doi:10.20944/preprints201909.0054.v1

Peer-reviewed version available at *Water* **2019**, *11*, 2176; doi:10.3390/w11102176

Freshwater Supply to Metropolitan Shanghai: Issues of Quality from Source to Consumers

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Abstract

Shanghai is experiencing water supply problems caused by heavy pollution of its raw water supply, deficiencies in its treatment processes and water quality deterioration in the distribution system. However, little attention has been paid these problems of water quality in raw water, water treatment and household drinking water. Based on water quality data we show that the raw water sources of the Huangpu River and the Changjiang (Yangtze River) estuary are polluted by microbes (TBC), eutrophication (TP, TN and NH^3-N), heavy metals (Fe, Mn and Hg) and organic contamination (chemical oxygen demand [COD], detergent and volatile phenols [VP]). The average concentrations of these contaminants in the Huangpu River are almost double that of the Changjiang estuary forcing a rapid shift to the Changjiang estuary for raw water. In spite of filtering and treatment, TN, NH^3-N, Fe, COD and chlorine maxima of the treated water and drinking water still exceed the Chinese National Standard (GB5749). We determine that the relevant threats from water source to household water in Shanghai are: 1) eutrophication arising from highly concentrated TN, TP, COD and algal density in the raw water; 2) increasing salinity in the river estuary, especially at the Qingcaosha Reservoir (currently the major freshwater source for Shanghai); 3) more than 50% of organic constituents and by-products remain in treated water; 4) bacteria and turbidity increase in the course of water delivery to users. The analysis presents a holistic assessment of the water quality threats to metropolitan Shanghai in relation to the city's rapid development.

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Keywords: Shanghai, water quality, eutrophication, conventional water treatment, secondary water pollution.

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1 Introduction

There is no substitute for freshwater and it plays an essential role in sustaining societies and supporting and enriching the culture (Covich et al., 2004; Jackson et al., 2001). Pollution from domestic, industrial and agricultural activities have led to the deterioration of water quality and exacerbated the problems of the availability of good quality water, especially in downstream coastal urban areas and in water-scarce areas (Liu and Diamond, 2005; Vörösmarty et al., 2010). Water contamination is usually categorized by different countries or regions depending on the purpose for which it is used, such as domestic consumption, industrial use, and environmental systems (Johnson et al., 1997). In China, the quality of surface freshwater is assessed based on 29 contaminants and then classified in five grades (I-V): grades I-III are suitable to be treated for drinking water, IV can be used by industry, and V is only suitable for agricultural or environmental use (GB3838, 2002). Water that fails to reach even the quality required for category V is classed as not being suitable for any functional use.

However, in 2012, 32.3% of all China's freshwater sources (river and lake) were categorized as worse than grade III and could not be used for human consumption (MEPC, 2016). In addition, more than 70% of the river reaches in urban areas had water quality of grade IV or worse (MEPC, 2016). As a consequence, 300 cities (45.3% of all China's cities) had severe water shortages due to pollution, and had to build large and complex systems to purify polluted water (Jiang, 2009), consisting of three subsystems: raw water plants, water treatment plants and drinking water equipment (World Water Assessment Program, 2009).

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Shanghai residents recognise that the piped water supply is substandard. In a survey based on a stratified random sampling procedure conducted in 2013 by the University of Melbourne and East China Normal University, only three of the 4,967 respondents said that they would drink the water directly from the public supply system. Residents clearly do not trust the water treatment system and boil the water before use or use commercially available bottled water (Zhen, 2017)

While Shanghai has access to an abundant supply of water, its use is limited as much of the local surface water is grade V or worse (Finlayson et al., 2013). Shanghai has a large water treatment and supply system to meet the freshwater demands of its 24 million inhabitants (Figure 1B). More importantly, Shanghai is one of the most developed cities in China, and while it has abundant primary water quality data recorded at raw water plants and treatment plants, timely access to this data is restricted. In this paper, on the basis of the data available to us, we attempt a holistic assessment of water quality and supply in metropolitan Shanghai. We identify the key issues and risks to water quality from raw water sources to household drinking water. From this, we discuss the potential for improving drinking water quality and provide a prototype reference for better management of raw water sources and supply for the megacity of Shanghai.

2. Shanghai Water Supply System

Shanghai, a city of 24 million, the largest in China, covers 6,340.5 square kilometres and is situated on a peninsula on the east coast of China between Hangzhou Bay and

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the Changjiang Estuary (Figure 1B). The water supply system of Shanghai consists of three sub-systems: raw water plants, water treatment plants and drinking water equipment installed at point of use (Figure 1A). In 2013, the raw water subsystem contained 8 municipal raw water plants (I-VIII, Figure 1B) with a total daily capacity of 16.17×10^6 m^3; the water treatment subsystem included 36 public waterworks (1-36, Figure 1B) with a daily capacity of 11.45×10^6 m^3; and the drinking water subsystem consisted of a 30×10^3 km pipe network, 40×10^3 pressure tanks and 200×10^3 building water tanks (Figure 1B). There are 8 water intake pumps: 4 (Songpu, Jinshan Xietang and Taipuhe) with a total capacity of 6.36×10^6 m^3d^{-1} (39.3% of the total withdrawal capacity) are located on the upper Huangpu River, and 4 (Qingcaosha, Chenhang, Huating and Dongfengxisha) with a total capacity of 9.81×10^6 m^3d^{-1} (60.7% of the total withdrawal capacity) are located on the Changjiang Estuary (Figure 1B).

The water treatment plants are located in 4 zones on the basis of different raw water sources. The Dongfengxisha zone, located on Chongming Island, consisting of 3 urban public water plants (1 to 3, Figure 1B) with a total capacity of only 0.14×10^6 m^3d^{-1} (1.2% of the total supply capacity of Shanghai) sources its raw water from Dongfengxisha Reservoir (Figure 1B); the Chenhang zone consisting of 7 urban public water plants (4 to 10, Figure 1B) with a total capacity of 1.95×10^6 m^3d^{-1} (13.8% of the total supply capacity of Shanghai) sources its freshwater from the Chenhang and Huating reservoirs sited in the upper Changjiang estuary (Figure 1B); the Qingcaosha zone consisting of 12 urban public water plants (11 to 22, Figure 1B) with a total capacity of 6.60×10^6 m^3d^{-1} (57.6% of the total supply capacity) sources its

