T2R2 東京科学大学 リサーチリポジトリ
Science Tokyo Research Repository

論文 / 著書情報
Article / Book Information

題目(和文)	水不足への施策に対する経済及び環境評価に関する研究
Title(English)	A Study on Economic and Environmental Assessment of Countermeasures against Water Scarcity
著者(和文)	コウロ
Author(English)	Lu Gao
出典(和文)	学位:博士(工学), 学位授与機関:東京工業大学, 報告番号:甲第10803号, 授与年月日:2018年3月26日, 学位の種別:課程博士, 審査員:鼎 信次郎,吉村 千洋,竹村 次朗,福田 大輔,藤井 学
Citation(English)	Degree:Doctor (Engineering), Conferring organization: Tokyo Institute of Technology, Report number:甲第10803号, Conferred date:2018/3/26, Degree Type:Course doctor, Examiner:,,,,
学位種別(和文)	博士論文
Type(English)	Doctoral Thesis

Powered by T2R2 (Science Tokyo Research Repository)

水不足への施策に対する経済及び環境評価に関する研究
A Study on Economic and Environmental Assessment of Countermeasures against Water Scarcity

コウ　ロ
高　璐
Gao　Lu

平成 29 年度
博士論文

東京工業大学大学院
理工学研究科
土木工学専攻

平成 29 年 11 月

Acknowledgement

I would like to express the deepest respect to Prof. Dr. Shinjiro Kanae, who served as my supervisor throughout my doctoral program. He gave me the chance to do this very interesting research and always encouraged me and gave me lots of suggestions and tremendous support throughout my study in Tokyo Institute of Technology that I truly appreciate all the time. His excellent guidance, friendly encouragement, optimistic attitude and persistent persevere did benefit me a lot and made this study more productive.

I would also gratefully acknowledge Dr. Sayaka Yoshikawa, Dr. Yoshihiko Iseri and Prof. Dr. Shinichiro Fujimori, as the co-advisor, for they kind guidance. Dr. Sayaka Yoshikawa, Dr. Yoshihiko Iseri and Prof. Dr. Shinichiro Fujimori were very kind for me and also gave many invaluable scientific advices and helps for my work. I would like to thank them at this moment.

I am grateful to all reviewers, i.e. Associate Prof. Dr. Daisuke Fukuda, Associate Prof. Dr. Manabu Fuji, Associate Prof. Dr. Jiro Takemura and Associate Prof. Dr. Chihiro Yoshimura both for the useful comments and advices.

As a member of KanaeLab, I feel very lucky. I would like to extend my thanks to all members of this lab: all professors (Prof. Shinjiro Kanae), all assistant professor (Dr. Rie Seto), all research staffs (Dr. Sayaka Yoshikawa, Dr. Yoshihiko Iseri, Dr. Aki Yanagawa and Dr. Kaoru Kakinuma), all students who study in the lab during 2014-2018 (Graduate: Aogu Ueki, Satsuki Kitamura, Kohei Hamaguchi, Suwathep Tiratas, Mari Arai, Shota Kobayashi, Nozomi Ando, Daiki Ikeshima, Shinya, Takegawa, Ryunosuke Tawataari, Che Wei Kuo; Doctoral student: Megumi Watanabe, Orie Sasaki, Menaka Revel, Dim Wanndet, Wognarin Kompor, Bahaa Elboshy; Master student: Shigehiro Ihara, Seiya Maruyama, Haruki Watababe, Ryosuke Irie, Natasumi Orimo, Atsushi Fujioka.), and sectaries (Ms.Yoko Umibe). Thank you very much!

In addition, I also would like to acknowledge Japan Student Services Organization (JASSO) and Mitsubishi Corporation for financially supporting me for Ph.D. degree in Japan.

Finally, I sincerely thank my parents, who know me, stand by my side and unconditionally support me. Most importantly, my doctoral studies would have not been possible without the love and patience of my husband Xiangbiao Yin. My words can’t express all the thanks for their understanding, patience and love during the past few years.

Lu Gao
Thursday
November 16, 2017

Abstract

Nowadays water availability is subject to shortages, given effects of climate change, economic development, and population growth worldwide. Therefore, many countries are already engaged in water demand management and looking for alternative renewable countermeasures. In order to clarify applicability and potential of various countermeasures against water scarcity, systematic methods are respectively proposed in this study to assess their economic and environmental change based on specific socioeconomic data and modeling techniques.

In the second chapter, increasing water use efficiency is highlighted as the representative approach of water demand management to deal with water scarcity. China is one of the countries which is facing a growing water scarcity because of the rapid population growing and economic growth. One way to alleviate the water scarcity is to increase the efficiency of water use without developing additional water supplies. Therefore it is essential to develop a holistic policy tool which can help the policy-makers to decide the usage of water wisely. The fundamental work is to explicitly quantify the agricultural water use efficiency in order to identify the potential areas for improving agricultural water use efficiency. Classical concept of irrigation efficiency just use some simple way to measure, such as amount of water to be applied per irrigated area. Although those ways can be used to evaluate the water use efficiency, it’s not fit to evaluate productive efficiency when we want to both increase the economic and water use efficiency. In this study, we choose the methodology by Data envelopment analysis (DEA) which has an economic rather than engineering meaning. This approach has been widely used in management science and economics. Researchers in the field of water resource management also utilizes DEA, for the static or comparatively static analysis. However, the efficiency change of the producers in different years cannot be expressed in detail due to these kinds of static analysis. Therefore, a dynamic DEA method named DEA Window Analysis is used in this study to evaluate the efficiency agriculture change for the period 1999-2011 when the rate of economic growth is high. 31 provinces in China are selected as the target areas. In terms of the agricultural water use efficiency, several major findings were obtained. First, agricultural water use efficiency trends to be lower in the regions where the water resource is sufficient. In addition, the developed area has higher agricultural water use efficiency than the developing area and the efficiency of the less-developed area is the worst. It may be thought that the economic development mode of China causes the relatively low agricultural water use efficiency. Lastly, we estimated the effect of increasing agricultural water use efficiency on alleviating water scarcity in China. The results show that the application of improving agricultural water efficiency will significantly reduce the number of provinces with the water scarcity from whole 31 to 6 remaining provinces, clearly suggesting the usefulness of such approach in alleviating water scarcity. Nevertheless, water scarcity will still appear in some provinces due to the great increasing demand of agricultural water in future, which clearly necessitates the applying of both water management and increasing water supply in dealing with water scarcity.

In the third chapter, we select seawater desalination as the representative approach of water supply to deal with the water scarcity, coupling with its potential evaluation. Seawater desalination is a promising adaptation measure to satisfy water demand in coastal countries suffering from water scarcity. Numerous studies have shown that production costs for desalination are decreasing and capacity is growing. Efforts have been made to incorporate desalinated water into various global hydrological models (GHMs). To improve the incorporation of desalinated water into GHMs, we proposed the use of a feasibility index (Fi) to analyze under which conditions developing desalination capacity is economically feasible for different countries. We considered both past and future periods and clarified in which countries seawater desalination might be economically feasible. The Fi index was defined in detail by comparing the production cost of desalination and conventional water prices simulated by two established statistical models. For historical validation, Fi was first evaluated for nine major desalination countries. The model achieved good agreement with the actual historical development of desalination in these countries on both spatial and temporal scales. We then simulated the period of 2015–2050. Our projected results suggested that desalination would become more cost-effective for further developing countries by 2050. The large spread of seawater desalination into yet more countries was mainly attributed to diminishing production cost and increasing water price in these countries under specific socioeconomic/climate scenarios. We predicted that, in determining the impact of seawater desalination over the period studied, water price would be overwhelmed by production cost.

Finally, the results of this thesis will provide new insights to help the policy-makers to determine appropriate policies for sustainable utilizing of water resources.

