

Seawater desalination in China: an overview

Zhongfan Zhu, Dingzhi Peng and Hongrui Wang

ABSTRACT

China, especially its coastal provinces, is facing water shortage issues, restricting its further development. To tackle the serious imbalance between water resource supply and demand, China has strived to develop alternative water resources to combat the water crisis, among which seawater desalination plays a major role. This paper reviews the current situation of utilization of desalinated seawater in China and includes: (1) a history of seawater desalination classified into three phases; (2) analysis of utilization sectors, geographic distribution and employed technologies of the desalination plants; (3) summaries of the policies, regulations and technological standards governing seawater desalination; (4) proposals for existing problems and some suggested measures regarding the current condition of seawater desalination; and (5) the seawater desalination programs in Tianjin and Zhoushan are presented as two representative examples. China's seawater desalination experience can provide some guidance for other countries facing similar water resource situations.

Key words | China, current status, overview, seawater desalination

Zhongfan Zhu
Dingzhi Peng
Hongrui Wang (corresponding author)
College of Water Sciences,
Beijing Normal University,
Beijing 100875,
China
E-mail: hrwangbnu@163.com

INTRODUCTION

China is facing increasing pressure on fresh water supplies (Yi *et al.* 2011). Its per capita water resource quantity was 2,354.9 m³ in 2016, approximately a quarter of the world's average level, and therefore it has been recognized as one of the 13 lowest water-availability countries throughout the world (Bai *et al.* 2007). Furthermore, the majority of the water resources is concentrated in southern China, leaving the northern and western regions to experience drought (Yi *et al.* 2011; Lyu *et al.* 2016). Some rivers, lakes and underground aquifers have dried up due to the overdraft. Some surface waters have been polluted so that they are no longer suitable for human use (Lyu *et al.* 2016). With population growth, accelerated urbanization and global climate change, shortages of water resources are becoming a key factor restricting economic development in China.

To address the serious disparity between water resource supply and demand, China has taken many measures to conserve and augment the limited water resources to meet the growing demands (Yi *et al.* 2011; Lyu *et al.* 2016). These measures include implementing a very stringent water management system that specifies water efficiency objectives (Wang *et al.* 2015), adjusting the inner structures of primary, second and tertiary industries for a series of water-saving targets (Chao *et al.* 2006), and implementing trans-basin water diversion projects across the country (such as the South-to-North Water Diversion Project) (Zhao *et al.* 2017).

In addition to regular water resources, China strives to develop alternative water resources to tackle water conflict, including wastewater recycling, household-level rainwater harvesting and seawater desalination (Zheng *et al.* 2014). Unlike long distance water transfer, which is uncertain and costly to develop, wastewater recycling has been considered a reliable and less costly water resource, but there are some concerns regarding environmental and health

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (<http://creativecommons.org/licenses/by/4.0/>).

doi: 10.2166/wrd.2018.034

risks for wastewater recycling (Lyu *et al.* 2016). Household-level rainwater collection can provide only limited additional water resources because of the complex climate characteristics in China (Gu *et al.* 2015). With the rapid development of seawater desalination technology, desalinated seawater is playing a more important role in addressing the water shortage issue in China (Zhang *et al.* 2005; Zheng *et al.* 2014).

As an overview, 43% of China's population lives in its 11 coastal provinces with a 1,800 km coastline occupying 13.7% of China's territory (by the end of 2010) (Chinese Statistical Yearbook 2010), and the average water resources per capita in these 11 coastal provinces are only 1,915 m³ (in 2010), much less than the national level (Bulletin of Water Resources in China 2010). Furthermore, urbanization, economic development and industry are much more advanced in coastal areas compared with those in Chinese inland areas, leading to strong water resources pressure in coastal regions. From the Chinese Statistical Yearbook (2010), the Gross Domestic Product (GDP) was 24.6 trillion yuan in 2010 in coastal provinces, accounting for 61.3% of the national GDP. However, the total water resources in coastal provinces only comprise 28.6% of the total national water resources. The total water use in coastal areas is 248 trillion m³, accounting for approximately 41.2% of the total national water use. In coastal areas, 28.1% of the water resources have been used, while the national average water use efficiency is only 19.5% (Bulletin of Water Resources in China 2010). The supply and demand imbalance of water resources in coastal provinces is worsening with increasing levels of urbanization, economic development and population growth (Zheng *et al.* 2014). This promotes the authority to greatly advance the development of seawater desalination as a vital solution in relieving the increasing imbalance between water supply and demand within coastal provinces.

On the global scale, more than 150 countries and regions around the world had engaged in the seawater desalination industry by the end of 2015. The total desalination capacity reached approximately 51.2 million m³ per a day. It is estimated that over 75 million people worldwide obtain fresh water by desalinating seawater or brackish water. Some countries have a large desalination capacity, including the United States, the United Arab Emirates, Morocco, Tunisia and Egypt. Especially, in the Middle East,

seawater desalination is a vital and dependable source of fresh water in countries such as Saudi Arabia, the United Arab Emirates, and Kuwait (Charcosset 2009; El Saliby *et al.* 2009). Saudi Arabia is the world's largest user of seawater desalination, and it has a capacity of 5.25 million m³/d, accounting for approximately 25.9% of the world's total seawater desalination. As the second largest user of desalination in the world, United Arab Emirates has built more than 30 sets of desalination plants, and the annual production capacity of these plants has reached 300 million m³. For Israel, 70% of potable water was being produced by desalination by 2015.

The three commonly used technologies worldwide for seawater desalination include multi-phase flash (MSF), multi-effect distillation (MED) and reverse osmosis (RO). MSF was adopted for water generation in the 1950s, and has advanced significantly since the 1980s. This technology was employed for 26% of total seawater desalination capacity worldwide (Ghaffour *et al.* 2013). MED was the primary technique for desalinating seawater before the 1960s, and this technology has been applied in more large desalination plants (Feng & Xie 2010). RO was applied in seawater desalination in the 1950s. With the advancement of high performance membranes, and installation of energy recovery devices, the cost and energy consumption for this technology has decreased significantly during past decades (Schiermeie 2008; Elimelech & Phillip 2011).

Focusing on China's seawater desalination, this study presents a systematic review of the development of seawater desalination in China. In this study, the history of seawater desalination is introduced in the section 'History of seawater desalination', and the present condition of the utilization of desalinated seawater is presented in detail in the section 'Present condition of utilization of seawater desalination'. Some policies, regulations and technological standards governing seawater desalination are listed in the 'Policies, regulations and technological standards governing seawater desalination' section of this paper. The 'Existing problems and suggestions regarding seawater desalination' section summarizes existing problems and provides some suggestions regarding the current development of seawater desalination. Two representative examples, seawater desalination in Tianjin (a typical northern water-deficient metropolis) and Zhoushan (a typical southern island city

with a sufficient amount of precipitation but still facing a serious shortage of fresh water resources), are presented in the 'Case studies' section as representative case studies. Finally, some simple concluding remarks are offered in the 'Concluding remarks' section.

HISTORY OF SEAWATER DESALINATION

China has carried out research on seawater desalination for approximately 60 years (Tan *et al.* 2007), and there has been significant progress in the development of seawater desalination during past decades (Zheng *et al.* 2014). The history of the development of seawater desalination can be simply divided into three phases, as discussed in this study.

Phase 1

1958–1990 was the phase of laboratory experiments and technological research. In 1958, the National Oceanic Bureau in China started research regarding electro-dialysis (ED) technology (Gao 2003). The Department of the Shipping Industry studied the instruments for pressure distillation and waste heat flash desalination. The reverse osmosis (RO) technology was investigated in the Shandong Institute of the Ocean in Shandong Province. Seawater desalination technologies, such as ED, RO, distillation (multi-stage flash distillation, MFD; pressure distillation; low-temperature multi-effect distillation, LT-MED; multi-effect distillation, MED) were extensively studied across the country from 1967 to 1969. In 1977, standpipe MED equipment was successfully developed in Dalian, Liaoning Province, with a capacity of 10–12 m³ per day. An ED seawater desalination station was established on Yongxing Island of the Xisha Islands in 1981, with a capacity of 200 m³/d (Zhu *et al.* 2014). An MFD seawater desalination project was set up at the Tianjin Dagang Electric Power Plant in 1990, and the project scale was 6 × 10³ m³/d (Zhu *et al.* 2014).

Phase 2

1991–2005 was the phase of industrialization of seawater desalination, including research regarding the technology and equipment for seawater desalination, the construction

of seawater desalination demonstration projects, and studies regarding the strategy, policy and outline of the development of seawater desalination. The first seawater RO desalination station was constructed on Shengshan Island of Zhoushan, Zhejiang Province in 1997, with the project scale of 500 m³/d, satisfying the requirement for drinking water of local residents (Ding 1999; Tan *et al.* 2000). A seawater desalination plant with a capacity of 10³ m³/d was completed on Dachangshan Island of Dalian in 1999, and this plant employed RO technology (Ruan *et al.* 2002). In 2003, a seawater desalination system with a capacity of 5 × 10³ m³/d was established in Rongcheng, Shandong Province, and this system employed RO technology. Furthermore, a seawater desalination project with the capacity of 3 × 10³ m³/d was completed at the Huangdao Power Plant of Qingdao, Shandong Province, and LT-MED technology was adopted in this project (Tan *et al.* 2004; Duan & Tan 2012).