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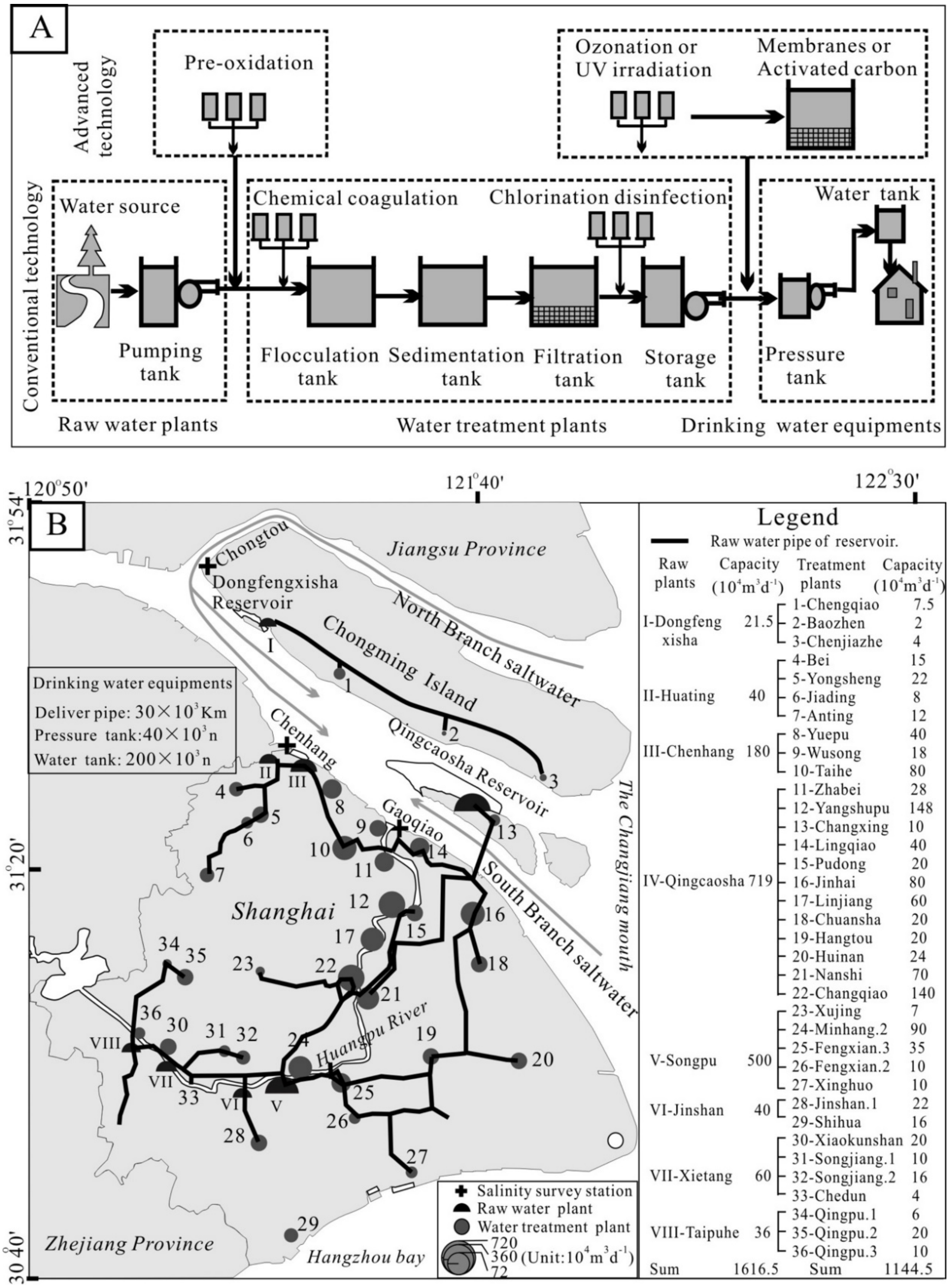

Figure 1. A) Flow chart of the water supply system in Shanghai, B) the distribution of raw water plants, water treatment plants and water delivery pipes in Shanghai in 2013, and the sites where water quality and threat factor data were collected.

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freshwater from the Qingcaosha Reservoir on the Changjiang Estuary (Figure 1B); the Huangpu River zone consisting of 14 urban public water plants (23 to 36, Figure 1B) with a total capacity of 2.76×10^6 m^3d^{-1} (19.5% of the total supply capacity) sources raw water from Songpu, Jinshan, Xietang and Taipuhe plants, all sited on the Huangpu River (Figure 1B).

3. Data Sources and Methods

The location and capacity of raw water plants, water treatment plants and the length of water supply pipes, numbers of pressure tanks and building tanks, were all extracted from local government documents and the online database of the Office of Shanghai Local Chronicles (OSLC, 2012; SWA, 2012).

The Chinese national water quality standards (GB3838, 2002; GB5749, 2006) cover 29 contaminants of raw water and 106 contaminants of treated and drinking water.12 priority contaminants of raw water, and 8 priority contaminants of treated and drinking water were selected on the basis of their severity rating and the health risks as given by the World Health Organisation (WHO, 2010). The 12 priority contaminants of raw water consist of a microbial measure (total bacteria count; TBC) and 11 chemical components: total phosphorus (TP), total nitrogen (TN), ammonia nitrogen (NH^3-N), iron (Fe), manganese (Mn), chemical oxygen demand (COD), dissolve oxygen (DO), mineral oil (MO), detergent, volatile phenols (VP) and mercury (Hg). In addition to TBC, NH^3-N, Fe, Mn, COD, the priority contaminants of treated and drinking water further include 2 acceptability aspects (chromaticity and

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turbidity) and 1 by-product (chlorine) (Figure 2). The details of the data sources are given in Table 1. All priority water contaminants are presented in Figure 2.

For threat factors in raw water, we selected 4 eutrophic factors, TN, TP, COD and algal density, to assess the level of threats of raw water because they serve as essential constituents that drive up other microbial and chemical aspects (Conley et al., 2009; Smith and Schindler, 2009; WHO, 2011). Salinity data from three hydrological stations in the Changjiang estuary (Gaoqiao, Chenhang and Chongtou, Figure 1) is also presented, because reservoirs in the estuary suffer events of saltwater intrusion when salinity exceeds 0.45 psu (practical salinity units) and is not suitable for treatment (Li et al., 2015, Webber et al., 2015). The data sources for eutrophication and salinity of raw water are detailed in Table 1.

Removal rates (%) of fourteen contaminants (chromaticity and turbidity, TBC, TP, TN, NH^3-N, Fe, Mn, COD, detergent, VP, chlorine, chloroform, carbon tetrachloride (CCl_4)) were selected from local water plants to assess the quality of treated water (Table 1). For assessing the quality of water delivered for drinking and household use, 4 contaminants (chlorine, TBC, COD and turbidity) were collected from two papers, Gao et al. (1998) and Zhang and Bai (2008) (Table 1).

By comparing all the key contaminants of raw water, treated water and drinking water based on the national standards of surface water (GB3838, 2002) and drinking water (GB5749, 2006), we elaborate on the risks and vulnerability of the three water supply subsystems.

4 Results

4.1 Variations in the quality of raw water, treated water and drinking water

The maximum values of the 10 priority contaminants of raw water sources of the Qingcaosha Reservoir, Chenhang Reservoir and Huangpu River generally exceeded the national standard for surface water (Figure 2A). Although these contaminants decreased after treatment, the concentration of NH^3-N, Fe, COD and chlorine exceeded the Chinese National Standard for drinking water (Figure 2A, 2B). Furthermore, after water has been delivered to households, some contaminants, such as TBC, NH^3-N, Fe, COD and turbidity have increased in concentration (Figure 2B, 2C).

Different water sources have a large impact on water quality. The mean values of the 10 priority contaminants at the Qingcaosha Reservoir were generally lower than those of the Chenhang Reservoir, and the Huangpu River has overall the poorest quality water. Mean values of 7 contaminants (TBC, TP, NH^3-N, Fe, Mn, COD and detergent) in the Huangpu River were at least double those of the Qingcaosha and Chenhang Reservoirs and exceeded the national standard of grade II water (Figure 2A). In treated water and drinking water, the mean values of the 8 priority contaminants of the Qingcaosha Reservoir were less than those of the Chenhang Reservoir and the Huangpu River (Figure 2B, 2C).