Contents

Figure list

Table list

1. Introduction

1.1. Background

As the basic natural resources, water contributes significantly to all aspects of the economic productivity and human activities. Obviously, the direct consumption of the blue water will lead to its depletion on account of various societal activities, which may include not only all nonagricultural activities (e.g., industrial usage, and domestic purposes) but also some agricultural activities (e.g., agricultural irrigation, livestock water drinking, use for inputs of factories producing, or those animal products producing). As such, it has been estimated that ~2,500 km^3 year $^{-1}$, which takes up 70% of total blue water use, contribute to the irrigation water use in the worldwide, and livestock water use is a significantly smaller irrigation, adding up to as little as 0.6% of the total blue water use (Steinfeld, *et al.*, 2006; Rost, *et al.*, 2008). Nevertheless, only about 17% of the world's cropland is irrigated (Pimentel, *et al.*, 2004). In addition, blue water, which account for ~20% of the total quantities, is mainly used for industry and energy generation, and relative large amount of industry water is used for cooling (Vassolo and Döll, 2005; Zhai and Rubina, 2011). For the others, the blue water is also be used for domestic with drinking, cleaning, washing, personal hygiene, and toilet flushing. These involved activities directly or indirectly influence public health (Hunter, *et al.*, 2010; DeNicola, *et al.*, 2015). Therefore, it is essential for our social and economic well-being to ensure the adequate supplies of the available water. However, in the past years, various studies have reported that water resource is insufficient and half of the world's population are under the water scarcity (Falkenmark, 1989; Postel, *et al.*, 1996; Oki and Kanae, 2006; Gleick, 2010; Famiglietti, *et al.*, 2011; Wada, *et al.*, 2011; Gleeson, *et al.*, 2012; Voss, *et al.*, 2013; Moore, *et al.*, 2015; Kummu, *et al.*, 2016; Wang and Zimmerman, 2016).

Generally, water scarcity happens when the available water supply fail to cover the water demand, which can be a result of the climate change, a growing world population. Notably, human activities are also some of the most significant factors influencing local and global availability of fresh water resources (Arnell, 1999; Oki and Kanae, 2006; Rodríguez Díaz, *et al.*, 2007; Srinivasan, *et al.*, 2013; Haddeland, *et al.*, 2014; Riediger, *et al.*, 2014; Schewe, *et al.*, 2014; Kundzewicz Zbigniew and Gerten, 2015; Gosling and Arnell, 2016; Kummu, et al., 2016). For example, Srinivasan, *et al.* (2013) suggest a nearly 16-time increase in population under water scarcity from the 1990s to 2000s, and the expansion of water scarcity is mainly interpreted by the effects of spatial distribution of population growth relative to water resources. Kummu, et al. (2016) suggest urbanization increase vulnerability to water scarcity. Moreover, increased variability of precipitation and higher temperature would generally result in an increase of irrigation water demand and inducing water shortages (Arnell, 1999; Döll, 2002; Oki and Kanae, 2006; Rodríguez Díaz, et al., 2007; Riediger, et al., 2014; Schewe, et al., 2014; Kundzewicz and Dieter, 2015; Gosling and Arnell, 2016). While, Haddeland, et al. (2014) once indicated that the direct impact of human activities on the water cycle in some regions are potentially the same order of magnitude, or even exceed impact to be expected for moderate levels of global warming (+2 K).

At present, total global water withdrawal is increasing since the traditional water sources (i.e., lakes, rivers, dams, and artesian wells) would be not enough to meet all the demand in the nearly future. As such, Hanasaki, *et al.* (2013) estimated the population living under water stress conditions will research 2,588 – 5,643 million capita (39% – 55% of total population) by 2071-2100. Similarly, Yoshikawa, *et al.* (2014) indicated that the irrigation water requirement will exceed the water which we can get it from the river and underground until 2050. Wada and Bierkens (2014) revealed an increasing trend of human water over-abstraction and the human water consumption from nonsustainable surface water and groundwater is increasing from 30% to 40%. On the basis of these various estimations, they have been suggesting that we will not have enough water to meet the need of economic productivity and societal activities and water scarcity will become a crucial issue over the global scale.

To address the problems of current and future water scarcity, more and more countries have already engaged in reducing water demand and looking for alternative renewable solutions (Ghaffour, *et al.*, 2013; Mays, 2013). To sum up the options to cope with water scarcity, they can be divided into two aspects including demand management and supply enhancement.

On one hand, for the demand management, it is defined as a set of actions controlling water demand, either by improving the overall economic efficiency of its usage as a natural resource, or by operating intra- and inter-sectoral re-allocation of water resources. Among the actions that commonly perceived the first most options, it devotes to improving the efficiency of water usage by saving water or increase water productivity (Hamdy, *et al.*, 2003; Deng, *et al.*, 2006; Bouman, 2007; Blum, 2009; Wang, *et al.*, 2009; Deng, *et al.*, 2016). Moreover, water diversions, which is the intentional movement of water over large distances, is also a possible approach to reduce spatial water scarcity (Gupta, *et al.*, 2010). For example, to address the disparity in water resource availability between the north and south areas in China, the South-North Water Transfer project has been implemented through a series of inter-basin transfer canals that could allow the water to be diverted from the Yangtze basin to the drier Yellow in the north (Ma, *et al.*, 2006;

Liu, *et al.*, 2013). Last but not least, the price of water is relatively low and undervalued in most countries. Therefore, it is generally believed that market-based water pricing for the optimal allocation of the water resource, is necessary for farmers, industries and resident (Renwick and Archibald, 1998; Doppler, *et al.*, 2002; Arbués, *et al.*, 2004; Olmstead and Stavins, 2009; Aidam, 2015).

On the other hand, regarding the supply enhancement, it potentially includes a series of measures to increase the water supply, such as the increased access to conventional water resources, re-use of drainage water and wastewater, desalination, and pollution control, et al (Willardson, *et al.*, 1997; Hamoda, 2004; Fritzmann, *et al.*, 2007; Qadir, *et al.*, 2007; Barnes, 2014). For instance, numerous of large multipurpose dams had been built in the past century for the preserving of water resources. They have been serving for the needs of agriculture, energy and growing cities, and helped protect population from flood hazards (Blazkova and Beven, 2004; Apichitchat and Jung, 2015; Ho, *et al.*, 2017; Mei, *et al.*, 2017; Owusu, *et al.*, 2017). In addition, groundwater exploitation, which has grown exponentially in scale over recent decades, is also a commonly approach to increase water resource (Rodell, *et al.*, 2007; Siebert, *et al.*, 2010; Wada, *et al.*, 2010; Scanlon, *et al.*, 2012). Moreover, the adoption of reused wastewater and desalted water have increased greatly in the last decade due to the rapid increase in water demand and a significant reduction in production cost with the technological advances (Angelakis and Durham, 2008; Karagiannis and Soldatos, 2008; Iglesias, *et al.*, 2010; Elimelech and Phillip, 2011; Ghaffour, et al., 2013; Mays, 2013).

To clarify the influence of the methods against water scarcity, current assessment are mainly focus on the effect of each countermeasures. For demand management, Berrittella, *et al.* (2008) estimated the economic impact of increasing water price to US$10 million per 10^9 m^3 based on computable general equilibrium model. They indicate that increasing water price would influence the water use, production and trade patterns. Li, *et al.* (2015) develops an integrated modeling approach to calculate the economic impact of a total water use control policy in the Heihe river basin, northwestern China, which indicate that such policy has a significant negative impact on several sectors, especially for agriculture and food processing. For supply enhancement, Amores, *et al.* (2013) used the Life cycle assessment methodology to carry out an environment impacts on urban water cycle with using reclaimed water and desalination plants.

However, regarding the characteristics and limitation of each method against water scarcity, they may only be potentially suitable for specific regions. Therefore, further studies are necessarily needed to clarify the applicable regions or countries of each different approaches, so as to help the policy-makers to select the suitable countermeasures for the sustainable use of local water resources. For example, seawater desalination is a separation process which takes water with high salinity and removes the salt to make fresh water (Kesieme, *et al.*, 2013). Since the seawater is unlimited availability and potentially climate-independent water resources, it has a strong potential as the reliable source of water to deal with water scarcity. However, the main impediment for desalination lies in its high cost and energy intensive. As a result, 50% of the world's desalination plants are installed in Middle East (Gorjian and Ghobadian, 2015). In this study, increasing water use efficiency and seawater desalination were selected as the representative countermeasures in demand management and supply enhancement to cope with water scarcity.

1.2. Objective

Assessing the countermeasures against water scarcity from economic and environmental perspectives so as to identify their potential regions.

1.3. Thesis Outline

This thesis is structured as follows (Figure1). Chapter 1 describes the background and objective of this study. Chapter 2 focus on water use efficiency and calculate the potential regions for improving water use efficiency. In Chapter 3, we propose a systematic method to evaluate the development of seawater desalination which was adopted as a supplement water resource on an economic perspective in 140 counties on a global scale to 2050. Chapter 4 concludes with a summary of the research result and provides an outlook on prospective research inspired by our findings.