Phase 3

2006–present is the phase of industry development of seawater desalination, including the establishment of the seawater desalination industry system (technology development, equipment manufacturing, project construction, maintenance, technology service, and raw material production) and the establishment of associated policies, standards and management systems, and seawater desalination demonstration projects. In 2005, a large-scale seawater desalination system with a capacity of 1.1 × 10⁴ m³/d was completed at the Datang Wangtan Power Plant in Hebei Province (Zhang 2011). In 2006, an RO seawater desalination plant with a capacity of 1.4 × 10³ m³/h was finished at the Yuhuan Power Plant in Zhejiang Province, and desalinated seawater was used as boiler make-up water (Yu *et al.* 2008; Zhu *et al.* 2014). In 2009, the first desalination plant with a capacity of over 10⁵ m³/d was completed in Tianjin (Zhu *et al.* 2014). Since 2005, the development of seawater desalination projects has increased significantly in China (Zheng *et al.* 2014).

The membrane industry has been well developed in China during the last six decades. Comprehensive applications of microfiltration, ultrafiltration and RO technologies in seawater desalination has advanced greatly. In 2010, the Chinese government released 'Decision of the State

Council on Accelerating the Fostering and Development of Strategic Emerging Industries', and high performance membrane materials were listed as a strategic emerging industry in the decision. This greatly promoted the development and advancement of membrane technology, the membrane industry and the membrane application market. In the 'National Twelfth Five-Year Science and Technology Development Plan' released in 2011, the specific requirement for membrane materials has been outlined, which included 'primarily develop membranes for water treatment, gas separation and speciality separation. Promote applications of membrane technologies in water treatment, iron and steel manufacturing, petrochemical industry and environment protections'. These indicate that membrane technologies, especially RO technology, are playing an important role in promoting the development of the seawater desalination industry in China (Zheng et al. 2014).

PRESENT CONDITION OF UTILIZATION OF SEAWATER DESALINATION

Figures 1 and 2 show the number growth and capacity growth of seawater desalination plants in China during

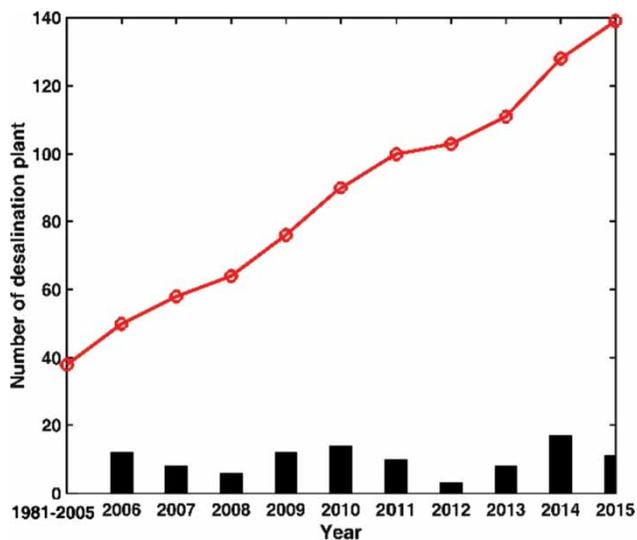


Figure 1 | Number growth of seawater desalination plants in China (the black bar denotes the number in the mentioned year and the red curve denotes the cumulative number value by the mentioned year). The full colour version of this figure is available in the online version of this paper at <http://dx.doi.org/10.2166/wrd.2018.034>.

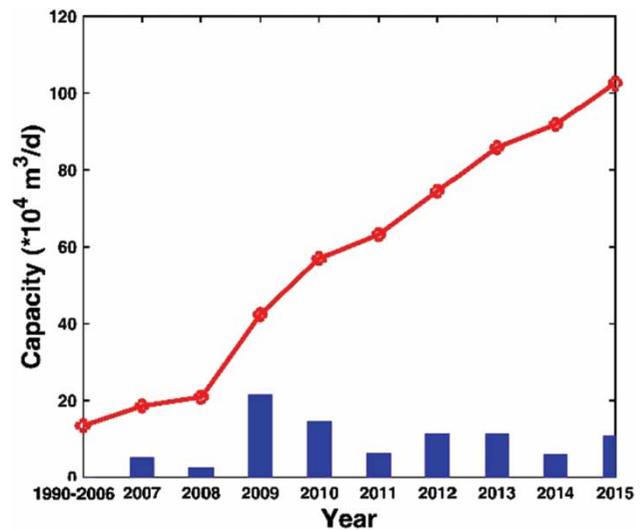


Figure 2 | Capacity growth of seawater desalination plants in China (the blue bar denotes the capacity in the mentioned year and the red curve denotes the cumulative capacity value by the mentioned year). The full colour version of this figure is available in the online version of this paper at <http://dx.doi.org/10.2166/wrd.2018.034>.

1981–2015. It is clear that the development of seawater desalination plants in China has entered a rapid growth phase since 2006. By the end of 2015, there were 139 seawater desalination plants put into operation in China, with a total production capacity of $1 \times 10^6 \text{ m}^3/\text{d}$ (Utilization report of seawater in China 2015). Table 1 lists the 10 largest seawater desalination plants present in China. Furthermore, by the end of 2015, 31 seawater desalination plants with capacities of over $10^4 \text{ m}^3/\text{d}$ were constructed throughout the country with a total capacity of $8.9 \times 10^5 \text{ m}^3/\text{d}$. Approximately 7.2% (10) and 19.4% (27) of the total seawater desalination plants have a capacity from 5,000 to 10,000 m^3/d and from 1,000 to 5,000 m^3/d , respectively, producing approximately $1.2 \times 10^5 \text{ m}^3/\text{d}$ in total. There were 71 seawater desalination plants with capacities below 1,000 m^3/d across China, yielding a new water resource quantity of $1.6 \times 10^4 \text{ m}^3/\text{d}$ (Utilization report of seawater in China 2015).

Utilization sector

Figure 3 shows the distribution of different utilization sectors of desalinated seawater in 2015 (Utilization report of seawater in China 2015). Of the total capacity ($1 \times 10^6 \text{ m}^3/\text{d}$) of seawater desalination plants in 2015,

Table 1 | Ten largest seawater desalination plants in China (Utilization report of seawater in China 2015)

Plants	Capacity (m ³ /d)	Technology	Start-up year	Energy source	Provinces
Tianjin Dagangxinquan SDP	10 ⁵	RO	2009	Electric power	Tianjin
Tianjin SDP of the Beijiang Electric Power Plant, first batch	10 ⁵	MED	2010	Electric power	Tianjin
Tianjin SDP of the Beijiang Electric Power Plant, second batch	10 ⁵	MED	2012	Electric power	Tianjin
Phase I Tianjin SDP of the Beijiang Electric Power Plant	10 ⁵	MED	2012	Electric power	Tianjin
Caofeidian Beikongakeling SDP	5*10 ⁴	RO	2011	Electric power	Hebei Province
Yuhuan Huaneng SDP of an Electric Power Plant	3.5*10 ⁴	RO	2006	Electric power	Zhejiang Province
Iron and Steel Base SDP in Zhanjiang, Guangdong	3*10 ⁴	MED	2015	Electric power, Steam power	Guangdong Province
Shougang Jingtang Iron and Steel SDP, first phase II	2.5*10 ⁴	MED	2010	Electric power, Steam power	Hebei Province
Shougang Jingtang Iron and Steel SDP, first phase I	2.5*10 ⁴	MED	2009	Electric power, Steam power	Hebei Province
Guohua Huanghua SDP of an Electric Power Plant, III	2.5*10 ⁴	MED	2014	Electric power	Hebei Province

Notes: SDP, seawater desalination project; MED, multi-effect distillation. Geographic locations of provinces in the right-hand column can be found in Figures 4 and 5.

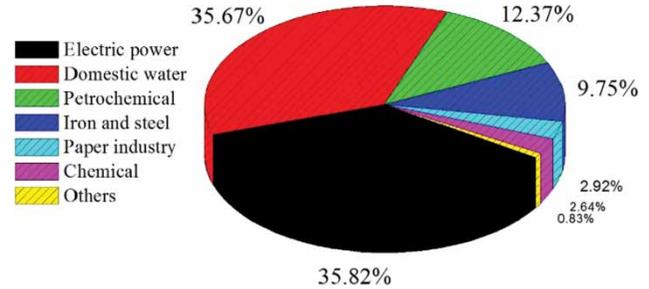


Figure 3 | Distribution of utilization sectors of China's desalinated seawater capacity in 2015.

6.5 × 10⁵ m³/d was adopted by industry, accounting for 63.6%, while 35.7% of desalinated seawater has been used for domestic living of residents, with a capacity of 3.7 × 10⁵ m³/d. The remaining 0.8% has been adopted in other sectors, such as shipping, harbour service and military affairs.

In industrial applications, the power generation industry accounts for the greatest portion, 35.8%; the petrochemical and iron and steel industry comprise 12.4% and 9.8%, respectively; and approximately 2.9% and 2.6% have been utilized in the paper and chemical industries, respectively. In summary, the power generation industry, domestic life of residents, petrochemical industry and iron and steel manufacturing are the four largest consumers of desalinated seawater in China.