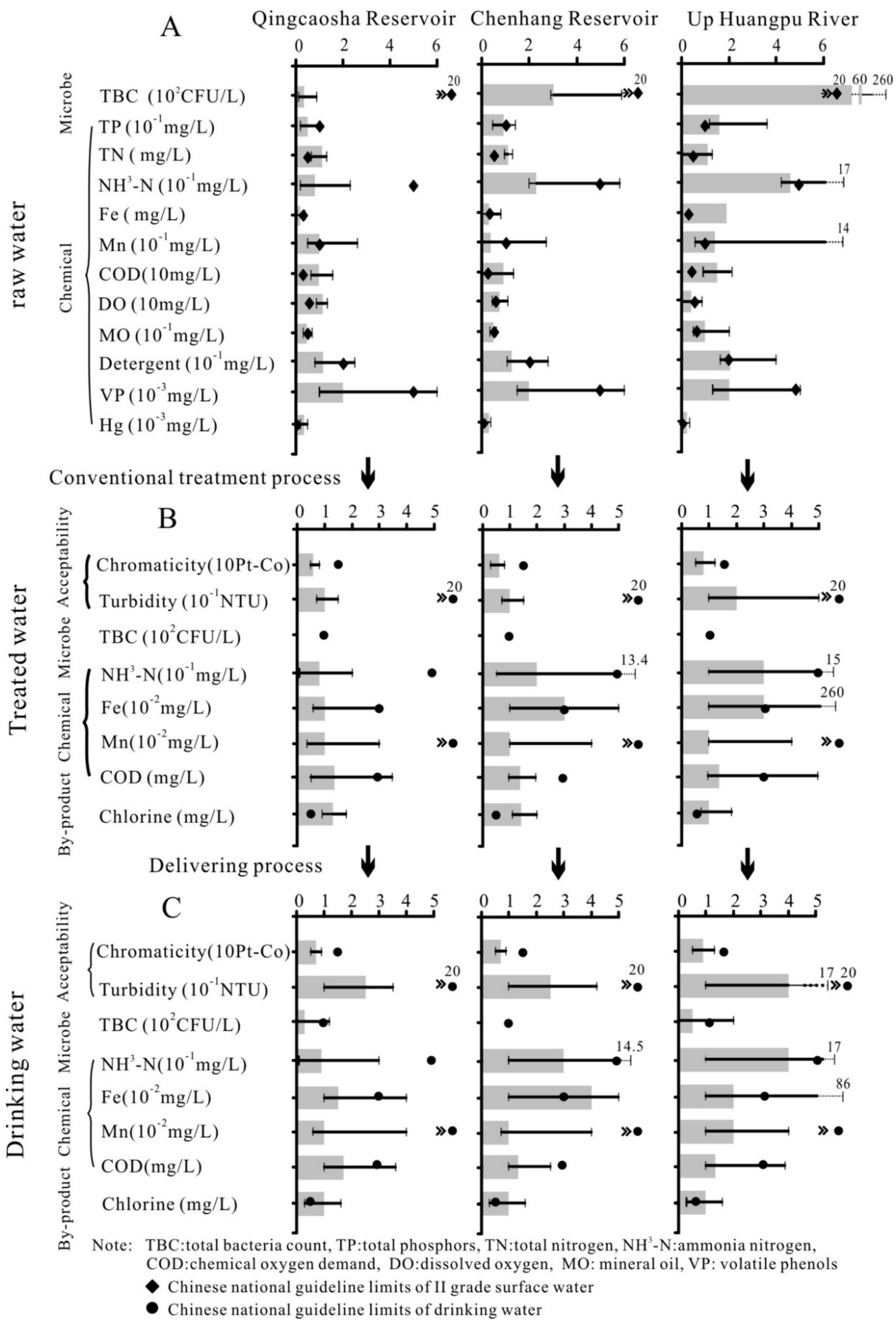

Figure 2. The quality of water from Qingcaosha Reservoir, Chenhang Reservoir and the Huangpu River as it proceeds from raw water (A) to treated water (B) and at its final delivery point (C).

Table 1.

Database name	Different water	Data		Water source	Station	Time	Data source
Water quality contaminants	Raw water	10 contaminants	YRE	QR	IV	2010-2011	(Le and Zhang, 2012; Sun and Yunzhou, 2011)
				CR	III	1992-1996	(Dong et al., 1998)
					III	2005-2009	(Chen et al., 2010)
				UHR	V	1991-1996	(Gao et al., 1998)
					V	1998-2003	(Le et al., 2005)
					V	2005-2009	(Chen et al., 2010)
	Treated water & drinking water	13 contaminants	YRE	QR	15, 16	2010-2011	(Sun and Yunzhou, 2011)
					15, 16	2012	(Mao et al., 2013)
					15,16,17	2013-2016	(SWA, 2013-2016)
				CR	8,9,10	2003-2004	(Le et al., 2005)
					8,9,10	2007	(Sun et al., 2009)
					8,9,10	2012	(Mao et al., 2013)
					8, 9,10	2013-2016	(SWA, 2013-2016)
				UHR	23,23,24	1991-1996	(Gao et al., 1998)
					17, 22	1996-1998	(Chen et al., 2000)
					23, 23, 24	2003-2004	(Le et al., 2005)
					23, 23, 24	2005	(Liu et al., 2007)
					23, 23, 24	2007	(Sun et al., 2009)
					23, 23, 24	2012	(Mao et al., 2013)
					31, 32, 33	2013-2016	(SWA, 2013-2016)
Treats factors	Raw water	Eutrophication	TN, TP, COD	YRE	III	1984-2012	(Chen et al., 2011; Dong et al., 1998; Wang et al., 2014)
				UHR	V	1986-2016	(WRPBTB, 2000-2014)
			Algae	YRE	III	2002-2003	(Chen et al., 2010)
					IV	2010	(Lu, 2011)
					IV	2010-2011	(Zhang, 2012)
				UHR	V	2004-2005	(Chen et al., 2010)
			Salinity	YRE	Chongtou	1979-2011	(Li, 2012; Mao, 1994; Mao et al., 2000; Mao et al., 1993; Tang et al., 2011; Wu, 2006; Xu and Yuan, 1994; Zhu et al., 2010)
					Chenhang	1979-2011	
					Gaoqiao	1979-2011	
	Treated water	Remove rate of 17 contaminants		CR	8	1992-1996	(Dong et al., 1998)
				UHR	24	1991-1996	(Gao et al., 1998)
					24	2005	(Zhang and Bai, 2008)
	Drinking water	Deterioration of 4 contaminants		UHR	24	2005	(Zhang and Bai, 2008)

Note: YRE-the Changjiang River Estuary, QR- the Qingcaosha Reservoir, CR- the Chenhang Reservoir, UHR- the Up Huangpu River; Location of station in figure 1

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Table 1. Data sources for water quality contaminants and threat factors for raw water, treated water and drinking water in Shanghai.

4.2 Variation of eutrophication in the Changjiang Estuary and the Huangpu River

The TN, TP and COD levels in the Huangpu River were generally at least twice those of the reservoirs in the Changjiang Estuary, exceeding the national standard of grade II water (Figure 3A-C). TN, TP and COD increased before the mid-1990s then decreased; however, TN, TP and COD of the Changjiang Estuary have continually increased since the 1980s (Figure 3A-C). Of note, algal blooms occurred in all freshwater sources in the last decade. Algal density in the Qingcaosha Reservoir has increased to 12 ×10^{6} l^{-1} since it began operation in December 2010 (Figure 3D). Similarly, the algal density of the Chenhang Reservoir even reached 30×10^{6} l^{-1} in May 2003 (Figure 3E), and that of the Huangpu River increased to 6 ×10^{6} l^{-1} in the summer of 2005 (Figure 3F).