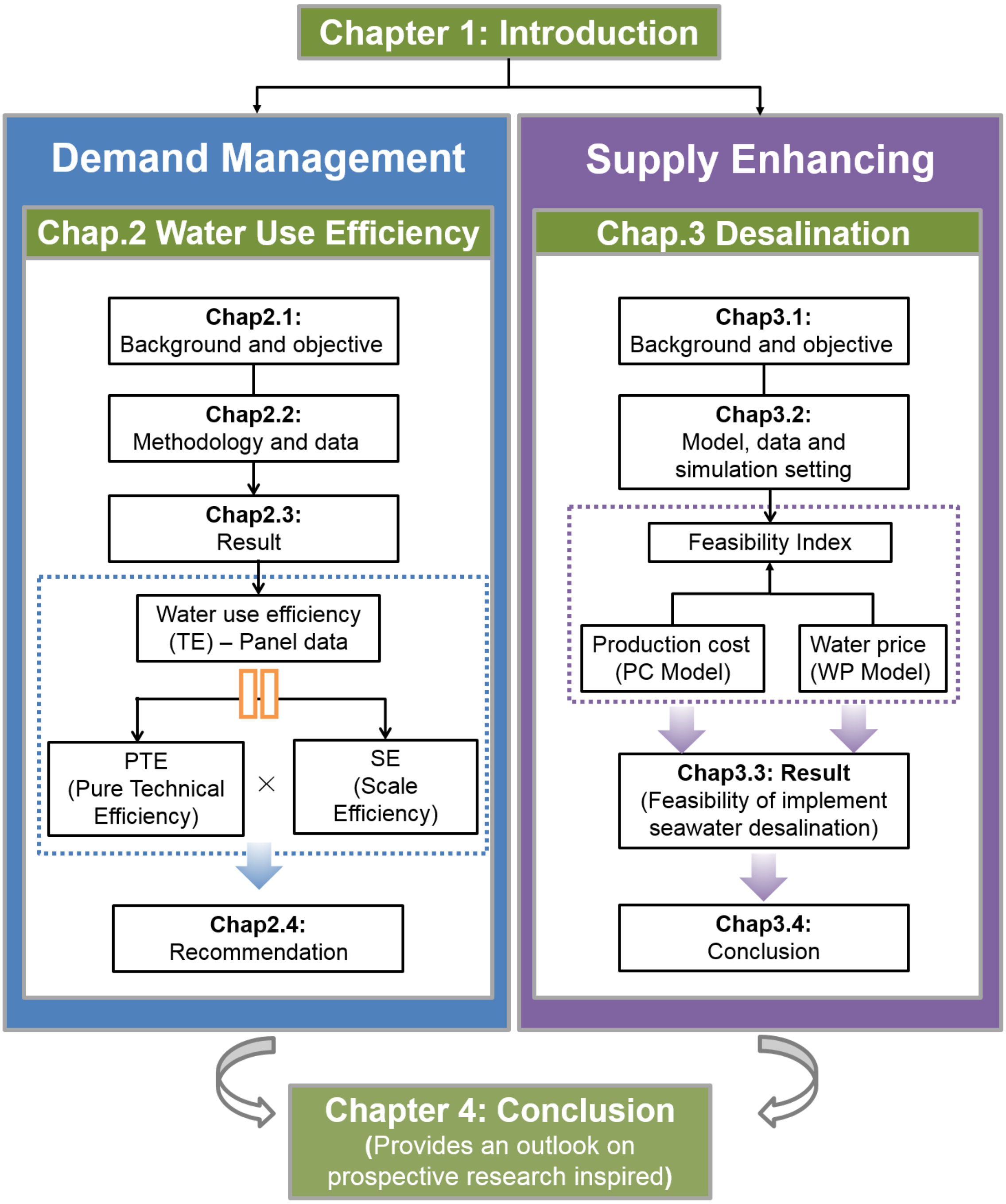

Figure 1. Framework of this thesis

2. The Evaluation of Water Use Efficiency Based on Economic and Environmental Perspective in China for the period 1999 – 2011

2.1 Introduction

2.1.1. Background

Water is the basic natural resources contribute to all the economic productivity and societal activities. Water availability is due to climate change and human activities (Oki and Kanae, 2006; Kundzewicz Zbigniew and Gerten, 2015). At present, total global water withdrawal is increasing and water shortage will become a crucial issue in the developing country because of rapidly growing population and economic (Rijsberman, 2006; Alcamo, *et al.*, 2007). Water resource is the restriction on the sustainable development of more and more countries.

China is one of the countries which facing a growing water scarcity because of the rapidly growing population and economic growth. In 2011, the total annually available water resources in China are 2,813 billion m^3. With a population of 1.4 billion, the available water per capita is 2,083 m3, just the one third of the world average. In addition, the five year plans are a guideline for the high rate of economic growth, it's about 10% annual year. At present, 61.3% of water is used for agriculture, which accounts for only 8.9% of GDP, and China's water use efficiency is lower than that of developed countries (Figure 2.1). Because industrial output has increasingly become much more profitable than agricultural output and the government want to reach the goal of economic, water resources are being transferred to industry (Figure 2.2). Consequently, irrigation water shortage is becoming an increasingly serious problem which will affect the agricultural production.

One of the countermeasures of alleviating water scarcity is by increasing the efficiency of water use without development of additional water supplies (Seckler, *et al.*, 2003). At present, agriculture water use efficiency is still low, and his is largely blamed for the poor irrigation management practices (such as tillage practice, water pricing policy instrument and so on (Guan, *et al.*, 2015; Mamitimin, *et al.*, 2015) and lack of investment in infrastructure (Fang, *et al.*, 2015). Furthermore, water resources in China are scarce with uneven distributions both spatially and temporally, which makes it difficult to achieve efficient agricultural water utilization. Therefore, to adequately clear the potential areas for increasing water resource efficiency, to some extent, strategic importance.

There are a lot of definition for the efficiency. In American Heritage Dictionary, Efficiency is defined as the ratio of effective or useful output to the total input in any system (Keller and Keller, 1995). Some scholar consider that efficiency means less waste or most efficient of using a given set resources to achieve a sustained development of economy, society and environment (Samuelson and Nordhaus, 1997).

Historically, agriculture is the dominant human water use and occupies an important position in the economic development, especially in the first stage of economic growth, so the early water use efficiency mainly focused on irrigation efficiency (Erie, 1968; Steffen, *et al.*, 2011). Classical concept of irrigation efficiency just use some simple way to measure, such as amount of water to be applied per irrigated area (Deng, et al., 2006), crop yield per unit of applied water (Balkhair, *et al.*, 2014).

Although those ways can be used to evaluate the water use efficiency, it’s not fit to evaluate productive efficiency when we want to both increase the economic and water use efficiency. For instance, if we used as same volume water as last year and the agricultural production was increased, but we used more fertilizer than last year, we can’t say the efficiency is improved. Consequently, we should choose the methodology which has an economic rather than an engineering meaning.

On economic perspective, two major approaches to measure efficiency have evolved, namely parametric and no-parametric approaches, with the stochastic frontier analysis (SFA) and the data envelopment analysis (DEA) respectively as most popular techniques. In this study, we adopt DEA to analyze water use efficiency, because there are some advantages over the econometric approach to efficiency measurement. Firstly, it doesn’t need to explicitly specify a mathematical form for the frontier technology or the distribution of the inefficiency term. Secondly, the approach allows the comparison of one production method with the others in terms of a performance index and provides a straightforward approach to calculating the efficiency gap that separates each producer’ s behavior from best productive practices.

This approach widely used in management science and economics. Research in the field of water resource management also utilizes DEA (Wang, 2010; Ali and Klein, 2014; Azad, *et al.*, 2015; Gadanakis, *et al.*, 2015). Wang (2010) used farmer’s level data in northwester China to analysis the water use efficiency by DEA. Ali and Klein (2014) related an application of DEA to establish technical efficiency for 12 irrigation districts in Southern Alberta. Gadanakis, et al. (2015) measured the water use efficiency and productivity to establish benchmarks of water use in England. Azad, et al. (2015) proposed an economic efficiency of irrigated agricultural enterprises evaluation method using DEA, and measured the water use efficiency and managerial efficiency of 17 natural resource management areas in Australia. These aforementioned studies calculated the water use efficiency and identified the best practices (e.g. farms or areas) that served as models or references for inefficiency. Further refinement is necessary to estimate the clarify efficiency change over time and the water saving potential under current production technology in order to clear the effect of alleviating water scarcity by increasing agricultural water use efficiency.