In the power generation industry, desalination plants are used to produce boiler make-up water. This is because local authorities in coastal regions are greatly encouraging seawater desalination plants to adopt desalination technology to provide water (Zhu et al. 2012). With the policy incentives and further development of desalination technology, seawater desalination could provide the majority of boiler make-up water for power plants in the future (Man et al. 2014).

At present, the water price in China is relatively high due to the high costs associated with the production, distribution, maintenance and management of domestic living water and strong requirements for its water quality. With the advancement of seawater desalination technologies and the construction and distribution of large-scale seawater desalination plants, the cost of the desalinated seawater will decrease (Zhang et al. 2005; Zheng et al. 2014). Seawater desalination plants would produce a large amount of water for the domestic living needs of residents within coastal regions.

Desalination plants can reuse the heat and steam generated in the petrochemical and iron and steel industries. Therefore, seawater desalination plants can not only produce reliable water resources but can also reuse heat and steam, reducing the associated costs (Zhou 2009; Shi et al. 2012). It is possible that more petrochemical and iron and steel industries could adopt seawater desalination technology in order to provide more water resources.

Geographic distribution

Figures 4 and 5 show the geographic distributions of the number and the capacity of seawater desalination plants along the Chinese coastline by the end of 2015

(Utilization report of seawater in China 2015). There are many seawater desalination projects with a wide geographic distribution, ranging from the eastern sea of Liaodong Island (to the north) to the South China Sea (to the south). In terms of number, most of the desalination plants were located in four provinces: Zhejiang, Shandong, Liaoning and Hainan. From the perspective of capacity, the majority of the desalination plants were concentrated in the six provinces of Tianjin (an autonomous city), Zhejiang, Hebei, Shandong, Guangdong and Liaoning. Forty-five seawater desalination plants were put into operation in Zhejiang, with a total capacity of $2 \times 10^5 \text{ m}^3/\text{d}$. Only nine desalination plants were in Tianjin, but the total capacity reached $3.2 \times 10^5 \text{ m}^3/\text{d}$,

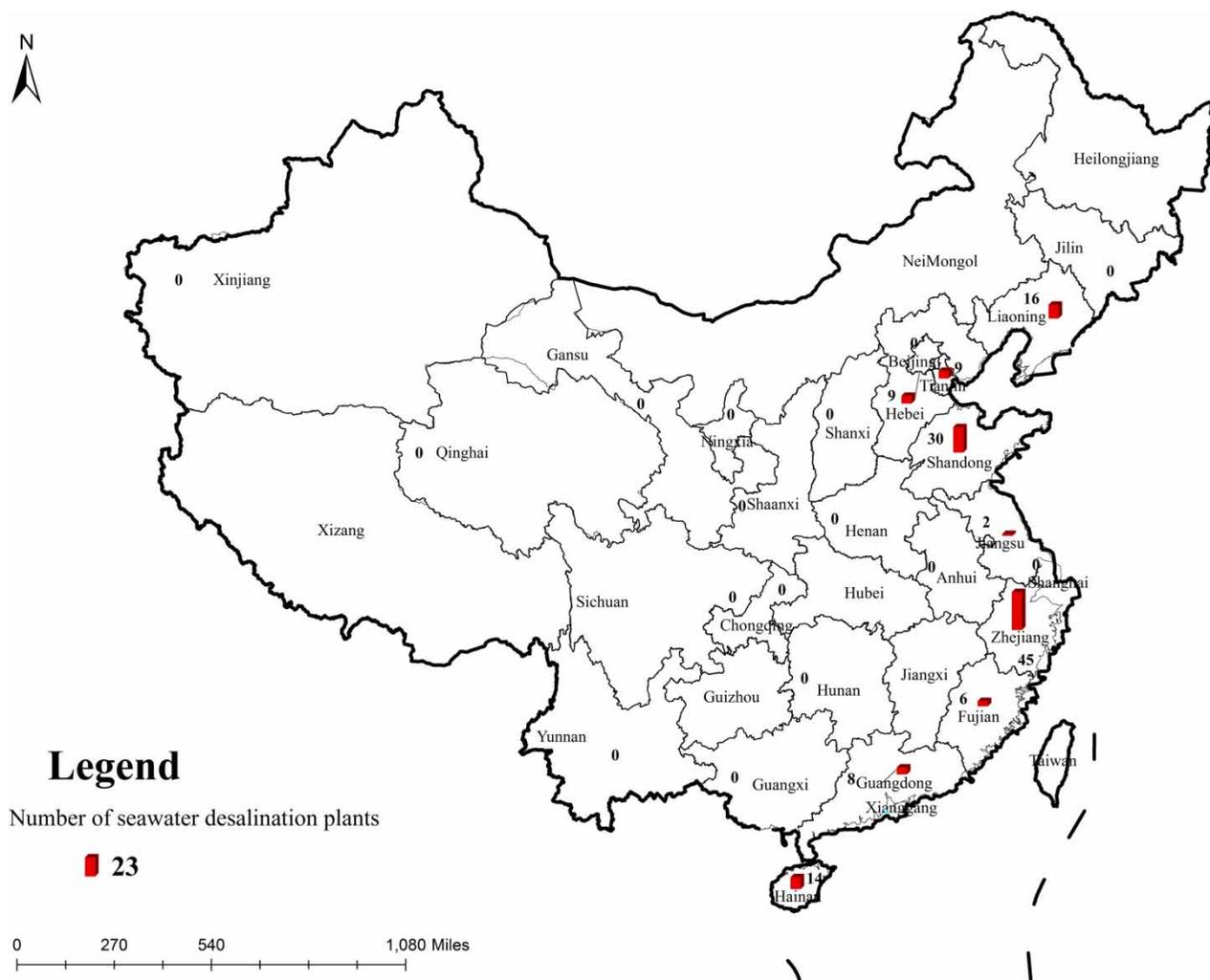


Figure 4 | Distribution of the number of seawater desalination plants within coastal provinces in China by the end of 2015.

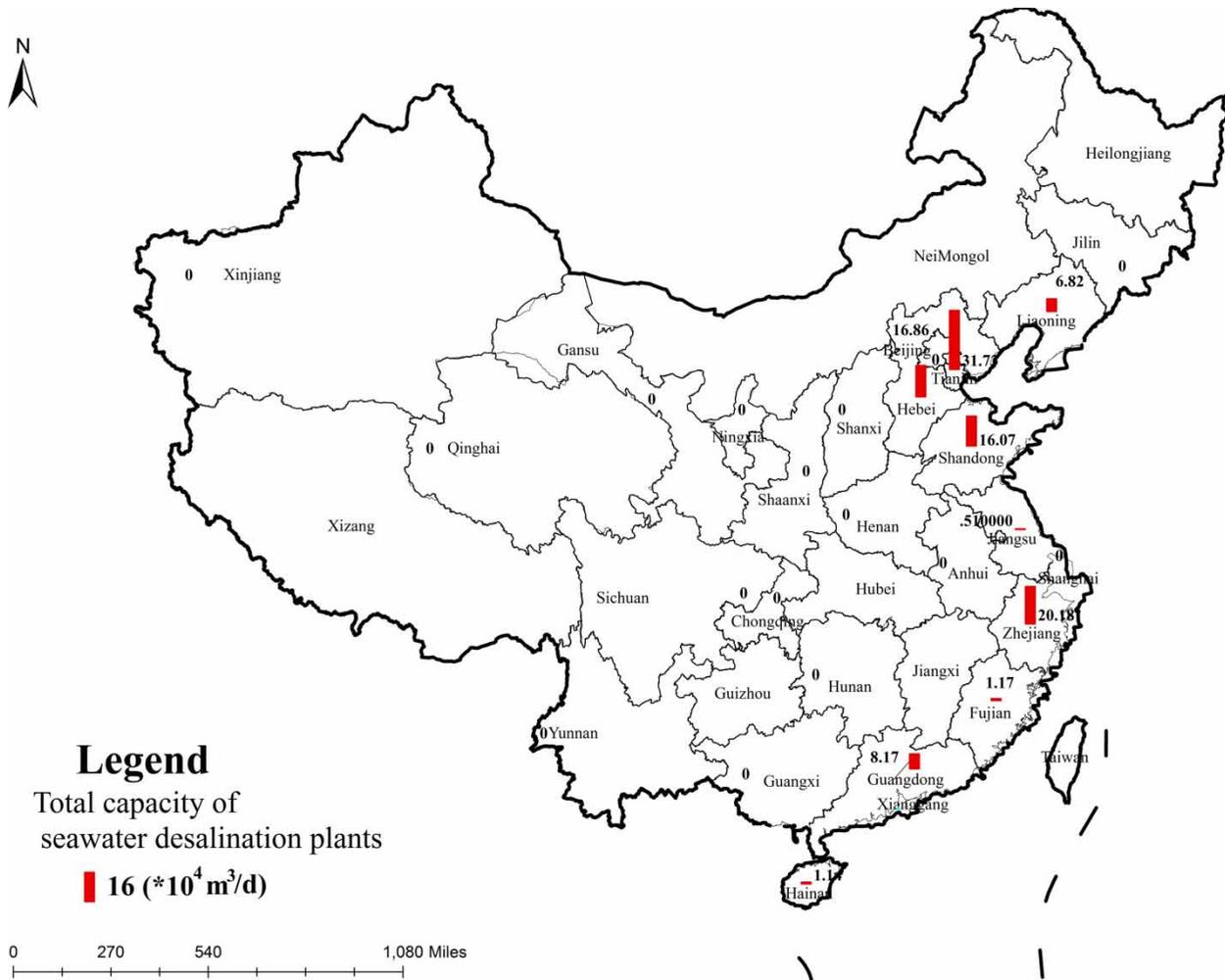


Figure 5 | Distribution of total capacity of seawater desalination plants within coastal provinces in China by the end of 2015.