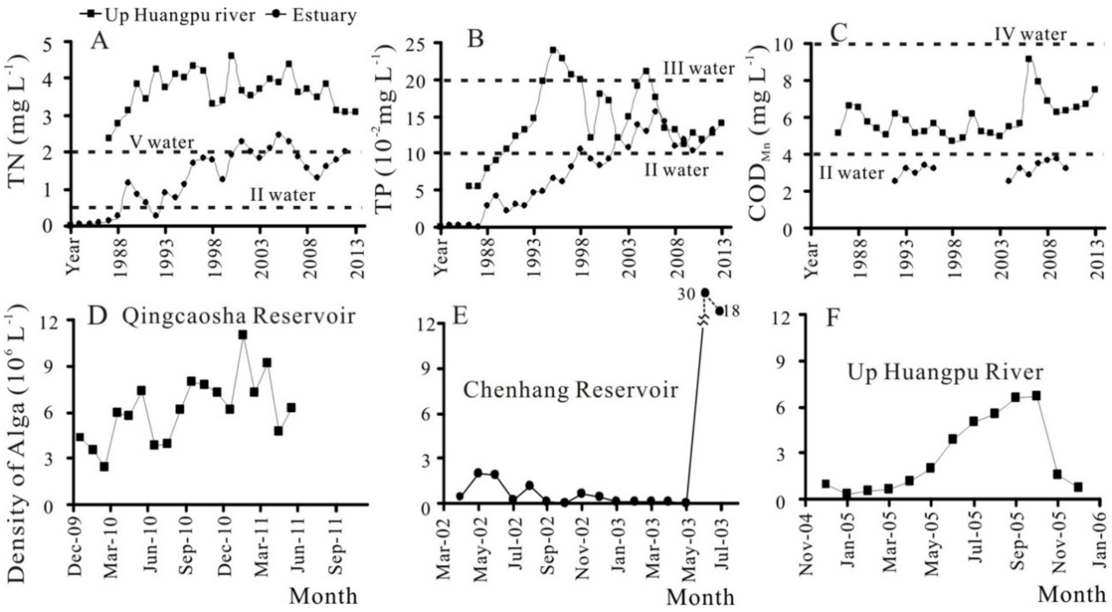


Figure 3. Eutrophication variations in the Changjiang Estuary and the Huangpu River. A) TN variations in 1984-2013; B) TP variations in 1984-2013; and C) COD variations in 1984-2013. Also presented are the algal densities in the Qingcaosha Reservoir (D), the Chenhang Reservoir (E), and the Huangpu River (F).

4.3 Salinity of saltwater intrusion events in the Changjiang Estuary

Salinity in the three estuarine salinity survey stations shown in Figure 4 increased as discharge fell in every saltwater intrusion event in the low flow season. The salinity generally increased from 0 to 6 psu as discharge fell from 20,000 m^{3}s^{-1} to 6,700 m^{3}s^{-1} as recorded at Datong station, the lowest hydrological station on the Changjiang River (Figure 1). Increasing salinity is closely related to lower discharge, especially when it was below 15,000 m^{3}s^{-1} (Figure 4).

The maximum salinity at Chongtou, Chenhang and Gaoqiao were 5.87 psu, 5.06 psu and 5.51 psu which corresponded to discharges of 10,000 m^{3}s^{-1}, 9600 m^{3}s^{-1} and 6,700 m^{3}s^{-1}, respectively (Figure 4). However, when discharge was in the range 15,000-20,000 m^{3}s^{-1}, salinity at Gaoqiao was mainly below 0.45 psu, some occurrences of higher psu occurred at Chenhang, even up to 1 psu, while frequent occurrences of salinity above 0.45 and up to 2 psu occurred at Chongtou, even at discharges close to 20,000 m^{3}s^{-1} (Figure 4). We discuss this pattern in Section 5.3 below.

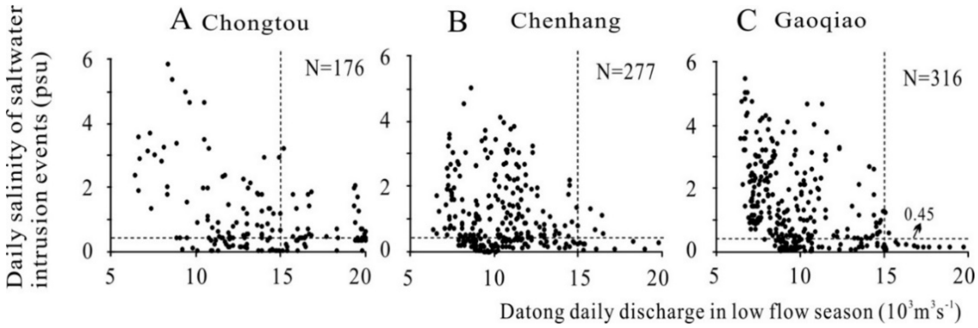
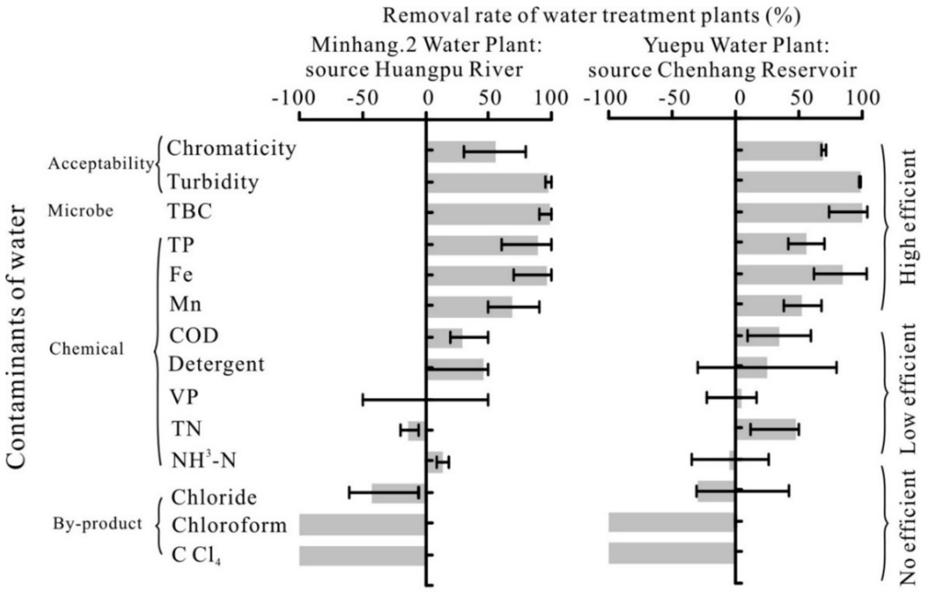


Figure 4. Daily salinity levels at the salinity survey stations in relation to daily discharge (as recorded at Datong with a 7-day lag for travel time to the estuary). A) Chongtou station, B) Chenhang station, and C) Gaoqiao station. Of note: while discharge >15,000 m^3/s, saltwater intrudes mainly from the North Branch, whereas discharge <15,000 m^3/s, saltwater comes from both the South and the North Branches.

4.4 Removal rates of contaminants in treated water

The ability of water treatment plants to remove contaminants is demonstrated here using the removal rate of two water plants, the Yuepu Water Plant, processing water from the Chenhang Reservoir on the Changjiang Estuary, and the Minghang No. 2 Water Plant, sourcing water from the Huangpu River at Songpu (Figure 1, Figure 5) .



Abbr. note: TBC:total bacteria count, TP:total phosphorous, COD:chemical oxygen demand, VP: volatile phenols, TN:total nitrogen, NH^3-N:ammonia nitrogen, $C\,Cl_4$:Carbon tetrachloride

Figure 5. The removal rates 14 contaminants at two typical water treatment plants: A) Minhang No 2 water plant, and B) Yuepu water plant.