2.1.2. Objective

The primary objective of this study is to identify the potential areas for improving agricultural water use efficiency. Therefore, agricultural water use efficiency has changed for the period 1999 – 2011 was estimated. We also identify the relationship between the rate of economic grow and agricultural water use efficiency by the correlation coefficient in order to discuss how to grow the economy under the limited water resource. Moreover, the exceeding water consumption was also estimated in order to clarify the water saving potential in each areas.

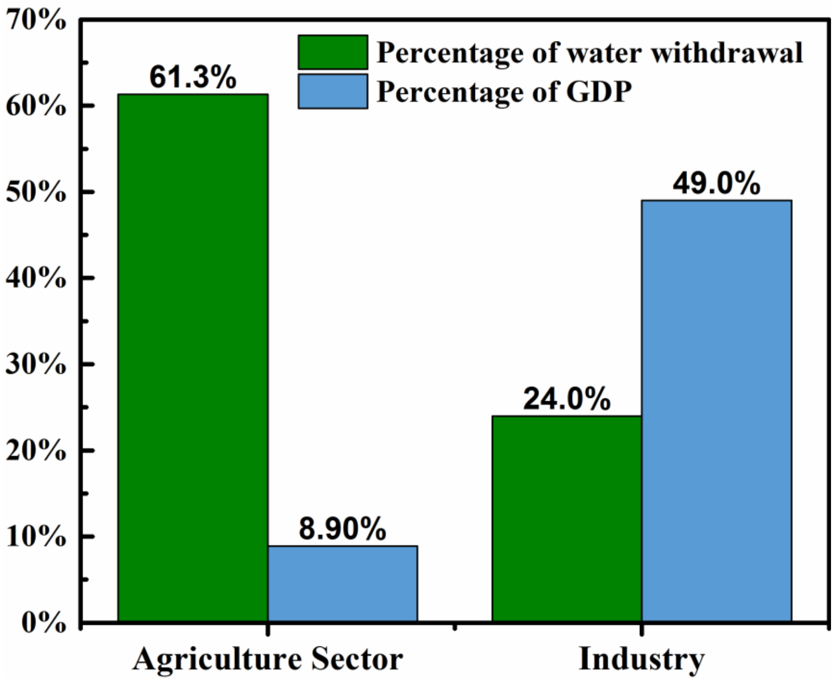

Figure 2.1 Water withdrawal and GDP of China in 2011
(Source: National Bureau of Statistics of China, 2011)

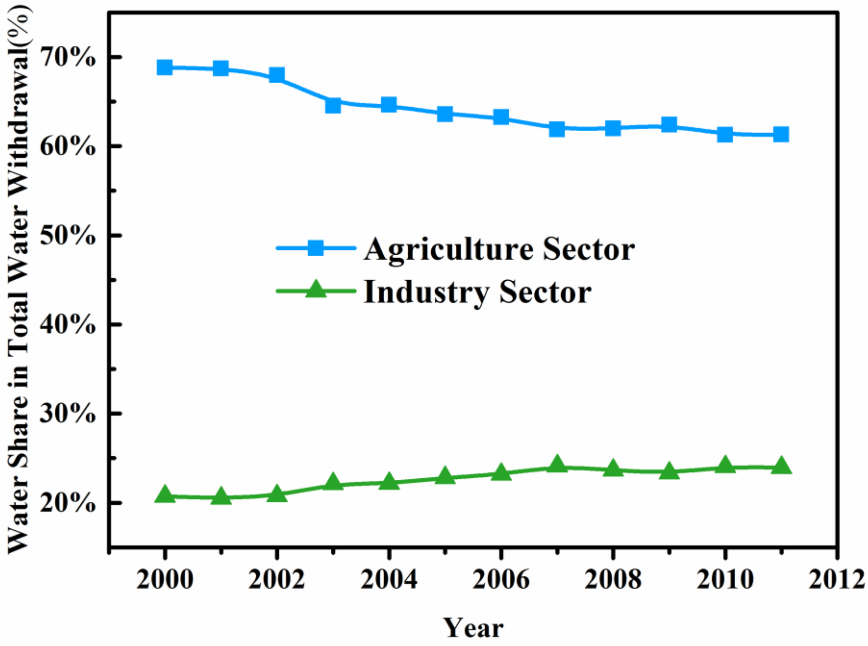

Figure 2.2 Comparison of Agriculture and Industry Water Withdrawal Change
(Source: National Bureau of Statistics of China, 2011)

2.2 Methods

2.2.1. Data Envelopment Analysis

Base on the earlier work initiated by Farrell (1957), DEA was described by Charnes, *et al.* (1978) to estimate an empirical production technology frontier for the first time and developed by the Banker, *et al.* (1984) and applied in various fields. Research in the field of water resource management also utilizes DEA. Speelman, *et al.* (2008) used small-scale irrigation schemes in North-West Province in South Africa to analyze the water use efficiency with DEA. Romano and Guerrini (2011) evaluated the performance of water utility companies by DEA in Italian and indicated the public owned firms are more efficient compared with mixed owned companies in 2007. Ren, *et al.* (2016) estimated the water resources use efficiency, which focuses on the entire water consumption process by utilizing DEA in Gansu Province, China.

While, most of those existing research is that they only evaluate DMUs within each period of time. Some research uses a Malmquist index in the DEA framework for measuring efficiency change over time, such as Ali and Klein (2014) measure the water use efficiency and productivity in Southern Alberta for the period 2008 – 12 to establish benchmarks of water use. But based on the character of water resource, we should know the intertemporal efficiency change to comprehend the actual water use efficiency.

For these reasons, the input-oriented model of the DEA window analysis, which is useful to detect performance trends of a unit over time was chosen to estimate the efficiency in this study.

(1) CCR model

Data envelopment analysis (DEA) is a non-parametric model in the sense that an a priori production function is not required to specify how to treat the data observed. This approach is used to measure the relative efficiency of homogenous units called decision making unit (DMU). The efficiency of each DMU is the ratio of the sum of weighted outputs to the sum of weighted inputs. For DMU k, let $y_{rk}(r = 1, \cdots, S)$denote the level of the rth output, and $x_{ik}(i = 1, \cdots, m)$the level of the ith input. We formed the virtual input and output by weights (v_i) and (u_r) respectively, the efficiency of DMU k (θ_k) is calculated by Eq. (1):

$$\theta_k = \frac{\text{weighted sum of outputs}}{\text{weighted sum of inputs}}$$

$$= \frac{u_1 y_{1k} + u_2 y_{2k} + \cdots + u_s y_{sk}}{v_1 x_{1k} + v_2 x_{2k} + \cdots + v_m x_{mk}} \qquad (1)$$

We solve the following linear programming problem to obtain values for the weights (v_i and u_r) as variables.

Max $\quad u_1 y_{1k} + u_2 y_{2k} + \cdots + u_s y_{sk}$ (2)

Subject to $\quad v_1 x_{1k} + v_2 x_{2k} + \cdots + v_m x_{mk} = 1$

$$u_1 y_{1k} + \cdots + u_s y_{sk} < v_1 x_{1k} + \cdots v_m v_{mk}$$

$$v_{1k}, \cdots, v_{mk} \geq 0 \quad u_{1k}, \cdots, u_{sk} \geq 0 \qquad (3)$$

Finally, before solving, the linear program is converted to its dual for computational efficiency reasons:

Min $\quad \theta_k$ (4)

Subject to $\quad \theta_k x_{ik} - \sum_{j=1}^{n} \lambda_j x_{ij} \geq 0, \quad i = 1, \ldots, m,$

$$\sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{rk}, \quad r = 1, \ldots, s,$$

$$\lambda_j \geq 0 \qquad \lambda_j \geq 0, j = 1, \ldots, n \qquad (5)$$

This is one of the most basic DEA models, CCR model which was proposed by Charnes, Cooper and Rhodes in 1978. This model is built on the assumption of constant returns to scales of activities. As a result, the objective value (or score) of CCR is designated technical efficiency (TE) to distinguish it from other types of efficiency such as ‘allocative efficiency’ in which nil costs and prices are used. Efficiency (θ_k) value is never greater than 1. If the efficiency is 1, it means that the DMU is efficient; otherwise, it is inefficient.