showing there were some large-scale plants in Tianjin. There were 30 desalination plants in Shandong, with a total capacity of $1.6 \times 10^5 \text{ m}^3/\text{d}$, whereas only nine seawater desalination plants were constructed in Hebei, but they had a capacity of $1.7 \times 10^5 \text{ m}^3/\text{d}$. There were 16 and eight desalination plants in Liaoning and Guangdong Provinces, yielding 6.8×10^4 and $8.2 \times 10^4 \text{ m}^3/\text{d}$ of water, respectively. The other 22 seawater desalination plants were set up in Fujian, Jiangsu and Hainan Provinces, but they produce a smaller total capacity of $2.8 \times 10^4 \text{ m}^3/\text{d}$. The desalination plants in northern China focused on large-scale projects for industrial needs, whereas the desalination plants in southern China focused on island projects for domestic living objectives (Zhu et al. 2012).

Desalination technology

Figure 6 shows the distributions of the number and the capacity of seawater desalination plants with different desalination technologies by the end of 2015 (Utilization report of seawater in China 2015). Most desalination plants have employed RO and/or MED technologies. For the number of desalination plants, 120 seawater desalination plants have adopted RO technology, and 17 desalination plants have employed MED technology to desalinate seawater. There was only one of each type of desalination plant that used MSF or ED technology. In terms of the capacity, the capacity of desalination plants with RO technology is $6.6 \times 10^5 \text{ m}^3/\text{d}$, accounting for approximately 63.9% of the

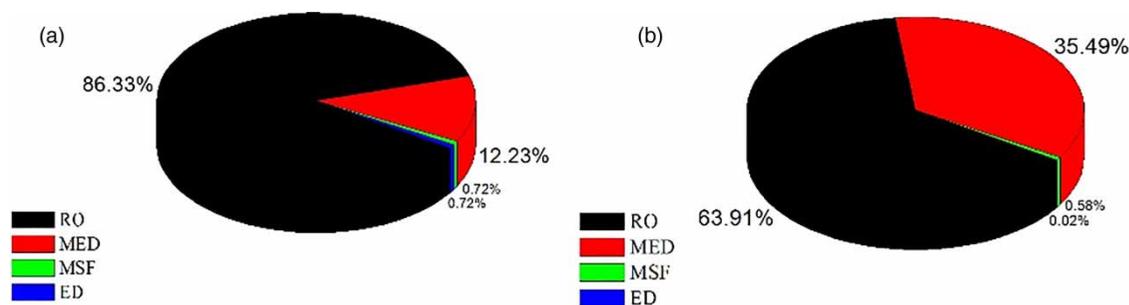


Figure 6 | (a) Number and (b) capacity (m^3/d) of seawater desalination plants with different desalination technologies by the end of 2015 (MSF is multi-stage flash distillation technology).

total capacity, whereas the desalination plants using MED technology have a total capacity of $3.6 \times 10^5 \text{ m}^3/\text{d}$, even though there are only 17 plants, showing that MED technology is generally used for large-scale desalination plants. The capacities of seawater desalination plants using other technologies such as MSF and ED are 6,000 and $200 \text{ m}^3/\text{d}$, respectively, accounting for only 0.6% and 0.02% of the total capacity.

The major drawback of RO technology is that the semi-permeable membrane in the RO system is very sensitive to oxidants, organisms, algae, bacteria, and other pollutants contained in the seawater, as well as the pH of the seawater. Hence it is necessary to carry out rigid pre-treatment towards seawater. Scale and fouling easily happen on the surface of the semipermeable membrane, consequently leading to a declining ratio of desalination and unstable water quality. Therefore it is necessary to wash and replace the semipermeable membrane in a timely manner (Zheng et al. 2016).

For MED technology, because the heat transfer coefficient for phase transition increases with rising temperature, a low top-brine temperature will hinder the improvement of heat efficiency. Scale deposits easily form on the outer wall of the heat exchange tube of MED systems. Hence it is important for a timely cleanout of the heat exchange tube to dislodge the scale, in order to maintain the effective operation of the desalination system (Zheng et al. 2016).

The major drawback of MSF desalination technology lies in the fact that structural materials are prone to corrode, and seawater is easily leaked into the condenser pipe when corrosion failure happens. Additionally, the MSF system needs an amount of seawater to circulate, leading to a large power consumption for the pump (Zheng et al. 2016). For ED technology, ions will gather on the surface of the electrode and the ion exchange membrane, consequently

leading to the formation of scale deposits. Additionally, it should be noted that there are some new methods (such as microbial desalination cells) for water desalination in the literature (e.g. Cao et al. 2009; Chen et al. 2011).

POLICIES, REGULATIONS AND TECHNOLOGICAL STANDARDS GOVERNING SEAWATER DESALINATION

At present, some policies and regulations have been published in nine provinces of the total of 11 coastal provinces. These are listed in Table 2.

At the country scale, seawater utilization had been incorporated as an important issue into some formal files by the end of 2015, including 'Suggestions on the Thirteenth Five-Year Planning of Economy and Social Development Formulated by the Central Committee of the Communist Party of China', 'Suggestions on Speeding Up the Construction of Ecological Culture issued by the Central Committee of the Communist Party of China and the State Council', and 'Water Pollution Prevention and Control Plan' issued by the State Council.

By the end of 2016, China had published 115 technological standards to govern the development and utilization of seawater desalination, including 23 national standards, 91 professional standards, and one provincial standard. These 23 national standards are listed in chronological order in Table 3.

The publishing of these policies, regulations and technological standards has played a critical role in the rapid development of the seawater desalination industry in China during the past decades, significantly relieving the

Table 2 | Policies and regulations governing seawater desalination within coastal provinces

Number	Province	Name of policy and regulation	Publishing date	Content introduction
1	Tianjin	Measure regarding the utilization of new water resources in economically developed region of Tianjin		Encourage wastewater reuse, desalinated seawater, desalinated brackish water, as well as other new water resources
2	Hebei Province	Subject plan for seawater utilization in Hebei Province	2005	Focus on the direct utilization of seawater, desalinated seawater and comprehensive utilization of chemical resources of seawater
		Control regulations on groundwater in Hebei Province	Nov. 28, 2014	Actively advance the utilization of alternative water resources, including rainwater, reclaimed water, seawater and brackish water
		Implementation of an outline regarding the protection of water safety	Mar. 7, 2015	Encourage local authorities to construct reclaimed water projects, enhance the utilization of brackish water, and speed up the construction of seawater desalination projects
3	Liaoning Province	Management regulations regarding water resources in Dalian, Liaoning Province	Aug. 30, 1994	Integrated planning for reclaimed water and seawater desalination, the allocation management and the promotion of the development of reclaimed water and seawater desalination
4	Jiangsu Province	Implementing opinions regarding the implementation of the most stringent water resources management system in Jiangsu Province	Jun. 28, 2012	Spread wastewater reuse in enterprises, and encourage and speed up the development and utilization of alternative water resources, including wastewater reuse, rainwater and seawater
5	Zhejiang Province	Notification regarding the planning of the industry development of seawater desalination industry during the 'Thirteenth Five Year Plan'	Jun. 9, 2013	Analyse the situation and present condition of seawater desalination in Zhejiang Province, identify the guiding objective and basic principles
		Notification regarding the adjustment of electricity prices by the National Development and Reform Commission, by the administration of commodity prices, Zhejiang Province	Oct. 25, 2013	Electricity use for seawater desalination should apply the electricity price for agricultural production from December 1, 2013
		Implementing scheme regarding the infrastructure construction of the special seawater industry in Hangzhou, Zhejiang Province	Oct. 14, 2014	Put forward the base construction of seawater desalination technology and equipment manufacturing, and gradually improve the industry system of seawater desalination
6	Fujian Province	Implementing opinions regarding the implementation of the most stringent water resources management system, Fujian Province	Feb. 21, 2013	Encourage the development of wastewater reuse, rainwater and desalinated seawater in water-deficit regions
		Regulations regarding the municipal water supply and water saving in Xiamen, Fujian Province	Aug. 4, 2006	Local governments should encourage and support the development and utilization of wastewater, reclaimed water, seawater and rainwater
		Regulations regarding water saving in Fujian Province	Sep. 16, 2015	Encourage and support the collection, development and utilization of rainwater and reclaimed water. Suggest the integration of seawater utilization into a comprehensive water resources allocation
7	Shandong Province	Opinions regarding enhancing seawater utilization	Apr. 29, 2007	Identify the principle, objective and development focus of seawater utilization
8	Guangxi Province	Implementing opinions regarding speeding up industry transformation by applying the most stringent water resources management	April, 2012	Encourage the utilization of alternative water resources, reasonably use the reclaimed water, rainwater and seawater
9	Hainan Province	Water regulations in economically developed regions, Hainan Province	May 1, 2010	Augment the utilization of alternative water resources, such as reclaimed water, rainwater and seawater; construct sewage treatment facilities when constructing municipal water supply facilities