Removal rates are shown in %, and negative values indicate increase, rather than removal. The outcomes can be divided into three levels (Figure 5). The removal of chromaticity, turbidity, TBC, TP, Fe and Mn, was highly efficient with rates 50% or greater at both plants. There is low efficiency of removal of COD, detergent and VP, with removal rates ranging from 0% to 50%. The lowest efficiency of removal was for TN, chlorine, chloroform, NH3-N and carbon tetrachloride, had removal rates ranging from 0% to -100% (Figure 5). Note that chlorine is added to provide disinfection during the treatment process and also provides ongoing protection for the water while it is being distributed through the pipe network. However, if the level of Residual Chlorine exceeds 0.05 mg l^{-1} it becomes a contaminant under the Chinese standards for drinking water quality (GB5749, 2006). This occurs when the chlorine demand of the water to be treated is excessively high because of the poor quality of the raw water.

4.5 Changes to chlorine, TBC, COD and turbidity levels in delivery pipes

Changes to water quality are here shown in Figure 6 for water distributed by pipeline over a distance of 21 km from the Minhang No 2 Treatment Plant. Even though Chlorine decreases from 1.9 mg l^{-1} to 1.1 mg l^{-1} during delivery it still exceeds the maximum level of the Chinese national guidelines at the point of consumption (Figure 6A). TBC, COD and turbidity levels increased during delivery, with TBC increasing from 11 × 10^{3} l^{-1} to 45 × 10^{3} l^{-1}, COD increased from 1.2 mg l^{-1} to 3.5 mg l^{-1}, and turbidity increased from 0.09 NTU to 0.3 NTU (Figure 6 B,C,D).

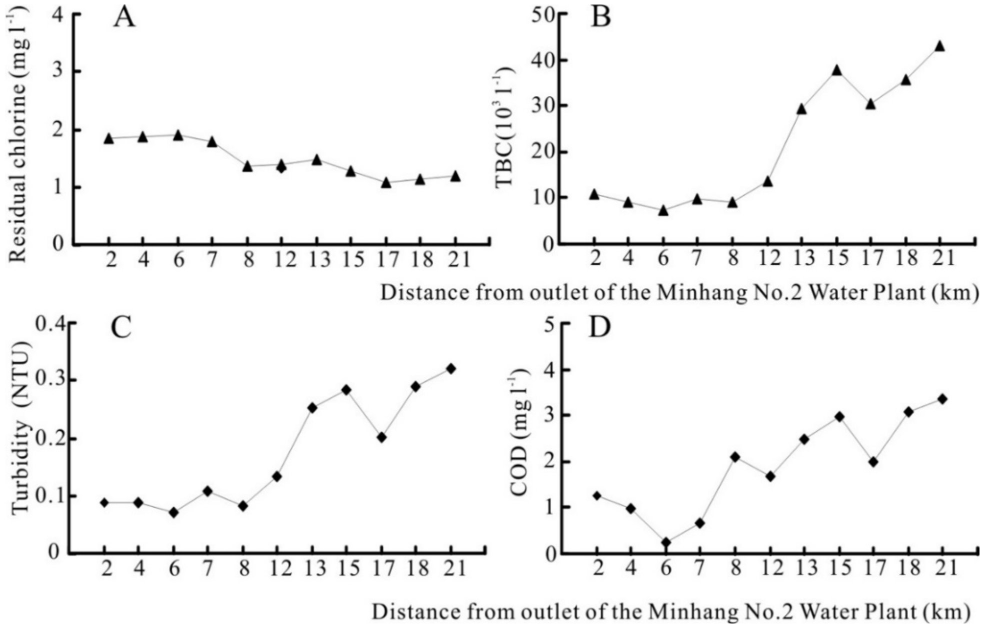


Figure 6. The deterioration of water quality during delivery via water pipeline. A) decreasing residual chlorine, B) increasing bacteria, C) increasing chemical oxygen demand, and D) increasing turbidity.

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5 Discussion

5.1 Water quality: pollutants in raw water

The maximum values of 12 major contaminants at all raw water sources generally exceeded the Chinese National Standard of grade II water and therefore indicate that all of the freshwater sources for Shanghai do not meet the national standard (Figure 2A). The quality of the raw water has been greatly improved by conventional water treatment, in terms of meeting the national standards (GB5749, 2006) (Figure 2A, 2B). However, the maxima of TN, NH^3-N, Fe, COD and Chlorine in treated water and drinking water still exceeded the national standards (GB5749, 2006) (Figure 2B). This indicates that the conventional treatment technology of the current water plants is inadequate in Shanghai. Furthermore, the quality of the treated water is being degraded during delivery through the pipe network due to the poor quality of the distribution system. (Figure 2B, 2C).

Water quality at the Qingcaosha and Chenhang Reservoirs was better than that of the Huangpu sources (Figure 2A). The Changjiang Estuary, as a freshwater source, is far better than the Huangpu River. This is also confirmed by comparing the levels of 8 contaminants in treated water and drinking water (Figure 2B, C). The values of many contaminants in the Huangpu River were 3 times higher than in the Qingcaosha Reservoir. This suggests that the Huangpu River is really no longer suitable to be a source of raw water (Figure 2), and explains why the Shanghai government has been

doi:10.20944/preprints201909.0054.v1

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progressively shifting to sourcing its raw water from the Changjiang Estuary (Finlayson et al., 2013).

5.2 Eutrophication threats to raw water

Eutrophication is known as one of the key threats to water quality globally. Nitrogen and phosphorus are the two essential factors driving eutrophication (Conley et al., 2009; Smith and Schindler, 2009). Increasing concentrations of TN, TP, and COD in the Changjiang Estuary and the Huangpu River indicate that the freshwater resources of Shanghai have remained at a high level of eutrophication since the 1980s when the economic boom began (Figure 3A-C)(Li et al., 2007; Xu et al., 2013). While TN and TP levels continue to be high in the Huangpu River raw water, they have actually declined since the mid 1990s while they continue a steady overall increase in the Changjiang Estuary (Figure 3A,B). Given the shift towards sourcing water from the estuary, these trends are of some concern. Xu et al. (2013) pointed out that the increasing levels of dissolved inorganic nitrogen (DIN) can be attributed to increasing levels of untreated sewage being disposed of in the Changjiang. Their predictions of future DIN concentrations indicate that concentrations would range from 2.2–3.0 mg l^{-1} over the period 2020–2050. This far exceeds the 2.0 mg l^{-1} maximum defined by the national standards and indicates the need for greatly inproved sewage treatment practices in the Changjiang catchment.

As the levels of TN and TP increase, algal blooms have occurred in all Shanghai raw water sources (Figure 3D, E, F). Generally, blue-green algae (*cyanobacteria*) is dominant (Heisler et al., 2008; Smith et al., 2006), especially in the lakes in the

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Changjiang delta, such as Taihu, the source of the Huangpu River (Ye et al., 2011). Blue-green algae not only metabolically produce toxins such as microcystin and anatoxin-a which can damage the liver, intestines and nervous system if ingested (Cheung et al., 2013), but also metabolically produce taste and odour components such as geosmin and methylisoborneol that affect drinking water (Merel et al., 2013). Furthermore, algal blooms also produce many pathogenic bacteria and cause many water-related diseases (Smith et al., 2006). However, little has been published about the algal bloom hazards of the Changjiang estuarine reservoirs. The Qingcaosha Reservoir has a water surface area of 70 km^2, a mean depth of only 6.2 m and a long-term storage time of 68 days. Such conditions readily initiate algal blooms in the high temperatures of the summer and autumn seasons, and the maximum algal density has reached up to 12 $\times 10^6$ l^{-1} (Figure 3D). Although the maximum microcystin concentration (0.55 ug/l) did not exceed the maximum specified by the WHO drinking water standard (1 μg/l), the extreme concentration of methylisoborneol (18 ng/l) has exceeded the threshold for odour (10 ng/l) and caused taste issues in drinking water (Lu, 2011). Therefore, algal blooms have become a severe potential threat to the safety of Shanghai's estuarine raw water reservoirs.