With the addition of slack variables, the dual problem becomes:

Min $\quad \theta_k$ (6)

Subject to $\quad \theta_k x_{ik} - \sum_{j=1}^{n} \lambda_j x_{ij} = \sum_{i=1}^{m} s_i^-, i = 1, \ldots, m,$

$$\sum_{j=1}^{n}\lambda_j y_{rj} = y_{rk} + \sum_{r}^{s} s_r^{+}, r = 1,\ldots,s,$$

$$\lambda_j \geq 0 \tag{7}$$

The slack variables can be interpreted as the output shortfall and the input overconsumption compared to the efficiency frontier.

(2) BCC model

The CCR model is designed with the assumption of constant returns to scale. This is means that there is no assumption that any positive or negative economies of scales exist. It is assumed that a small scale irrigation should be able to be as efficient as a large one, that is, constant returns to scale. In order to address this, Banker, Charnes, and Cooper (1984) developed the BCC model which is built on the assumption of variable returns to scales of activities.

The BCC model is closely related to the CCR model as evident in the dual of the BCC model:

$$\text{Min} \quad \theta_k \tag{8}$$

$$\text{Subject to} \quad \theta_k x_{ik} - \sum_{j=1}^{n}\lambda_j x_{ij} \geq 0, \quad i = 1,\ldots,m,$$

$$\sum_{j=1}^{n}\lambda_j y_{rj} \geq y_{rk}, \quad r = 1,\ldots,s,$$

$$\lambda_j \geq 0, \sum_{j-1}^{n}\lambda_j = 1 \quad j = 1,\ldots,n, \tag{9}$$

The DEA defines three different forms of efficiency: technical efficiency (TE), pure technical efficiency (PTE), and scale efficiency (SE). Table 2.1 explains the three efficiencies. Similar to the TE of CCR, the objective value of BCC is said to reflect pure technical efficiency (PTE). Compared to CCR, imposing the additional constraint $\sum_{j=1}^{n}\lambda_j = 1$causes the feasible region of BCC to be a subset of that of CCR, which means PTE is not less than TE. The PTE measures how a DMU utilizes the resources under exogenous environments; a low PTE implies that the DMU inefficiently manages its resources. Use of the BCC model allows decomposition of TE into PTE and scale efficiency (SE), where the relationship between them is

$$\text{SE} = \frac{\text{TE (CCR scores)}}{\text{PTE (BCC scores)}} \tag{10}$$

and the SE measures how the scale size affects efficiency. If a DMU achieves a high PTE but a low TE, and thus low SE, it implies that the DMU should consider adjusting to proper scale size.

(3) DEA window analysis

A DEA window analysis work on the principle of moving averages and is useful to detect efficiency trends of DMUs over times. The rationale is that each DMU in a window is regarded as an entirely different one. This treatment enables comparison of a DMU's efficiency in a particular period with its behavior in other periods. It increases the number of DMUs so that discriminating power can be increased when a limited number of DMUs is available. As for the selection of a window width, Asmild, *et al.* (2004) pointed out that it should be as small as possible to minimize the unfairness comparison over time, but still large enough to have a sufficient sample size.

We measure the efficiency of each DMU once and hence need N ($n = 1,\ldots,N$) optimizations over T terms ($t = 1, \ldots, T$). At each term, DMUs have common r inputs, s outputs. The vector of inputs for DMU_n^t is denoted by

$$X_n^t = \begin{bmatrix} X_n^{1t} \\ \vdots \\ X_n^{rt} \end{bmatrix} \text{ and the vector of outputs } Y_n^t = \begin{bmatrix} Y_n^{1t} \\ \vdots \\ Y_n^{st} \end{bmatrix}$$

If the window starts at time $k(1 \leq k \leq T)$ with width $w(1 \leq w \leq T - k)$, then the matrices of inputs and outputs are represented as follows:

$$X_{kw} = \begin{bmatrix} x_1^k & x_2^k & \cdots & x_N^k \\ x_1^{k+1} & x_2^{K+1} & \cdots & x_N^{k+1} \\ \vdots & \vdots & \ddots & \vdots \\ x_1^{K+w} & x_2^{k+w} & \cdots & x_N^{k+w} \end{bmatrix}, \quad Y_{kw} = \begin{bmatrix} y_1^k & y_2^k & \cdots & y_N^k \\ y_1^{k+1} & y_2^{k+1} & \cdots & y_N^{k+1} \\ \vdots & \vdots & \ddots & \vdots \\ y_1^{k+w} & y_2^{k+w} & \cdots & y_N^{k+w} \end{bmatrix}$$

Substituting inputs and outputs of DMU_n^t into CCR or BCC model will get the results of DEA window analysis.

Table 2.1 DEA efficiencies and their explanations

Concept	Explanation	Detail
TE	The combination of pure technical and scale efficiency.	Is technically efficient if it is both pure technically and scale efficient.
PTE	The conversion of physical inputs into outputs relative to the best practice	For the current technical level, the inputs are completely utilized.
SE	For a given level of output, inputs are chosen to minimize the cost of production	Indicates whether the scale of production is overlarge or insufference

2.2.2. Variables

Assessment indexes are composed of input indicators and output indicators based on the windows DEA model. Indexes should be chosen in conformity to four rules: reasonableness, comprehensiveness, representativeness and practicability. The choice of inputs and outputs is usually a critical part of the analysis, as it involves different aspects of the agricultural water uses Indeed, it is possible to fully capture the whole range of agricultural activities due to their multi-factor determinable nature. Therefore, regarding the specification of the inputs and outputs, we employ the following two input indicators and one output variables as the model systems. The input and output indexes are defied as follows:

(1) Input: Agricultural Water Consumption

This variable means the volume of water consumption by irrigation of farming fields and by forestry, animal husbandry and fishing. Water consumption by forestry, animal husbandry and fishing includes irrigation of forestry and orchards, irrigation of grassland and replenishment of fishing pools.

(2) Input: Labor

This factor indicates that the full time equivalent number of employee in agriculture, forestry, animal husbandry and fishery.

(3) Output: The Added Value of Agriculture

This factor represents the economic benefit status, which is calculated as the total agricultural output minus the intermediate consumption in the agricultural production process.

Total agricultural output refers to the total value of products of agriculture, forestry, animal husbandry and fishery, and total value of services in support of agriculture, forestry, animal husbandry and fishery activities. It reflects the total scale and results of agricultural production during a given period. Prior to 1957, China’s gross agricultural output value included barnyard manure and handicraft products for self-consumption (clothes, shoes, stockings, and initial grain processing undertaken by peasants). Since 1958, cutting and felling of bamboo and trees by villages and other cooperative organizations under villages have been included in forestry; value of barnyard manure has been excluded from animal husbandry; self-consumed handicrafts have not been included from sideline occupations, while the output value of industries run by villages and cooperative organizations under village has been included in sideline occupations; and the output value of fish catches by motor fishing boats has been added to fishery. Since 1980, the value of handicraft products made for sale by individuals in households has been added to sideline occupations. Since 1984, industries run by villages and under villages have been included in the sector of industry. Since 1993, the subdivision of sideline occupations has been cancelled, and the hunting of wild animals has been classified into animal husbandry, and the gathering of wild plants and commodity industry run by rural household have been included in farming. A new industrial classification of economic activities was introduced in 2003. Under the new classification, value of services to agriculture, forestry, animal husbandry and fishery is included in the gross output value of agriculture, value of wood felling and transport is included in forestry, value of industrial output by rural households is not included in agriculture, and the collection of wild forest products is taken from agriculture and included in forestry. The First Agriculture Census of China revealed some discrepancy between the production of animal products from the annual reports and that from the census. According to the result of the First Agriculture census, efforts were made to adjust the annual reports of animal husbandry output and the output value of animal husbandry to make the figures from the annual reports consistent with the census data. “The Classification of Products for Statistical Purposes” implemented in 2010 made relevant revision on the output value of agriculture and forestry.

Gross output value of agriculture is obtained by multiplying the output of each product or by-product by its price, resulting in the output value of each single item. For a small number of products, annual output of which is not available or difficult to get due to the long production (growing) process involved, the output value is estimated through an indirect approach. The sum of output values of all products of agriculture, forestry, animal husbandry and fishery and services in support to those industries is then equal to the gross output value of agriculture.