Table 3 | National technological standards governing seawater desalination at the end of 2016

Number	Standard number	Standard nomenclature
1	GB/T19249 – 2003	Reverse osmosis water treatment equipment
2	GB/T 20103 – 2006	Technological nomenclature for membrane separation
3	GB/T 20502 – 2006	Nomenclature for membrane assembly and equipment model
4	GB/T 22413 – 2008	Technological guide for the evaluation of the engineering environment of comprehensive seawater utilization
5	GB/T 23248 – 2009	Treatment and plan specification for seawater recycling cooling water
6	GB/T 23954 – 2009	Technological specification for the cleanout of the reverse osmosis membrane system
7	GB/T 23609 – 2009	Seamless tube made of copper alloy for seawater desalination equipment
8	GB/T 25279 – 2010	Membrane assembly of fibre curtain
9	GB/T 50619 – 2010	Planning specification for seawater desalination engineering in thermal power plants
10	GB/T 16166 – 2013	Cathodic protection (anodic sacrifice) in seawater cooling systems in coastal electric power plants
11	GB/T 30070 – 2013	Seamless tube made of alloy steel for seawater transport
12	GB/T 30299 – 2013	Common technological specifications for reverse osmosis energy recycling equipment
13	GB/T 30300 – 2013	Shell for separation membrane
14	GB/T 30665 – 2014	Closed bottle method for biodegradation in chemical seawater
15	GB/T 31316 – 2014	Guide on cathodic protection in seawater
16	GB/T 31327 – 2014	Planning specification for membrane system in the pretreatment of seawater desalination
17	GB/T 31328 – 2014	Management specifications for reverse osmosis system maintenance in seawater desalination
18	GB/T 31404 – 2015	Technological specification for anti-corrosion operation in seawater circulation system of nuclear power plants
19	GB/T 32359 – 2015	Test and evaluation method for reverse osmosis membrane equipment in seawater desalination
20	GB/T 32373 – 2015	Test method for reverse osmosis membranes
21	GB/T 32361 – 2015	Test method for pore size of separation membranes
22	GB/T32569 – 2016	Stainless steel pipe for seawater desalination equipment
23	GB/T51189 – 2016	Test and examination specification for seawater desalination engineering in thermal power plants

serious situation of the imbalance between water supply and water demand within coastal provinces.

EXISTING PROBLEMS AND SUGGESTIONS REGARDING SEAWATER DESALINATION

Existing problems

Lack of legal security and insufficient policy support

At present, the Water Law of China does not incorporate the utilization of seawater into the category of water resources and does not specify the responsibility and obligation regarding seawater use, leading to a lack of legal security for the promotion of seawater utilization-related policies

(Chen *et al.* 2015). There is also insufficient policy support for the utilization of desalinated seawater at present. The capital investment for industry development could not be completely guaranteed, and seawater desalination is not also incorporated into the subsidy range provided by the government (Zhang *et al.* 2005). The policy related to the investment and water price subsidy remains incomplete. At present, a rational market mechanism for the development and utilization of water resources including seawater desalination is not formed.

Relatively high cost of desalinated seawater compared with tap water

The cost of seawater desalination is comprised of the investment, operation and maintenance, and energy consumption costs. The operation and maintenance cost

includes maintenance, chemicals, membrane exchange, management and labour. With the advancement of seawater desalination technology and the increase in capacity, the cost for seawater desalination has decreased, concentrating at 5–8 yuan/m³ in China, but when compared with tap water, this cost is still high. This may lead to a decrease in competitive benefits of desalinated seawater compared with other alternative water resources (Liu *et al.* 2010; Zheng *et al.* 2014; Chen *et al.* 2015).

Difficulty in putting desalinated seawater into municipal pipelines and overcapacity

The capacities of seawater desalination plants are different depending on their utilization objectives. At present, desalination plants for domestic living of island residents operate with different capacities according to the water needs of residents, while those desalination plants for industrial use have capacities adjusted according to the industrial water need. However, for some desalination plants for water use in both domestic living and industry, their actual capacities are low because there is a constraint for putting desalinated seawater into municipal pipelines (Wang *et al.* 2013; Chen *et al.* 2015). For example, it has been reported that there is some idle capacity in desalination plants in Tianjin, China (Wang *et al.* 2011).

Obstacle in the industrialization of seawater desalination industry

At present, there are only small-scale enterprises that could carry out equipment manufacturing for seawater desalination and associated projects, and a weak foundation for manufacturing hinders the industrialization of seawater desalination technology (Zhou 2009; Duan & Tan 2012; Zhu *et al.* 2012). Furthermore, the construction of seawater desalination plants is in an isolated and scattered state (Chen *et al.* 2015). The large-scale companies that have strong competitive power around the world in the field of equipment manufacturing for seawater desalination have not appeared in China until the present. International desalination companies will still dominate the seawater desalination market for the foreseeable future (Zheng *et al.* 2014). The market in China still needs activation.

Independent innovation ability for seawater desalination technology

At present, there are a few key seawater desalination technologies that have self-help intellectual property rights, and there is a relatively weak ability for equipment manufacturing in China (Duan & Tan 2012; Zhu *et al.* 2012). Most seawater desalination plants, especially with capacities of over 10⁴ m³/d, have employed imported technologies from international desalination companies (Chen *et al.* 2015). For example, for some key materials and equipment in RO desalination instruments, such as energy recovery equipment, the seawater membrane unit, high-pressure pumps and some chemical materials, China should still import them from international desalination companies due to the immature technology and a long period needed for their final applications in China (Ruan 2008; Chen *et al.* 2015). Additionally, some technologies in which desalination technology, nuclear energy, wind energy and solar energy are coupled together are in the preliminary development phase, and a long time is needed for their final applications in China.

Environmental risks due to concentrated seawater and high waste heat from desalination plants

In the process of seawater desalination, a large amount of concentrated seawater (brine) will be produced. At present, there are two kinds of comprehensive utilization methods for brine. The first kind is direct discharge of brine: discharge brine into ocean, surface water and sewage treatment systems directly through the pipeline, or lead it into an evaporation tank or bore. This method does not need any treatment measures, and can only be applicable for small-scale discharge of brine (Yu *et al.* 2017; Dai *et al.* 2018). The direct discharge of brine will damage the coastal water environment (Yu *et al.* 2005; Zhang *et al.* 2010). Additionally, the waste heat discharged from the seawater desalination process could increase the seawater temperature of regional waters, resulting in rapid reproduction and highly dense phytoplankton, and sometimes a phenomenon termed 'harmful algal blooms' occurs in some coastal waters (Ma 2008; Nie & Tao 2008). The increasing seawater temperature lowers the concentration of dissolved oxygen in

seawater, influences the metabolism of organisms, and finally causes deterioration of the living environment of organisms (Zhou 2009). For example, seawater desalination facilities were identified as the potential reason for harmful algal blooms in the sea area of 1.6×10^5 km² around Huanghua, Hebei Province (Ma 2008).

The second method is resource reuse of brine: salt manufacturing, and extraction of chemical raw materials (Yu et al. 2017; Dai et al. 2018). Circumfluence and distillation are two common methods adopted for small-scale brine treatment in China. There are some developed technologies for the comprehensive utilization of brine, including multi-effect distillation of brine, softening of calcium and magnesium of brine, salt-making method of brine, and bromine and potassium extraction from brine (Dai et al. 2018). Zero discharge technology is an ideal way of brine treatment. It not only protects the water environment and ecological balance of the inner sea, but also recycles brine resources and provides resource guarantee for economic development. This technology adopts the evaporator, brine concentrator and crystallizer to complete the separation of chemical products (such as calcium chloride, calcium carbonate and sodium carbonate) from water. There is potential for zero-discharge technology to be applied to large-scale brine treatment in China (Yu et al. 2017).

Public involvement and receptivity towards the use of desalinated

The successful implementation of seawater desalination projects heavily depends on public involvement and a positive attitude towards desalinated seawater (Fielding et al. 2015; Hurlimann & Dolnicar 2016). At present, the public lack strong knowledge of the role that seawater desalination plays in the integrated water resources supply system, and people are more or less concerned about environmental and health risks related to the utilization of desalinated seawater (Yu et al. 2005; Zhang et al. 2010).

Some suggested measures

With the abovementioned existing problems in mind, we propose the following suggested measures.

Setting up a complete legal system related to seawater desalination

It is necessary to set up a complete legal system related to seawater desalination according to the strategic requirements and actual demand for sustainable utilization of water resources, promoting the utilization of seawater desalination in a gradually standardized and legal manner (Chen et al. 2015). The law related to seawater desalination should specify the responsibility and obligations for individuals and enterprises using desalinated seawater, especially specifying the legal responsibility to those individuals and enterprises who can adopt the desalinated seawater but still do not use it.