5.3 Salinity threat to estuarine raw water

Salinity is a limiting factor in estuarine freshwater availability as the water cannot be used in the treatment plants with salinity > 0.45 psu (Hong and Shen, 2012; Huang and Foo, 2002; Shen et al., 2003). The salinity variations of the three stations shown in Figure 4 clearly illustrate saltwater intrusions in relation to discharge. While discharge remains below 15,000 m^3s^{-1}, the maximum salinity in downstream sequence of 5.87 psu at Chongtou > 5.00 psu at Chenhang < 5.51 psu at Gaoqiao (Figure 4) shows the salinity at the three reservoirs resulted not only from the saltwater intrusion coming up the South Branch of the main estuary but also from the North Branch around the upstream end of Chongming Island, as shown by the black arrows on the estuary in Figure 1B (Shen et al., 2003; Xue et al., 2009). While discharge remained between 15,000-20,000 m^3s^{-1}, the salinity gradually decreased from upstream Chongtou downstream to Chenhang and Gaoqiao (Figure 4). This indicates that the salinity of the three reservoirs mainly results from the saltwater intrusion coming around the North Branch (Mao et al., 2000; Shen et al., 2003; Xue et al., 2009). The North Branch saltwater intrusion causes the Dongfengxisha Reservoir and the Chenhang Reservoir (15% of the total water supply capacity) to be unable to supply raw water to Shanghai for most of the dry season (about 126 days), when daily discharge is less than 20,000 m^3s^{-1} (Li et al., 2015).

The Qingcaosha Reservoir (IV in Figure 1) now supplies 57.6% of the total water supply to Shanghai and it draws on flow with the same salinity pattern as shown in Figure 4 for the Gaoqiao salinity survey station with very high values especially during the extreme low flow season. There is a probability of an increase in periods of extreme low discharge as about 2000 m^3s^{-1} will potentially be diverted for other cities along the mid-lower Changjiang in the next 50 years, water is now being diverted into the east branch of the south to north water transfer scheme, while local sea level rise in the river estuary of 2 mm y^{-1} will also increase the frequency and severity of saline

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intrusions (Chen et al., 2001; Zhang et al., 2012). Given this, at Qingcaosha by 2040 maximum salinity could reach 9 psu and the duration of saltwater intrusions reach 124 days (Li et al., 2015). This is would mean that the capacity of the Qingcaosha Reservoir would be inadequate as it can store only 68 days of raw water supply for Shanghai.

5.4 Inadequacy of the present water treatment process

The high removal rates demonstrate that the present water treatment technologies are adequate for removing inorganic and biological contaminants. However the low removal rates indicate inadequate technology for removing organic and integrated contaminants such as COD, NH^3-N, detergent, and volatile phenols (Figure 5). The concentrations of COD and NH^3-N in raw water sources indicates that all Shanghai freshwater sources are polluted by organic materials and domestic sewage (Figure 2). The conventional water treatment processes produce many disinfection by-products such as chlorine, chloroform and carbon tetrachloride (Figure 5). The high concentrations of COD, NH^3-N and by-products in drinking water indicate that Shanghai is facing threats from organic and domestic contaminants. This is also a global issue as freshwater becomes more polluted by anthropogenic organic contaminants and disinfection by-products (Heisler et al., 2008; Smith et al., 2006).

The conventional water treatment in Shanghai generally consists of retention-based treatments (chemical coagulation, flocculation and filtration) and degradation-based treatment (chlorination disinfection) (Figure 1A). The inefficiency of removal of COD is due to the present conventional retention-degradation technologies that are unable

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to eliminate the micro and lower molecular weight organics (Dong et al., 2001; Le et al., 2005). It is noted that many advanced retention-based technologies such as activated carbon, membranes and advanced UV irradiation and ozonation have been applied in many developed countries (Chong et al., 2010; Lee et al., 1988; WHO, 2011) to remove micro organics and eliminate the disinfection by-products (Li et al., 2002; WHO, 2010). Currently there are only two water treatment plants in Shanghai that have experimented with advanced water treatment technologies. It is therefore urgent that a long-term strategy for the improvement of Shanghai water treatment processes needs to be developed.

In addition to these problems with standards of treatment, it is also the case that Shanghai has a deficiency in treatment capacity that will become more severe as its population continues to grow. Li et al. (2017) constructed three scenarios of future water needs in Shanghai based on predictions of GDP and population growth to 2050 and showed that water treatment capacity will need to increase by between 35% and 83% beyond present levels.

5.5 Deterioration of drinking water

The decrease in chlorine levels along water delivery pipes reduces its disinfection capability, while the increase in total bacterial count, COD and turbidity along the pipes demonstrates the deterioration of drinking water quality during delivery (Figure 6). As the disinfection capability declines there is a consistent rise in total bacterial

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count, COD and turbidity (Figure 6). Deterioration of drinking water quality would generally cause an increase in microbial and chemical contamination (Lee, 2013).

Bacteria counts increase along the pipe not only because the existing nitrogen and phosphorus removal rates in the treatment plants are below 90%, but also in relation to the decrease in chlorine disinfection (Figures 5, 6). Bacterial growth breeds worms such as red worm (*limnodrilus hoffmeisteri*) in drinking water, which is one of the most severe problems (Sun et al., 2009). The bacterial increase also causes COD to increase along the pipe (Figure 6), and further develops taste and odour components such as geosmin and methylisoborneol which make drinking water smell bad (Merel et al., 2013). In order to prevent bacterial and odour deterioration, excessive chlorine is added to drinking water which explains the obvious smell of disinfection in household drinking water in Shanghai. Better treatment and higher quality raw water would reduce the need for such high chlorine levels.

The turbidity increase along the pipe is partly caused by increased bacteria but is mostly sourced from the corrosion and erosion of concrete and cast-iron pipes and tanks that accounts for 60% of all water supply pipes and tanks in Shanghai. Replacing the ageing concrete and cast-iron pipes and tanks by new steel or plastic composites could gradually improve the household drinking water quality.

6 Conclusions

Water quality for supply to urban areas is determined in terms of common standards of water constituents that ensure the water is safe for human consumption.

The water supply process for most cities consists of three stages: raw water, treated water and drinking water designed to eliminate pollutants. In this study we have dealt with these three stages and the nature of contamination at each stage.

Many of the contaminants reported here have concentrations in the Huangpu River raw water double that of water from the Changjiang Estuary. This has caused the Shanghai government to reduce its historic dependence on the Huangpu River for raw water and to shift its raw water intake to the Changjiang estuary in order to meet the clean water demands of the metropolitan population of 24 million. However, the Changjiang Estuary, like the Huangpu River, also has water quality problems with eutrophication, organic pollution and algal blooms. Furthermore, saltwater, particularly that entering the estuary via the North Branch around Chongming Island, threatens the ability of the estuarine reservoirs to supply water suitable for treatment while the Changjiang discharge is in the range 15,000-20,000 m^3/s, and saltwater in the South Branch would exacerbate salinity while discharge is below 15,000 m^3/s, especially for the Qingcaosha reservoir that supplies 56.7% of Shanghai's raw water.

Large amounts of inorganic and biological contaminants are removed efficiently by water treatment plants. However more than 50% of organic and domestic contaminants such as COD, NH^3-N and some disinfection by-products such as chlorine are still retained in treated water and household drinking water. In addition, bacteria or worms and increased turbidity reappear in the delivery pipes and tanks due to the decrease of residual chlorine and corrosion of cast-iron and concrete pipework and tanks. Therefore, Shanghai must efficiently remove organic contaminants by

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upgrading to advanced treatment technologies such as activated carbon and ozonation and prevent drinking water deterioration during delivery by renewing the old pipe and tank systems. This is a challenge for Shanghai as it involves huge investment and complicated construction procedures in this high density city. Not all of the problems can be dealt with by the Shanghai government alone, as increasing levels of untreated or poorly treated sewage are being put into the river as urbanization increasingly concentrates the population within the catchment.

