity and intense saltwater intrusion in the Yangtze Estuary.

It is commonly assumed that the early shift of intense saltwater intrusion in the Yangtze Estuary from December to September was a result of the second impact phase of the TGD. However, the majority of the intense saltwater intrusion events in September were not coinciding with the impact period of the TGD in 2006. In reality, the extreme drought in 2006 caused the historical lowest water level in late August (normal flood season) along the middle and lower reaches of the Yangtze River (Dai et al. 2008a). The discharge at Datong in September in 2006 was only 53% of the mean discharge during 1950–2005 (Fig. 2), as the lowest record in history over that period. In addition, water consumption was about 1,900 m³/s upstream of the estuary in middle September. Subsequently, the actual discharge into the Yangtze Estuary was less than 17,000 m³/s, which resulted in the intense saltwater intrusion period shifting forward to September during 2006.

Three intense saltwater intrusion events (10/3, 10/11, and 10/21) occurred in coincidence with the impact of the TGD. Are these associated with the TGD? The second impact phase of the TGD stored 10.5 billion m³ water

Fig. 5 Frequency of occurrence of saltwater intrusion as a function of the discharge



within 37 days, from September 20 to October 27, with a discharge of about 3,200 m³/s. During the impact period, the discharge at Datong was about 16,000 m³/s. The actual discharge at Datong would have been over 19,000 m³/s, if the stored water was added. In addition, if the consumed water was added, the discharge into the estuary would have amounted to 20,000 m³/s. This means that an intense saltwater intrusion might not have occurred, as was also suggested by previous studies on other dry years (Mao and Shen 1994; Chen and Xu 1995). Although the discharge at Datong was much lower than the historical records, intense saltwater intrusion would not have occurred without the impoundment of TGD and water consumption along the Yangtze. In addition, salinity in November–December was much lower in 2006 compared to those in the normal years (Fig. 2), it could be induced by water release from TGD during November–December (Yang et al. 2009).

The TGD caused a decrease of the discharge into the estuary with about 3,200 m³/s during its second impoundment phase in 2006. The amount of water consumption along the river course between Datong and Xuliujing was about 1,350 m³/s during the same period. Thus, we can quantify the contributions of the TGD and the water consumption along the lower reach of the Yangtze to high salinity and intense saltwater intrusion in the estuary to be about 70 and 30%, respectively, during the second impoundment phase in 2006.

Relation Between Fresh Water Discharge and Salinity

Since we have shown that the salinity depends not only on the discharge at Datong but also on the water consumption downstream to Datong, we have corrected the discharge at

Datong to account for the water consumption. We then applied the following frequency method. A total of 17 discharge ranges at Datong with an interval of 2,000 m³/s were selected to assess the frequency of occurrence of salinity over 100, 250 and 400 mg/l from our data. The occurrence of each salinity class is shown in Fig. 5. It can be concluded that salinity levels over 400 mg/l hardly occur when the discharge is larger than 20,000 m³/s. Occurrences of high saltwater intrusion coincide with discharges in the range of 12,000–14,000 m³/s, which mainly occurs in the dry season (December to February). With the discharge increasing, the saltwater intrusion magnitudes decrease first, but high occurrences of saltwater intrusion occur within the discharge range of 16,000–18,000 m³/s, which is the result of the strong water consumption for rice farming, typically in April and May (Fig. 3).

CONCLUSIONS

Both an extreme drought and human activities, i.e. the second impoundment phase of the TGD and intense water consumption in the lower reaches of Yangtze River, simultaneously occurred in 2006. This resulted in 275 days during which salinity was over 100 mg/l in the Yangtze Estuary. It is shown that the large amounts of water consumed in the lower reach of the Yangtze seriously aggravated the saltwater intrusion. Moreover, intense saltwater intrusions occurred during the second impoundment phase of the TGD (37 days in total) with the contribution of the TGD impoundment and water consumption in the lower reaches of 70 and 30%, respectively. Statistical results show that saltwater intrusion occurs frequently with discharges at Datong in the ranges of 12,000–14,000 m³/s and

16,000–18,000 m³/s, which are the typical discharges in the dry season and the rice farming season.

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