Decreasing the costs related to seawater desalination

It is of great importance to decrease the effective cost of seawater desalination by coupling it with some production segments, such as solar electrical energy generators, wind electrical energy generators, heat systems, seawater desalination, and salt chemical production, forming a comprehensive utilization system of resources and expanding the industry chain of seawater desalination. Meanwhile, it is also of vital importance to strengthen the competitive power of the seawater desalination industry by combining it with regional water resources demand and by producing salted and bottled water in China (Liu et al. 2010; Zheng et al. 2014).

Perfecting supporting policies for the development of seawater desalination

It is necessary to adopt a 'market-oriented operation and enterprise management' pattern for the development of the seawater desalination industry. It is also important to set up a pluralistic, multi-channel and multilevel investment assurance system for the development and utilization of seawater desalination (Zheng et al. 2014). It is necessary to construct a special fund for seawater desalination to support some demonstration projects for seawater desalination (Utilization report of seawater in China 2015). A favourable tax policy and an economic subsidy for the management of seawater desalination facilities should be supported (Liu et al. 2010).

Improving the localization rate of seawater desalination equipment

Governments should encourage special studies on the key technologies of the seawater desalination process and comprehensive utilization process, import and absorb advanced desalination technologies and engineering experiences from overseas, and finally speed up the localization of key seawater desalination equipment (Duan & Tan 2012; Zhu *et al.* 2012).

Strengthening the industrial layout of seawater desalination

It is critical to stress the industrial layout and large-scale development of seawater desalination. Some industrial matching should be considered before constructing new desalination projects. Pipeline development should be planned before planning the desalination industry, and it is necessary to incorporate desalinated seawater into an integrated water-resources allocation system within coastal water-deficient regions (Chen *et al.* 2015).

Mitigation against the environment pollution due to seawater desalination plants

Applications of combined water and power and some desalination technologies are commonly used to mitigate environment risks. They could decrease the cost of steam generation by using the low-grade superheated steam and reduce the energy consumption by using cooling water. Some studies have indicated that it is possible to combine the process of seawater desalination and salt production (Feng & Xie 2010). Concentrated seawater utilization and zero-discharge technology are warranted to facilitate the sustainable development of the seawater desalination industry (Ruan 2008).

Improving public involvement and receptivity towards the desalinated seawater

It is important to improve public awareness and receptivity towards desalinated seawater. Measures should be adopted to encourage the public to engage in the comprehensive management of water resources and to decrease their

concern regarding the environmental and health risks, especially when the desalinated seawater enters the municipal pipelines (Fielding *et al.* 2015; Hurlimann & Dolnicar 2016).

CASE STUDIES

Case 1 – seawater desalination in Tianjin

Tianjin is a large, rapidly growing urban centre in northern China. The annual water use per capita in Tianjin is 153 m^3 , which is substantially less than the national average of 455 m^3 (Tianjin Water Resources Bulletin 2015). This is because there are a very limited surface and ground water resources in Tianjin due to the semi-arid climate, with long-term annual precipitation of 550 mm (Tianjin Water Resources Bulletin 2015). Tianjin has a thriving economy and a growing population with a substantial and growing water need. To solve the serious water shortage issue in Tianjin, water diversion and alternative water resources have been developed to supply water to Tianjin (Gu *et al.* 2015). Several large-scale water diversion projects are operating (Tianjin Water Resources Bulletin 2015), including the South-to-North Water Diversion, the East Route Diversion and the Luan River Diversion. Of the alternative water resources, seawater desalination plays a major role.

By the end of 2015, the total capacity of seawater desalination plants reached $3.3 \times 10^5 \text{ m}^3/\text{d}$ in Tianjin (Utilization report of seawater in China 2015): the Dagangxinquan seawater desalination plant with a capacity of $10^5 \text{ m}^3/\text{d}$, the seawater desalination plant of Dagang electric power supplies a capacity of $0.6 \times 10^4 \text{ m}^3/\text{d}$, the seawater desalination plant of Taida new water source provides a capacity of $2 \times 10^4 \text{ m}^3/\text{d}$ and the seawater desalination plant of Beijiang electric power provides the most capacity at $2 \times 10^5 \text{ m}^3/\text{d}$. The seawater desalination plant of Beijiang electric power transported and distributed the desalinated seawater to the tap water plant by constructing a special water supply pipeline. The Dagangxinquan seawater desalination plant supplied a new water source for large-scale ethylene projects by also constructing a special water transport pipeline. The seawater desalination plant of Dagang electric power provided the water source for boiler make-up water. In 2013,

all of the seawater desalination plants provided new water resources of $3.7 \times 10^7 \text{ m}^3$, of which $2.8 \times 10^7 \text{ m}^3$ was for industrial needs and the remaining $0.9 \times 10^7 \text{ m}^3$ was for domestic living of residents. In 2014, the total water resources provided by all of the desalination plants was $3.1 \times 10^7 \text{ m}^3$, including $2.6 \times 10^7 \text{ m}^3$ for industrial development and the remaining $0.5 \times 10^7 \text{ m}^3$ for domestic living.

The following are brief introductions to four large-scale seawater desalination plants ([Utilization report of seawater in China 2015](#)).

Dagangxinquan seawater desalination plant

The Dagangxinquan seawater desalination plant is located in Dagang Chemical Industrial Park in Tianjin, and it is a financial investment of the Kaifa Group of Singapore. The first phase capacity of this plant was $10^5 \text{ m}^3/\text{d}$ since it went into operation in 2010. This project used a double membrane system as the technology for water production, and seawater pretreatment of this project adopted a hyper-filtration membrane system. The plant employed reverse osmosis and an energy recycling system to improve the desalination capacity and water-recycling rate.

The water supply target of the Dagangxinquan seawater desalination plant is some large-scale ethylene enterprises in the petrochemical industry of Tianjin. The water supply has reached $6\text{--}7 \times 10^4 \text{ m}^3/\text{d}$ since operation in 2010. The water supply cost is not high due to the short supply distance between the desalination plant and the enterprises and the relatively low requirement for water quality of the supplied water in the petrochemical industry. Due to the low cost, the price of desalination could be kept initially at 6.7 yuan/ m^3 , and adjusted to 7.6 yuan/ m^3 , similar to the price of tap water in Tianjin. With the increasing petrochemical projects and the increasing water demands, the capacity of the Dagangxinquan seawater desalination plant will be expanded greatly in future.

Seawater desalination plant of Dagang electric power

The Dagang electric plant has four thermal generator sets, and each set has a volume of 300 MW. Desalinated seawater comprises 90% of boiler make-up water. Seawater desalination in this plant belongs to a dual-purpose power and

water plant; that is, it utilizes the waste heat from the electric plant to produce the desalinated seawater. The employed technology is MSF, with a capacity of $6 \times 10^3 \text{ m}^3/\text{d}$.

Seawater desalination plant of Taida new water source

This plant is located in an economically developed region of Tianjin. It imported the technology from Vaire Corporation of France and employed LT-MED technology with a capacity of $2 \times 10^4 \text{ m}^3/\text{d}$. The majority of the desalinated seawater produced from this plant was utilized as boiler make-up water for Taida No. 5 thermal source plant during the heating period, and the remainder is used for the water requirement of the enterprises in an economically developed region of Tianjin.

Seawater desalination plant of Beijiang electric power

This plant is located in Yingcheng Town of Hangu in Tianjin, occupying an area of $2.2 \times 10^6 \text{ m}^2$. The plant plans to construct four coal-fired generator sets with a capacity of 10^6 W and seawater desalination equipment with a capacity of $5 \times 10^5 \text{ m}^3/\text{d}$. The first stage of the project has constructed two coal-fired generator sets with a capacity of 10^6 W and seawater desalination equipment with a capacity of $2 \times 10^5 \text{ m}^3/\text{d}$. This plant has employed LT-MED desalination technology and uses the waste heat to desalinate seawater.

Beijiang electric power achieved a capacity of $10^5 \text{ m}^3/\text{d}$ in 2010 and $2 \times 10^5 \text{ m}^3/\text{d}$ in 2014. The desalinated seawater has been transported directly into the Hangu Water Plant through a specific water transport pipeline with a discharge of $6\text{--}8 \times 10^3 \text{ m}^3/\text{d}$ since October 21, 2010. The desalinated seawater was first mixed with tap water before entering the forebay of the water plant and was then treated using the treatment technology for tap water, before finally entering the municipal pipe network in Hangu. The water quality of desalinated seawater, before entering the forebay and after mixing, was determined to ensure it satisfied the standard for tap water in China. This was the first time a municipal pipe network was utilized to transport desalinated seawater in China. In 2015, the seawater desalination plant of Beijiang electric power produced $2 \times 10^4 \text{ m}^3/\text{d}$ of desalinated seawater for self-use in the electric power plant and an additional $2\text{--}3 \times 10^4 \text{ m}^3/\text{d}$ of desalinated

seawater for the Taida Water Plant and Hangu Water Plant; this water was transported into the municipal pipeline after being mixed with regular water and then treated according to the treatment technology for tap water.