7 Acknowledgements

This research is funded by the National Key Research and Development Program of China (2017YFC0506000), and the Australian Research Council (P110103381).

References

Chen, G., Chen, J. and Le, L., (2000). Water quality of treatment water of Shanghai. Public Utilities (in Chinese), 14(2): 17-19.

Chen, G., Shen, Y., Meng, M. and Chen, Y., (2010). Characters of water quality of Shanghai and measures of improving water quality to guideline standard until 2012. Water and Wastewater Engineering (in Chinese), 36(11): 24-31.

Chen, H., Sun, C. and Xu, Y., (2011). Analysis of trend of nutrient structure and influencing factors in Changjiang Estuary and its adjacent sea during 23 years. Marine Environment Science (in Chinese), 30(4): 551-553.

Peer-reviewed version available at Water 2019, 11, 2176; doi:10.3390/w11102176

Chen, X., Zong, Y., Zhang, E., Xu, J. and Li, S., (2001). Human impacts on the Changjiang Yangtze River basin, China, with special reference to the impacts on the dry season water discharges into the sea. Geomorphology, 41: 111-123.

Cheung, M.Y., Liang, S. and Lee, J., (2013). Toxin-producing cyanobacteria in freshwater: a review of the problems, impact on drinking water safety, and efforts for protecting public health. Journal of Microbiology, 51(1): 1-10.

Chong, M.N., Jin, B., Chow, C.W.K. and Saint, C., (2010). Recent developments in photocatalytic water treatment technology: A review. Water Research, 44: 2997-3027.

Conley, D.J., Paerl, H.W., Howarth, R.W., Boesch, D.F., Seitzinger, S.P., Havens, K.E., Lancelot, C. and Likens, G.E., (2009). Controlling eutrophication: Nitrogen and phosphorus. Science, 323: 1014-1015.

Covich, A.P., Ewel, K.C., Hall, R.O., Giller, P.S., Goedkoop, W. and Merritt, D.M., (2004). Ecosystem services provided by freshwater benthos. In: D.H. Wall (Editor), Sustaining biodiversity and ecosystem services in soils and sediments. Sland Press, Washington, DC, pp. 45-72.

Dong, B., Cao, D., Fan, J., Li, J. and Xu, Q., (2001). Characteristics of changes in distribution of molecular weight of dissolved organics in Huangpu River water source. Acta Scientiae Circumstantiae (in Chinese), 21(5): 553-556.

Dong, B., Fan, J., Sun, Y., Le, L., Mo, X. and Zhou, Y., (1998). Water quality and treatment technology of raw water sourced from the Changjiang estuary. Water and Wastewater Engineering (in Chinese), 24(5): 6-10.

Finlayson, B.L., Barnett, J., Wei, T., Webber, M., Li, M., Wang, M.Y., Chen, J., Xu, H. and Chen, Z., (2013). The drivers of risk to water security in Shanghai. Regional Environment Change, 13: 329-340.

Gao, N., Le, L., Fan, J., Mo, X., Chen, W. and Tang, Y., (1998). Water quality investigation of Huangpujiang River and Minhang waterworks. Water and Wastwater Engineering (in Chinese), 24(9): 22-24.

GB3838, (2002). Environmental quality standards for surface water (In Chinese). State Environmental Protection Administration of China (editor). China Environmental Science Press, Beijing, 12 pp.

GB5749, (2006). Standards for Drinking Water Quality (In Chinese). Ministry of Public Health of China (editor). Beijing, 12 pp.

Heisler, J., Glibert, P.M., Burkholder, J.M., Anderson, D.M., Cochlan, W., Dennison, W.C., Dortch, Q., Gobler, C.J., Heil, C.A., Humphries, E., Lewitus, A., Magnienie, R., Marshall, H.G., Sellner, K., Stockwel, D.A., Stoecker, D.K. and Suddleson, M., (2008). Eutrophication and harmful algal blooms: A scientific consensus. Harmful Algae, 8: 3-13.

Hong, B. and Shen, J., (2012). Responses of estuarine salinity and transport processes to potential future sea-level rise in the Chesapeake Bay. Estuarine, Coastal and Shelf Science, 104-105: 33-45.

Huang, W. and Foo, S., (2002). Neural network modeling of salinity variation in Apalachicola River. Water Research, 36(1): 356-362.

Peer-reviewed version available at Water 2019, 11, 2176; doi:10.3390/w11102176

Jackson, R.B., Carpenter, S.R., Dahm, C.N., McKnight, D.M., Naiman, R.J., Postel, S.L. and Running, S.W., (2001). Water in a changing world Ecological Applications 11: 1027-1045.

Jiang, Y., (2009). China's water scarcity. Journal of Environmental Management, 90: 3185-3196.

Johnson, D.L., Ambrose, S.H., Bassett, T.J., Bowen, M.L., Crummey, D.E., Isaacson, J.S., Johnson, D.N., Lamb, P., Saul, M. and Nelson, A.E.W., (1997). Meanings of environmental terms. Journal of Environmental Quality, 26: 581-589.

Le, C. and Zhang, H., (2012). Research on the water quality of Qingcaosha water resources. Guangzhou Chemical Industry (in Chinese), 40(3): 135-140.

Le, L., Bao, S., Kang, L. and Zhang, D., (2005). Water quality and treatment strategy of raw water from the up Huangpu River. Water and Wastewater Engineering (in Chinese), 31(7): 26-31.

Lee, M.C., L, V., Snoeyink and Crittenden, J.C., (1988). Activated carbon adsorption of humic substances. American Water Works Association Journal, 73(8): 440-446.

Lee, Y., (2013). An evaluation of microbial and chemical contamination sources related to the deterioration of tap water quality in the household water supply system. International Journal of Environmental Research and Public Health, 10(9): 4143-4160.

Li, L., (2012). Spatial-temporal dynamic characteristics of saltwater intrusion in the Changjiang Estuary, Ph. D. dissertation (in Chinese), East China Normal University, Shanghai, 161 pp.

Li, L., Zhou, Y. and Wang, Z., (2002). Effect of advanced drinking-water treatment techniques on removal of organic pollutants. China Environmental Science (in Chinese), 22(6): 542-545.

Li, M., Chen, Z., Finlayson, B., Wei, T., Chen, J., Wu, X., Xu, H., Webber, M., Barnett, J. and Wang, M., (2015). Water diversion and sea-level rise: potential threats to freshwater supplies in the Changjiang River estuary Estuarine, Coastal and Shelf Science. 156**:** 52-60.

Li, M., Xu, K., Watanabe, M. and Chen, Z., (2007). Long-term variation of dissolved silicate flux from the Yangtze River into the East China Sea and impact of estuarine ecosystem. Estuary, Coastal and Shelf Science, 71: 3-12.

Li M, Finlayson B, Webber M, Barnett J, Webber S, Rogers S, Chen Z, Wei T, Chen J, Wu X, Wang M, (2017), Estimating urban water demand under conditions of rapid growth: the case of Shanghai, Regional Environmental Change, 17:1153–1161

Liu, H., Wu, J., Yao, Z., Ge, Z., Lao, B., Pan, W., Jiang, F., Tang, Y. and Wang, Y., (2007). Investigation of harmful factors to the quality of water supply in Luwan district of Shanghai, Proceeding of International Forum for Public Health. Proceeding of International Forum for Public Health (in Chinese), Shanghai, pp. 137-140.