2.2.3. Data Collection

For the purpose of agriculture water use efficiency of 31 provinces in China for the period 1999 – 2011, the major sources of data were obtained from NBS Database, China Statistical Yearbook, and China Water Resources Bulletin (Detail are shown in Table 2.2). In the calculation procedure, one year and one provinces are regarded as the DMUs in the temporal and spatial scale, respectively. Considering data availability and what has been used in previous literature, the inputs is aggregated into two categories: the full time equivalent number of employee, the volume of agricultural water consumption, and output is the added value of agricultural product. Table 2.3 and Table 2.4 presents the observed data and the descriptive statistics of the variables, respectively. We could see that, on average, the agriculture water consumption and number of labor for the 31 provinces of china all decrease from 1999 – 2011, while the added value of agricultural product have a decrease during 1990 – 2011.

Table 2.2 Data sources &variables used for estimate agricultural water use efficiency

Province	Input		Output
	Agricultural Water Consumption (100 million m^3)	Labor (10,000 persons)	Added Value of Agricultural Product (100 million Yuan)
Anhui	China Water Resources Bulletin (1999 – 2011)	NBS Database (National Bureau of Statistics of China) (1999 – 2011)	NBS Database (1999 – 2011)
Beijing			
Chongqing			
Fujian			
Gansu			
Guangdong			
Guangxi			
Guizhou			
Hainan			
Hebei			
Heilongjiang			
Henan			
Hubei			
Hunan			
Inner Mongolia			
Jiangsu			
Jiangxi			
Jilin			
Liaoning			
Ningxia			
Qinghai			
Shaanxi			
Shandong			
Shanghai			
Shanxi			
Sichuan			
Tianjin			
Tibet			
Xinjiang			
Yunnan			
Zhejiang			

Table 2.3 Observed data on inputs and output used in efficiency analysis

Year	Province	Input		Output
		Agricultural Water Consumption (100 million m^3)	Labor (10,000 persons)	Added Value of Agricultural Product (100 million Yuan)[a]
1999	Beijing	18.45	71.1	50.2
	Tianjin	12.95	81.46	46.3
	Hebei	174.82	1639.9	491.2
	Shanxi	35.56	654.78	105.9
	Inner Mongolia	150.24	525.58	208.2
	Liaoning	92.57	643.17	308.9
	Jilin	80.11	519.64	274.3
	Heilongjiang	198.08	744.67	309.7
	Shanghai	17.55	90.42	40.9
	Jiangsu	248.17	1505.01	594.6
	Zhejiang	127.48	1073.58	368.6
	Anhui	140.3	1991.07	449.4
	Fujian	114.52	779.7	279.9
	Jiangxi	152.86	1060.23	247.7
	Shandong	187.99	2474.13	734.8
	Henan	159.69	3299.25	735.8
	Hubei	163.68	1210.91	408.3
	Hunan	222.42	2074.13	446.2
	Guangdong	260.29	1530.94	565.7
	Guangxi	208.9	1603.4	325.6
	Hainan	36.8	171.97	86.2
	Chongqing	19.63	955.1	186.7
	Sichuan	131.41	2735.08	586.6
	Guizhou	48.33	1427.42	186.9
	Yunnan	113.29	1654.9	263.4
	Tibet	23.45	91.75	18.3
	Shaanxi	57.06	1008.91	201.5
	Gansu	97.21	689.79	141.3
	Qinghai	21.22	144.03	18.1
	Ningxia	90.23	152.79	35.6
	Xinjiang	463.82	306.95	199.6

Year	Province	Input		Output
		Agricultural Water Consumption (100 million m^3)	Labor (10,000 persons)	Added Value of Agricultural Product (100 million Yuan)[a]
2000	Beijing	16.49	69.7	50.3
	Tianjin	12.08	79.65	41.7
	Hebei	161.74	1665.45	487.2
	Shanxi	35.06	658.25	124.3
	Inner Mongolia	155.13	524.3	193.8
	Liaoning	86.89	651.15	265
	Jilin	85.42	516.83	214.4
	Heilongjiang	185.58	744.08	271.7
	Shanghai	15.31	84.6	39.7
	Jiangsu	261.42	1480.22	601.6
	Zhejiang	121.23	1014.93	367.5
	Anhui	121.31	2001.82	429.6
	Fujian	110.71	768.73	277.2
	Jiangxi	152.79	983.37	252.9
	Shandong	175.92	2462.62	760.6
	Henan	134.1	3558.55	749.1
	Hubei	164.9	1159.13	380.2
	Hunan	222.94	2071.38	437.3
	Guangdong	258.42	1570.12	528.4
	Guangxi	224.7	1556.84	297.1
	Hainan	35.43	177.21	94.8
	Chongqing	18.54	921.5	183
	Sichuan	132.3	2631.07	577.7
	Guizhou	50.19	1372.12	187.3
	Yunnan	111.8	1674.25	275.6
	Tibet	24.72	90.12	18.4
	Shaanxi	55.8	1002.15	199.7
	Gansu	97.42	697.53	138.1
	Qinghai	21.23	142.25	13.3
	Ningxia	80.75	153.13	30.3
	Xinjiang	453.21	314.45	215.7

Year	Province	Input		Output
		Agricultural Water Consumption (100 million m^3)	Labor (10,000 persons)	Added Value of Agricultural Product (100 million Yuan)[a]
2001	Beijing	17.4	67.87	48.7
	Tianjin	9.97	81.02	43.2
	Hebei	161.23	1664.96	527.4
	Shanxi	36.27	657.98	107.9
	Inner Mongolia	156.74	518.38	195.7
	Liaoning	84.03	648.95	289.6
	Jilin	77.43	514.34	272.8
	Heilongjiang	188.61	742.47	306.8
	Shanghai	13.66	83.18	42.3
	Jiangsu	280.76	1452.3	630.4
	Zhejiang	117.22	985.11	377.1
	Anhui	123.99	1975.55	432.8
	Fujian	111.45	760.39	284.6
	Jiangxi	150.43	977.37	266.8
	Shandong	182.91	2434.28	824.2
	Henan	159.59	3472.27	798.7
	Hubei	175.46	1143.72	408.5
	Hunan	224.43	2058.67	494.8
	Guangdong	257.68	1566.43	531.8
	Guangxi	216.94	1555.07	309.1
	Hainan	34.92	179.88	89.1
	Chongqing	20.25	884.62	188.2
	Sichuan	123.56	2582.64	567
	Guizhou	51.98	1368.28	187.4
	Yunnan	110.36	1689.43	286.6
	Tibet	24.86	88.84	19.2
	Shaanxi	54.78	985.93	205.2
	Gansu	96.26	696.75	146.9
	Qinghai	20.5	141.57	16.7
	Ningxia	78.23	151.73	31.5
	Xinjiang	463.84	321.03	199.8

Year	Province	Input		Output
		Agricultural Water Consumption (100 million m^3)	Labor (10,000 persons)	Added Value of Agricultural Product (100 million Yuan)[a]
2002	Beijing	15.45	64.11	46.7
	Tianjin	10.71	80.28	43.4
	Hebei	161.37	1651.97	563.4
	Shanxi	35.5	658.43	128.1
	Inner Mongolia	158.84	535.68	211.8
	Liaoning	83.16	659.19	312.6
	Jilin	83.61	509.14	284.6
	Heilongjiang	174.8	745.91	330.1
	Shanghai	11.98	81.45	44.8
	Jiangsu	289.19	1354.16	644.5
	Zhejiang	118.14	929.58	400.6
	Anhui	127.88	1931.49	442.6
	Fujian	111.45	756.57	292.7
	Jiangxi	136.77	983.53	281.7
	Shandong	188.27	2370.91	832.4
	Henan	145.74	3392.97	816.2
	Hubei	136.09	1130.97	417.1
	Hunan	205.84	2019.6	497
	Guangdong	250.42	1555.02	545.5
	Guangxi	225.86	1557.01	329.1
	Hainan	35.76	181.7	97.4
	Chongqing	20.7	852.72	204.3
	Sichuan	122.25	2503.26	593.2
	Guizhou	51.32	1353.92	184.6
	Yunnan	110.72	1696.05	295.7
	Tibet	27.25	88.8	20.1
	Shaanxi	54.62	994.93	214.8
	Gansu	97.25	738.22	150
	Qinghai	20.36	136.5	17.1
	Ningxia	76.03	150.52	34.2
	Xinjiang	448.85	325.99	205.8