Case 2 – seawater desalination in Zhoushan, Zhejiang Province

Zhoushan is located in the north-eastern part of Zhejiang Province, south of the passage of Yangtze River to the East China Sea, and it is an island group comprised of 1,390 small islands. The annual average precipitation in Zhoushan is 1,209 mm, and the per capita water resource quantity in Zhoushan is 601 m^3 (Bulletin of Water Resources in Zhejiang Province 2015). However, the islands within Zhoushan are very scattered, and the majority are mountainous or have hilly lands, leading to difficulty in producing large runoff and effectively collecting the limited fresh water resources (Wang *et al.* 2013). Meanwhile, the islands in Zhoushan have complex topography (exhibiting a radial pattern and incomplete development conditions of surface water systems), which makes it much more difficult to carry out water diversion projects in Zhoushan (Wang *et al.* 2013).

The advancement of urbanization and improvement of people's livelihoods lead to an increasing need for fresh water. Furthermore, the water pollution issue due to economic growth has become increasingly serious, and some large steelworks, dockyards and electric power plants have been constructed in Zhoushan since 2006 (Zhejiang Statistical Yearbook 2015). These factors have caused a serious shortage of fresh water resources in Zhoushan. To relieve this serious shortage of fresh water resources and ensure the sustainable development of the economy in Zhoushan, it has become urgent for the Zhoushan Authority to strive to develop seawater desalination.

Zhoushan is a region in which the earliest seawater desalination was carried out across China. The first RO seawater desalination project, with a capacity of $5 \times 10^5 \text{ m}^3/\text{d}$, was constructed and put into operation in Shengshan Town, Shengsi County in 1997 (Chen *et al.* 2015). Then, seawater desalination was applied widely around Zhoushan, including in Gaoting Town, Qushan Town, Changtu Town, Dongji Town, Liheng Town, Yangshan Town and Gouqi Town. By the end of 2015, there were 21 seawater

desalination projects in operation in Zhoushan, and the total capacity reached $1.2 \times 10^5 \text{ m}^3/\text{d}$ (Utilization report of seawater in China 2015). Table 4 lists all of the seawater desalination projects present in Zhoushan. As seen in the second column of this table, the majority of the seawater desalination plants are developed for municipal needs, while the remainder are for nearshore industrial development, port logistics and marine tourism.

At present, all seawater desalination plants in Zhoushan have employed the RO desalination technology (Wang *et al.* 2013). Additionally, some desalination technologies are associated with solar energy technology. The Liheng seawater desalination project, with a capacity of $10^5 \text{ m}^3/\text{d}$ in Putuo district, Zhoushan, was chosen as a demonstration project by the National Key Technology Research and Development Program of the Ministry of Science and Technology of China during the Eleventh Five Year Plan (2006–2010).

From the perspective of engineering operations, local water authorities and tap water companies are responsible for operating most desalination projects. Desalinated seawater has been transported directly into municipal pipelines in order to solve the drinking water problems of local residents (Wang *et al.* 2013). Desalinated seawater was supplied for the domestic needs of local residents during dry seasons. Taking Shengsi County in Zhoushan as a typical example (Wang *et al.* 2013), the desalinated seawater supply accounted for approximately 80% of the total water supply. Local health and epidemic prevention departments have continually checked the water quality of desalinated seawater to ensure the safety of the municipal water supply in Zhoushan. Additionally, with the increasing capacity of seawater desalination, the cost of desalinated seawater has decreased to 5.5 yuan/ m^3 at present.

With the advancement of seawater desalination technology and the increase in seawater desalination capacity, seawater desalination is becoming a vital water supply source for the development of the Zhoushan region, playing an important role in ensuring the safety of water resources in Zhoushan.

CONCLUDING REMARKS

China, especially its coastal provinces, is facing a serious shortage of fresh water resources and a water pollution

Table 4 | Information about seawater desalination projects in Zhoushan by the end of 2015 (Utilization report of seawater in China 2015)

Number	Project name	Utilization objective	Total investment capital (10 ⁷ yuan)	Capacity (10 ³ m ³ /d)
1	Shengsi Caiyuan SDP first stage to five stage	Municipal use	8.5	10.6
2	Shengshan Island SDP	Municipal use	1.3	1
3	Yangshan Island SDP	Municipal use	1.5	2
4	Gouqi Island SDP	Municipal use	2.4	2
5	Dongji SDP	Municipal use, marine tourism	0.5	0.3
6	Daishan Huangzeshan Island SDP	Port logistics	0.9	0.3
7	Changtu Island SDP	Municipal use	3.5	5
8	Daishan Xiushan Island SDP, first stage	Municipal use	2.5	3
9	Daishan Xiushan Island SDP, second stage	Municipal use	2.35	3
10	Shuliang Island SDP	Marine tourism	2.5	0.6
11	Daishan home Island SDP, first stage	Municipal use	2	5
12	Daishan Qushan SDP, first stage	Municipal use	5	5
13	Daishan Qushan SDP, second stage	Municipal use	4	5
14	Liuhe SDP of electric power	Dual-purpose power and water plant	13	24
15	Second-stage expanded SDP of Zhoushan electric power	Dual-purpose power and water plant/ Industry	14	12
16	Liuhe SDP with the capacity of 10 ⁵ m ³ /d, first stage	Municipal use	8.1	20
17	Liuhe SDP with the capacity of 10 ⁵ m ³ /d, second stage	Municipal use	13	20
18	Xiazhi SDP	Municipal use	0.9	0.6
19	Luoji mountain SDP in Putuo Town	Municipal use	0.3	0.1
20	Baisha SDP in Putuo Town	Municipal use	0.6	0.5
In sum			86.7	12

Note: SDP, seawater desalination project.

issue, restricting further development. To address the serious imbalance between water resource supply and demand, in addition to efficiently utilizing the regular water resources, China has strived to develop alternative water resources to combat the water crisis, among which seawater desalination plays an important role. This paper reviewed the current situation of the utilization of desalinated seawater in China, including the points outlined below.

The history of seawater desalination in China was simply classified into three phases according to chronological order: the phase of laboratory experiments and technological research (1958–1990), the phase of industrialization of seawater desalination (1991–2005), and the phase of industry development of seawater desalination (2006–present).

The number and capacity of seawater desalination plants rapidly increased during 1981–2015. Most of the

desalinated seawater has been utilized in industry sectors (mainly including the power generation industry, and the petrochemical and iron and steel industries) and domestic living of residents. In terms of the number of seawater desalination plants, most of the desalination plants are located in four provinces: Zhejiang, Shandong, Liaoning and Hainan. From the perspective of capacity, the majority of the desalination plants are concentrated in the six provinces of Tianjin (an autonomous city), Zhejiang, Hebei, Shandong, Guangdong and Liaoning. Most desalination plants have employed RO and/or MED technologies.

Policies, regulations and technological standards governing seawater desalination were listed in this study along with existing problems and some suggestions regarding the present status of seawater desalination have been proposed.

Two representative examples were given: seawater desalination in Tianjin (a typical northern water-deficient metropolis); and Zhoushan (a typical southern island city that has a sufficient amount of precipitation but still faces a serious shortage of fresh water resources).

On August 14th 2017, the Ministry of Water Resources of China first published an official file 'Guide on putting alternative water resources under an integrated water resource allocation in China' that specifies allocation requirements, allocation areas, strengthening measures, supervisory managements and organizational guarantees using alternative water resources for all of the provincial administrative regions in China in order to speed up the development and utilization of alternative water resources. The allocation of alternative water resources (not including the directly used seawater) was planned to exceed 10^{10} m^3 by 2020 in this file, and in particular, at least $2 \times 10^9 \text{ m}^3$ of alternative water resources needs to be allocated in the Beijing-Tianjin-Hebei regions. The file specifies the allocation of the desalinated seawater for industrial needs: the desalinated seawater should be encouraged to allocate for industrial water use in coastal water-deficient regions; coastal regions should greatly utilize seawater as industrial cooling water. Some strengthening measures have been taken to promote the allocation of desalinated seawater in an integrated water resources system in this file, including strengthening the planning guide, strengthening the management of planned water use, accelerating the construction of alternative water resources projects, and implementing examination and motivation mechanisms. Some supervisory management measures were also proposed in the file, including making up a complete technological standard system, strengthening the monitoring and statistical management of seawater desalination, and strengthening the supervision and control of the safety of seawater desalination. Finally, some organizational guarantee measures were also presented in the official file, such as making up a complete operating system, supporting the market to play a role, strengthening policy motivation using a positive guide, and improving the public involvement by broadly dispersing information.

With the advancement of seawater desalination technology, increasing capital investment and strong policy support, seawater desalination is developing rapidly, and desalinated

seawater is expected to play a vital role in dealing with the serious shortages of water resources within the coastal regions of China.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (Number: 51479003, 51509004). Considering some references cited in this paper are in Chinese, the interested readers could feel free to contact the authors for the English translated edition of those references.