Peer-reviewed version available at Water 2019, 11, 2176; doi:10.3390/w11102176

Liu, J. and Diamond, J., (2005). China's environment in a globalizing world. Nature, 435: 1179-1186.

Lu, N., (2011). Primary study on water quality variation and algal population dynamics in Qingcaosha reservior, Postdoctoral report (in Chinese), Shanghai, Tongji University, 173 pp.

Mao, J., Zhou, Y., Zhou, X., Ying, L., Yu, S., Cai, Y., Ni, S., Yu, X. and Jiang, C., (2013). Impact of source water and water treatment process on drinking water quality in Shanghai. Journal Environment Occupation Medica (in Chinese), 30(12): 928-930.

Mao, Z., (1994). The salt intrusion character of the South Channel in the Changjiang mouth. Shanghai Water Conservancy (in Chinese), 4: 22-32.

Mao, Z., Shen, H. and Xu, P., (2000). The pattern of saltwater intruding into the Changjiang Estuary and the utilization of freshwater resources. Acta Geograph Sinica (in Chinese), 55 (2), 243-250 (2): 243-250

Mao, Z., Shen, H. and Yao, Y., (1993). Analysis of sources of saltwater intrusion along south bank of south branch of the Yangtze River estuary. Marine Science Bulletin (in Chinese), 12(1): 17-26.

MEPC, (2016). Report on the state of the environment in China. In: Ministry of Environmental Protection of China (editor). http://www.zhb.gov.cn/hjzl/ zghjzkgb/lnzghjzkgb/201706/P020170605833655914077.pdf, 61 pp. (Accessed 26 Aug 2018)

Merel, S., Walker, D., Chicana, R., Snyder, S., Baurèsd, E. and Thomas, O., (2013). State of knowledge and concerns on cyanobacterial blooms and cyanotoxins. Environment International, 59: 303-327.

OSLC, (2012). Chorography of Shanghai public utilities. In: the office of Shanghai Local Chronical Shanghai (editor), http://shtong.gov.cn/node2/node2245/node4516/node55029/node55075/index.html. (Accessed 16 Aug 2018)

Shen, H., Mao, Z. and Zhu, J., (2003). Saltwater Intrusion in the Changjiang Estuary (in Chinese). China Ocean Press, Beijing, 175 pp.

Smith, V.H., Joye, S.B. and Howarth, R.W., (2006). Eutrophication of freshwater and marine ecosystems. Limnology and Oceanography, 51(1): 351-355.

Smith, V.H. and Schindler, D.W., (2009). Eutrophication science: where do we go from here? Trends in Ecology & Evolution, 24(4): 201-207.

SWA, (2013-2016). Report of supply water quality. In: Shanghai Water Authority (editor), http://www.shanghaiwater.gov.cn/shwaterweb/gb/sswj/n32/index.html. (Accessed 10 Jun 2017)

Sun, J., Lu, Y., Zhou, Y. and Tao, C., (2009). Investigation on water quality status of secondary water supply in Shanghai City. Water & Wastewater Engineering (in Chinese), 35(8): 9-12.

Sun, J. and Yunzhou, (2011). The water quality of traditional water plants sourced from the Qingchaosha Reservoir. Water and Wastwater Engineering (in Chinese), 37(8): 39-43.

Peer-reviewed version available at Water 2019, 11, 2176; doi:10.3390/w11102176

SWA, (2012). Report of the 12th five-year plan of renovation and construction of urban water supply facilities in Shanghai. In: ShanghaiWater Authority (Editor), http://www.wsa.gov.cn/1125/manage_view.asp?type_id=218,499&id=3507, 21 pp.

Tang, J., Xu, J., Zhao, S. and Liu, W., (2011). Research on saltwater intrusion of the south branch on the Changjiang Estuary based on measured data. Resources and environment in the Yangtze Basin (in Chinese), 20(6): 677-685.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R. and Davies, P.M., (2010). Global threats to human water security and river biodiversity. Nature, 467: 555–561.

Wang, J., Zhu, Y. and Cheng, C., (2014). Nitrogen change of Chenhang Reservior during recent 10 years. China Water Transport (in Chinese), 14(2): 201-202.

Webber, M., Li, M. T., Chen, J., Finlayson, B., Chen, D., Chen, Z. Y., Wang, M. and Barnett, J., 2015, Impact of the Three Gorges Dam, the South–North Water Transfer Project and water abstractions on the duration and intensity of salt intrusions in the Yangtze River estuary. *Hydrol. Earth Syst. Sci*., **19**: 4411–4425

WHO, (2010). Global annual assessment of sanitation and drinking-water UN-water. World Health Organization press, Switzerland, 16 pp.

WHO, (2011). Guidelines for drinking-water quality. World Health Organization Press, Geneva, Switzerland, 564 pp.

Peer-reviewed version available at *Water* **2019**, *11*, 2176; doi:10.3390/w11102176

WRPBTB, (2000-2016). Water quality report of Taihu basin and southeast rivers. In: Water Resources Protection Bureau of Taihu Basin (editor), Shanghai. http://www.tba.gov.cn/tba/content/TBA/lygb/sjsztb/, (Accessed 10 Jun 2017.)

Wu, H., (2006). Saltwater intrusion in the Changjiang Estuary, Ph. D. dissertation (in Chinese), East China Normal University, Shanghai, 205 pp.

World Water Assessment Program, (2009). The United Nations World Water Development Report 3: Water in a changing world, UNESCO Publishing, Paris. http://www.unesco.org/new/en/ natural-sciences/environment/water/wwap/wwdr/. (Accessed 16 August 2018)

Xu, H., Chen, Z., Finlayson, B., Webber, M., Wu, X., Li, M., Chen, J., Wei, T., Barnett, J. and Wang, M., (2013). Assessing dissolved inorganic nitrogen flux in the Yangtze River, China: Sources and scenarios. Global and Planetary Change, 106: 84-89.

Xu, J. and Yuan, J., (1994). The research on salt-water intrusion into the south branch of the Yangtze estuary. Hydrology, 5: 1-5.

Xue, P., Chen, C., Ding, P., Beardsley, R.C., Lin, H., Ge, J. and Kong, Y., (2009). Saltwater intrusion into the Changjiang River: A model-guided mechanism study. Journal of Geophysical Research, 114(C02006): 1-15.

Ye, W., Tan, J., Liu, X., Lin, S., Pan, J., Li, D. and Yang, H., (2011). Temporal variability of cyanobacterial populations in the water and sediment samples of

Peer-reviewed version available at *Water* **2019**, *11*, 2176; doi:10.3390/w11102176

Lake Taihu as determined by DGGE and real-time PCR. Harmful Algae, 10:472-479.

Zhang, E., Savenije, H.H.G., Chen, S. and Chen, J., (2012). Water abstraction along the lower Yangtze River, China, and its impact on water discharge into the estuary. Physics and Chemistry of the Earth, 47-48: 76-85.

Zhang, H., (2012). The study on algae growth and the formation of toxins in Qingcaosha Researvoir., M.Sc. dessertation (in Chinese), Fudan University, Shanghai, 85 pp.

Zhang, L. and Bai, X., (2008). Variation Rule of Water Quality Indexes in a Waterworks and Its Water Supply System in Shanghai. China Water & Wastwater (in Chinese), 24(11): 64-69.

Zhen, N., 2017, Political Trust in China: Evidence from Water Consumption in Shanghai, Unpublished PhD thesis, School of Geography, University of Melbourne. (https://minerva-access.unimelb.edu.au/handle/11343/191624, Accessed 26 Aug 2018)

Zhu, J., Wu, H., Li, L. and Wang, B., (2010). Saltwater intrusion in the Changjiang Estuary in the extremely drought hydrological year 2006. Journal of East China Normal University (in Chinese) 4: 1-4.