Year	Province	Input		Output
		Agricultural Water Consumption (100 million m^3)	Labor (10,000 persons)	Added Value of Agricultural Product (100 million Yuan)[a]
2003	Beijing	12.9	59.53	44.2
	Tianjin	11.2	81.16	43.6
	Hebei	149.6	1660.24	648.3
	Shanxi	33.3	645.97	143
	Inner Mongolia	146.1	514.38	219
	Liaoning	83.5	667.33	292.3
	Jilin	67.5	502.47	287.1
	Heilongjiang	171.4	734.8	340.3
	Shanghai	16.3	71.74	44.5
	Jiangsu	223.1	1230.29	678.6
	Zhejiang	110.2	872.96	389.3
	Anhui	93.8	1860.57	377.8
	Fujian	101	735.92	305.3
	Jiangxi	104.1	971.26	257
	Shandong	157	2264.62	894.6
	Henan	113.4	3321.24	673.5
	Hubei	136.2	1110.71	451.5
	Hunan	209.4	1997.67	493.6
	Guangdong	242.6	1543.41	586.6
	Guangxi	205.4	1541.02	353.7
	Hainan	35.7	187.25	97.5
	Chongqing	20.7	813.19	213.4
	Sichuan	121.7	2413.99	590
	Guizhou	52.2	1322.1	181.5
	Yunnan	109.6	1690.22	286.1
	Tibet	22.6	84.4	23.8
	Shaanxi	50.7	988.96	205.4
	Gansu	96.4	760.75	165.5
	Qinghai	21.7	134.8	18.4
	Ningxia	58.5	145.82	34.9
	Xinjiang	454.9	330.86	308.9

Year	Province	Input		Output
		Agricultural Water Consumption (100 million m^3)	Labor (10,000 persons)	Added Value of Agricultural Product (100 million Yuan)[a]
2004	Beijing	12.97	57.9	48.1
	Tianjin	11.98	80.54	47.1
	Hebei	147.07	1600.43	766.8
	Shanxi	32.93	640.32	175.5
	Inner Mongolia	149.43	523.78	274.9
	Liaoning	85.71	685.82	366.8
	Jilin	66.44	496.69	324
	Heilongjiang	186.25	706.14	405.1
	Shanghai	18.81	65.22	50.4
	Jiangsu	288.53	1134.85	885.4
	Zhejiang	107.29	826.63	436.4
	Anhui	121.74	1794.67	522.1
	Fujian	104.2	722.74	341.8
	Jiangxi	128.54	960.97	328.6
	Shandong	154.29	2180.12	1070.8
	Henan	124.54	3234.98	956.9
	Hubei	131.71	1105.71	564
	Hunan	202.3	1975.89	638.8
	Guangdong	240.3	1524.97	670.6
	Guangxi	210.1	1516.13	437.5
	Hainan	37.85	190.76	109.2
	Chongqing	20.32	800.83	265.7
	Sichuan	121.17	2367	727.6
	Guizhou	51.92	1288.49	208.1
	Yunnan	109.65	1693.73	346
	Tibet	25.65	85.19	14.7
	Shaanxi	49.72	957.05	256.3
	Gansu	96.73	763.21	195.4
	Qinghai	21.83	131.85	21.8
	Ningxia	68.61	143.98	44.3
	Xinjiang	457.04	339.41	327.2

Year	Province	Input		Output
		Agricultural Water Consumption (100 million m^3)	Labor (10,000 persons)	Added Value of Agricultural Product (100 million Yuan)[a]
2005	Beijing	12.67	58.58	51.4
	Tianjin	13.59	79.55	48.1
	Hebei	150.22	1552.75	848.5
	Shanxi	32.68	637.44	155.1
	Inner Mongolia	143.88	529.18	316.5
	Liaoning	87.16	686.38	384.1
	Jilin	66.38	502.06	344.1
	Heilongjiang	192.08	696.67	472.4
	Shanghai	18.46	59.05	50.2
	Jiangsu	263.81	1058.28	918.1
	Zhejiang	106.73	786.92	480.8
	Anhui	113.55	1766.94	503.4
	Fujian	101.54	692.17	367.9
	Jiangxi	134.6	951.03	341.6
	Shandong	156.32	2045.93	1155.4
	Henan	114.49	3127.67	1068.9
	Hubei	142.12	1101.78	571.9
	Hunan	201.33	1951.9	698.6
	Guangdong	230.65	1533.48	774.8
	Guangxi	225.38	1503.06	499.7
	Hainan	35.14	193.39	114.7
	Chongqing	21.39	775.88	283.1
	Sichuan	121.83	2317.67	758.7
	Guizhou	50.45	1268.09	218.3
	Yunnan	108.41	1690.14	366.8
	Tibet	30.27	85.53	14.3
	Shaanxi	52.22	949.22	293.1
	Gansu	94.98	761.37	210.7
	Qinghai	21.06	128.73	23.3
	Ningxia	72.27	140.64	46.2
	Xinjiang	464.36	344.05	377.8

Year	Province	Input		Output
		Agricultural Water Consumption (100 million m^3)	Labor (10,000 persons)	Added Value of Agricultural Product (100 million Yuan)[a]
2006	Beijing	12.05	65.66	49.27
	Tianjin	13.43	78.27	54.45
	Hebei	152.57	1513.04	945.48
	Shanxi	34.22	635.68	162.28
	Inner Mongolia	142.18	533.87	353.5
	Liaoning	91.54	680.91	426.29
	Jilin	70.35	499.8	398.44
	Heilongjiang	208.26	689.6	542.24
	Shanghai	18.37	46.08	52.79
	Jiangsu	270.69	981.37	995.07
	Zhejiang	101.06	732.92	491.08
	Anhui	136.44	1740.98	592.25
	Fujian	97.96	664.82	394.73
	Jiangxi	132.92	937.75	372.92
	Shandong	169.4	2011.82	1313.23
	Henan	140.15	3039.48	1196.87
	Hubei	142.96	1085.81	610.7
	Hunan	198.4	1921.34	761.91
	Guangdong	226.92	1532.89	859.57
	Guangxi	222.28	1504.43	576.67
	Hainan	36.74	196.64	137.55
	Chongqing	18.12	741.67	243.82
	Sichuan	121.2	2263.56	785.6
	Guizhou	54.33	1247.08	225.33
	Yunnan	105.57	1677.18	394.77
	Tibet	31.77	86.6	21.02
	Shaanxi	56.8	948.41	324.48
	Gansu	94.31	751.01	229.99
	Qinghai	21.79	124.03	24.33
	Ningxia	71.73	136.54	52.74
	Xinjiang	469.95	349.2	348.54

Year	Province	Input		Output
		Agricultural Water Consumption (100 million m^3)	Labor (10,000 persons)	Added Value of Agricultural Product (100 million Yuan)[a]
2007	Beijing	11.73	61.53	53
	Tianjin	13.84	76.98	58
	Hebei	151.59	1479.04	1105
	Shanxi	34.32	633.92	179
	Inner Mongolia	141.77	538.56	426
	Liaoning	91.67	669.09	501
	Jilin	67.53	492.2	438
	Heilongjiang	214.75	675.15	651
	Shanghai	16.21	51.78	58
	Jiangsu	268.51	930.17	1084
	Zhejiang	100.22	688.04	525
	Anhui	120.56	1639.67	647
	Fujian	100.94	637.46	436
	Jiangxi	151.35	897.51	415
	Shandong	159.71	1949.98	1502
	Henan	120.07	2909.88	1337
	Hubei	132.65	1047.67	720
	Hunan	193.89	1890.78	906
	Guangdong	224.84	1532.3	929
	Guangxi	208.39	1504.92	668
	Hainan	35.84	199.89	144
	Chongqing	18.75	699.28	303
	Sichuan	118.71	2200.45	955
	Guizhou	48.72	1203.62	260
	Yunnan	105.95	1664.21	442
	Tibet	33.43	87.67	27
	Shaanxi	55.51	925.66	390
	Gansu	96.05	741.39	271
	Qinghai	20.47	119.82	31
	Ningxia	64.75	137.72	65
	Xinjiang	476.77	354.34	464