REFERENCES

- Bai, J., Zheng, S. H. & Wu, Q. L. 2007 Study on the current status of water resources. *Modern Agric. Sci. Technol.* **12**, 187–188.
- Bulletin of Water Resources in China 2010 <http://www.mwr.gov.cn/sj/tjgb/szygb/> (accessed 31 December 2010).
- Bulletin of Water Resources in Zhejiang Province 2015 <http://www.zjsw.cn/> (accessed 31 December 2015).
- Cao, X. X., Huang, X., Liang, P., Xiao, K., Zhou, Y. Q., Zhang, X. Y. & Logan, B. E. 2009 A new method for water desalination using microbial desalination cells. *Environ. Sci. Technol.* **43**, 7148–7152.
- Chao, B., Fang, C. L. & Chen, F. 2006 Mutual optimization of water utilization structure and industrial structure in arid inland river basins of Northwest China. *J. Geogr. Sci.* **16**, 87–98.
- Charcosset, C. 2009 A review of membrane processes and renewable energies for desalination. *Desalination* **245**, 214–231.
- Chen, X., Xia, X., Liang, P., Cao, X. X., Sun, H. T. & Huang, X. 2011 Stacked microbial desalination cells to enhance water desalination efficiency. *Environ. Sci. Technol.* **45**, 2465–2470.
- Chen, Y. L., Song, W. L., Wang, B. & Hu, W. M. 2015 Status quo and problem analysis of China's seawater utilization. *Marine Econom.* **5**, 11–25.
- China Statistical Year Book 2010 <http://www.stats.gov.cn/tjsj/ndsj/> (accessed 31 June 2011).
- Dai, J. Y., Wu, L. Y., Zhang, Y. G. & Tang, Z. X. 2018 Brief analysis on environmental influence and comprehensive utilization of brine from thermal desalination. *Guangdong Chem.* **45**, 48–52.
- Ding, L. C. 1999 The first seawater desalination project in Zhejiang Zhoushan Shengshan island. *Energy Eng.* **2**, 8–9.
- Duan, H. Q. & Tan, T. 2012 Current situation and tendency of China's seawater desalination industry. *Water Ind. Market* **3**, 29–33.
- El Saliby, I., Okour, Y., Shon, H. K., Kandasamy, J. & Kim, I. S. 2009 Desalination plants in Australia, review and facts. *Desalination* **247**, 1–14.

- Elimelech, M. & Phillip, W. A. 2011 The future of seawater desalination: energy. *Technol. Environ. Sci.* **333**, 712–717.
- Feng, H. J. & Xie, C. G. 2010 Status and prospect of Chinese seawater desalination technology. *Chem. Ind. Eng.* **27**, 103–109.
- Fielding, K. S., Gardner, J., Leviston, Z. & Price, J. 2015 Comparing public perceptions of alternative water sources for potable use: the case of rainwater, storm water, desalinated water, and recycled water. *Water Resour. Manage.* **29**, 4501–4518.
- Gao, C. J. 2003 Brief discussion of seawater desalination. *Chem. Technol. Econom.* **11**, 24–26.
- Ghaffour, N., Missimer, T. M. & Amy, G. L. 2013 Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability. *Desalination* **309**, 97–207.
- Gu, Q. X., Chen, Y., Pody, R., Cheng, R., Zheng, X. & Zhang, Z. X. 2015 Public perception and acceptability toward reclaimed water in Tianjin. *Resour. Conserv. Recy.* **104**, 292–299.
- Hurlimann, A. & Dolnicar, S. 2016 Public acceptance and perceptions of alternative water sources: a comparative study in nine locations. *Int. J. Water Resour. D* **32**, 650–673.
- Liu, B. W., Liu, W. J. & Hu, W. P. 2010 Techno-economic analysis and selection for the desalination in power plant. *Ind. Safety Environ. Prot.* **36**, 4–26.
- Lyu, S. D., Chen, W. P., Zhang, W. L., Fan, Y. P. & Jiao, W. T. 2016 Wastewater reclamation and reuse in China: opportunities and challenges. *J. Environ. Sci.-China* **39**, 86–96.
- Ma, J. H. 2008 Recommendation for Tianjin to formulate the desalination waste discharge standard as soon as possible. *Decision-making Cons. Commun.* **3**, 25–71.
- Man, Y. N., Wang, X. J., Wang, Y. T. & Fang, Y. J. 2014 New search progress and development trend of seawater desalination technology. *Ind. Water Treat.* **34**, 8–12.
- Nie, H. T. & Tao, J. H. 2008 Impact of coastal exploration on the eco-environment of Bohai Bay. *Ocean Eng.* **26**, 44–50.
- Ruan, G. L. 2008 Make the complete industry chain of Chinese seawater desalination market. *Water Ind. Market* **6**, 16–18.
- Ruan, G. L., Xie, L. X. & Lu, Q. C. 2002 Seawater reverse osmosis desalination project in Changhai County. *Ocean Technol.* **21**, 13–16.
- Schiermeie, Q. 2008 Purification with a pinch of salt. *Nature* **452**, 260–261.
- Shi, L. H., Wang, X. J. & Wang, Y. T. 2012 The research of situation and development for ship seawater desalination technology. *Technol. Water Treat.* **38**, 4–7.
- Tan, Y. W., Shen, Y. Z. & Lu, G. R. 2000 Sea water desalination plot project with 500t/d in Shengshan. *Technol. Water Treat.* **26**, 49–54.
- Tan, Y. W., Zhang, X. J. & Chen, W. S. 2004 A pilot project for reverse osmosis sea water desalination at 10,000 m³/d in Rongcheng. *Technol. Water Treat.* **30**, 157–161.
- Tan, Y. W., Tan, B. & Wang, Q. 2007 Progress in seawater desalination projects in China. *Technol. Water Treat.* **1**, 1–3.
- Tianjin Water Resources Bulletin 2015 <http://www.tjsw.gov.cn/pub/tjwcb/> (accessed 31 December 2015).
- Utilization report of seawater in China 2015 <http://www.soa.gov.cn/zwgk/hygb/> (accessed 31 August 2016).
- Wang, Q., Zheng, G. & Tan, Y. 2011 The operation status of desalination project of China. *Technol. Water Treat.* **37**, 12–14.
- Wang, J., Liu, S. J., Hou, C. Y., Xing, S. Y., Shi, Y. L. & Jia, D. 2013 Research on development pattern of seawater desalination in China. *China Soft Sci.* **12**, 24–31.
- Wang, J. H., Shang, Y. Z., Wang, H., Zhao, Y. & Yin, Y. 2015 Beijing water resources: challenges and solutions. *J. Am. Water Resour. Assoc.* **51**, 614–623.
- Yi, L., Jiao, W., Chen, X. & Chen, W. 2011 An overview of reclaimed water reuse in China. *J. Environ. Sci.* **23**, 1585–1593.
- Yu, R. X., Wang, Y. & Wang, S. C. 2005 A review in brine disposal from desalination plants. *Technol. Water Treat.* **6**, 1–3.
- Yu, K. L., Lu, Q. C. & Ruan, G. L. 2008 Progress in engineering and technology of low temperature multiple effect distillation for seawater desalination. *China Water Wastewater* **22**, 82–85.
- Yu, J. Q., Hu, Y. J., Wang, Z. J., Liu, Y. J., Cheng, F. L. & Zhang, S. J. 2017 Brief analysis on environmental influence and comprehensive utilization of brine from thermal desalination. *Guangdong Chem.* **44**, 193–194.
- Zhang, J. 2011 Application progress of seawater desalination technology in China's steel enterprise. *Metall. Power* **5**, 55–57.
- Zhang, L., Xie, L., Chen, H. L. & Gao, C. J. 2005 Progress and prospects of seawater desalination in China. *Desalination* **182**, 13–18.
- Zhang, Y. L., Ni, H. J., Chen, A. G., Jiang, Z. H., Yuan, D. & Zhang, H. 2010 Progress in the research on effect of desalinated seawater on environment and human health. *J. Environ. Occup. Med.* **27**, 317–318.
- Zhao, Z., Zuo, Y. & Zillante, J. G. 2017 Transformation of water resource management: a case study of the South-to-North water diversion project. *J. Clean. Prod.* **163**, 136–145.
- Zhejiang Statistical Yearbook 2015 <http://tjj.zj.gov.cn/tjsj/tjnj/> (accessed 31 August 2016).
- Zheng, X., Chen, D., Wang, Q. & Zhang, Z. X. 2014 Seawater desalination in China: retrospect and prospect. *Chem. Eng. J.* **242**, 404–413.
- Zheng, Z., Li, F., Li, Q., Wang, L., Cai, W., Li, X. & Zhang, H. 2016 State-of-the-art of R&D on seawater desalination technology. *Chin. Sci. Bull.* **61**, 2344–2370.
- Zhou, J. J. 2009 Development status and problem research of seawater utilization industry in China. *Marine Econom.* **4**, 19–23.
- Zhu, Q. P., Shi, X. M., Zhan, H. L. & Jiang, H. 2012 Seawater utilization in China: current situation, issue and development strategy. *China Water Resour.* **21**, 30–33.
- Zhu, S. F., Xue, L. B. & Xu, Z. D. 2014 The development history and an analysis of status quo of desalination at home and abroad. *Technol. Water Treat.* **40**, 12–23.

First received 29 May 2018; accepted in revised form 13 September 2018. Available online 1 October 2018