Year	Province	Input		Output
		Agricultural Water Consumption (100 million m^3)	Labor (10,000 persons)	Added Value of Agricultural Product (100 million Yuan)[a]
2008	Beijing	11.35	61.83	59
	Tianjin	12.99	76.28	63
	Hebei	143.23	1478.23	1187
	Shanxi	32.92	637.85	200
	Inner Mongolia	134.1	526.74	469
	Liaoning	90.89	662.27	536
	Jilin	69.29	491.07	504
	Heilongjiang	218.15	678.01	738
	Shanghai	16.74	47.52	62
	Jiangsu	287.34	896.37	1214
	Zhejiang	98.73	666.35	579
	Anhui	151.91	1592.8	736
	Fujian	99.3	636.55	484
	Jiangxi	148.89	887.12	463
	Shandong	157.61	1991.87	1697
	Henan	133.49	2837.24	1515
	Hubei	142.8	995.76	878
	Hunan	193.19	1877.91	1055
	Guangdong	227.74	1537.76	1037
	Guangxi	202.91	1534.59	758
	Hainan	35.63	201.04	176
	Chongqing	18.93	676.09	351
	Sichuan	113.64	2181.24	1162
	Guizhou	51.58	1202.06	307
	Yunnan	105.06	1659.15	515
	Tibet	33.94	88.28	29
	Shaanxi	57.7	902.02	481
	Gansu	96.93	727.57	312
	Qinghai	22.37	120.61	36
	Ningxia	67.97	133.02	76
	Xinjiang	486.15	358.39	472

Year	Province	Input		Output
		Agricultural Water Consumption (100 million m^3)	Labor (10,000 persons)	Added Value of Agricultural Product (100 million Yuan)[a]
2009	Beijing	11.38	60.87	64.3
	Tianjin	12.84	75.7	68.6
	Hebei	143.91	1472.5	1338.5
	Shanxi	34.41	631.62	280.5
	Inner Mongolia	138.67	528.19	474.9
	Liaoning	91.12	661.41	544.2
	Jilin	71.15	495.82	523.1
	Heilongjiang	237.4	684.1	772.9
	Shanghai	16.78	45.55	65.5
	Jiangsu	300.12	876.31	1355.1
	Zhejiang	97.28	653.55	627
	Anhui	167.22	1566.05	794
	Fujian	100.83	626.28	522.7
	Jiangxi	157.21	866.39	492.8
	Shandong	156.4	1984.42	1883.4
	Henan	138.1	2754.21	1670.2
	Hubei	149.43	965.73	938.3
	Hunan	189.25	1867.33	1167
	Guangdong	228.71	1521.76	1085.1
	Guangxi	195.26	1546.94	777.5
	Hainan	34.03	207.47	197.8
	Chongqing	19.02	649.69	390.5
	Sichuan	123.64	2148.07	1267.9
	Guizhou	50.8	1207.08	330.5
	Yunnan	103.46	1657.83	569.9
	Tibet	27.45	91.19	28.4
	Shaanxi	57.21	872.48	509.4
	Gansu	93.77	732.9	345
	Qinghai	21.61	120.07	37.1
	Ningxia	65.26	127.59	84.2
	Xinjiang	489.39	366.18	532.4

Year	Province	Input		Output
		Agricultural Water Consumption (100 million m^3)	Labor (10,000 persons)	Added Value of Agricultural Product (100 million Yuan)[a]
2010	Beijing	10.83	60.12	71.55
	Tianjin	10.97	73.85	81.9
	Hebei	143.77	1458.33	1670.46
	Shanxi	37.98	632.44	374.45
	Inner Mongolia	134.52	540.53	586.37
	Liaoning	89.82	663.56	675.5
	Jilin	73.84	501.85	577.03
	Heilongjiang	249.6	677.52	876.29
	Shanghai	16.76	34.06	66.86
	Jiangsu	304.23	859.83	1556.24
	Zhejiang	94.64	627.43	747.66
	Anhui	166.7	1521.85	952.47
	Fujian	97.19	623.73	616.32
	Jiangxi	151.02	851.41	534.52
	Shandong	154.76	1993.42	2146.57
	Henan	125.59	2698.45	2080.78
	Hubei	138.29	900.14	1244.73
	Hunan	185.79	1861.85	1432.89
	Guangdong	227.47	1468.25	1229.29
	Guangxi	194.57	1556.9	911.32
	Hainan	33.88	205.29	219.78
	Chongqing	19.84	626.12	465.3
	Sichuan	127.26	2131.01	1436.71
	Guizhou	50.05	1188.27	385.61
	Yunnan	95.32	1649.46	609.24
	Tibet	31.72	91.56	30.49
	Shaanxi	55.47	850.61	684.87
	Gansu	94.28	724.82	441.3
	Qinghai	23.19	120.99	55.1
	Ningxia	65.05	125.09	110.53
	Xinjiang	484.64	376.03	812.36

Year	Province	Input		Output
		Agricultural Water Consumption (100 million m^3)	Labor (10,000 persons)	Added Value of Agricultural Product (100 million Yuan)[a]
2011	Beijing	10.2	58.05	75.19
	Tianjin	11.55	73.18	87.42
	Hebei	140.49	1433.17	1876.81
	Shanxi	43.4	643.43	431.03
	Inner Mongolia	135.94	542.33	688.45
	Liaoning	89.74	663.63	789.64
	Jilin	81.64	510.17	676.16
	Heilongjiang	272.26	677.71	1150.19
	Shanghai	16.47	33.38	71.32
	Jiangsu	307.6	821.69	1809.83
	Zhejiang	92.07	616.76	831.66
	Anhui	168.38	1493.01	1057.55
	Fujian	98.62	620.37	716.77
	Jiangxi	171.74	849.51	611.72
	Shandong	148.92	1981.21	2255.03
	Henan	124.6	2655.29	2108.83
	Hubei	142.26	885.63	1495.89
	Hunan	183.12	1863.91	1692.86
	Guangdong	224.16	1402.33	1426.17
	Guangxi	193.21	1546.23	1089.84
	Hainan	33.84	208.73	260.46
	Chongqing	23.62	604.04	560.77
	Sichuan	128.44	2086.16	1700.8
	Guizhou	49.7	1165.32	430.84
	Yunnan	96.08	1646.28	742.65
	Tibet	27.37	91.88	32.59
	Shaanxi	56.22	822.17	841.6
	Gansu	93.84	715.42	498.04
	Qinghai	23.48	118.11	61.33
	Ningxia	66.12	123.94	126.54
	Xinjiang	488.41	402.4	844.8

Table 2.4 Descriptive statistics on inputs and output used in efficiency analysis

Year	Units	Input		Output
		Agricultural Water Consumption (100 million m^3)	Labor (10,000 persons)	Added Value of Agricultural Product (100 million Yuan[a])
1999	Average	124.81	1061.67	287.63
	SD[b]	95.07	829.95	204.90
	Minimum	12.95	71.10	18.10
	Maximum	463.82	3299.25	735.80
2000	Average	170.44	1057.98	280.76
	SD	288.59	846.50	204.94
	Minimum	12.08	69.70	13.30
	Maximum	1664.90	3558.55	760.60
2001	Average	123.41	1046.81	294.54
	SD	97.03	832.76	217.82
	Minimum	9.97	67.87	16.70
	Maximum	463.84	3472.27	824.20
2002	Average	120.52	1031.95	305.87
	SD	94.35	811.86	222.33
	Minimum	10.71	64.11	17.10
	Maximum	448.85	3392.97	832.40
2003	Average	110.73	1008.38	311.26
	SD	90.40	790.55	223.21
	Minimum	11.20	59.53	18.40
	Maximum	454.90	3321.24	894.60
2004	Average	115.67	986.97	381.55
	SD	93.61	769.44	282.96
	Minimum	11.98	57.90	14.70
	Maximum	457.04	3234.98	1070.80
2005	Average	115.48	966.95	411.56
	SD	93.30	747.04	307.91
	Minimum	12.67	58.58	14.30
	Maximum	464.36	3127.67	1155.40

2006	Average	118.21	948.98	449.61
	SD	94.58	731.59	343.88
	Minimum	12.05	46.08	21.02
	Maximum	469.95	3039.48	1313.23
2007	Average	116.11	923.89	515.81
	SD	94.96	707.86	390.24
	Minimum	11.73	51.78	27.00
	Maximum	476.77	2909.88	1502.00
2008	Average	118.18	914.95	585.52
	SD	97.10	701.75	442.50
	Minimum	11.35	47.52	29.00
	Maximum	486.15	2837.24	1697.00
2009	Average	120.10	905.33	636.73
	SD	99.34	690.94	486.90
	Minimum	11.38	45.55	28.40
	Maximum	489.39	2754.21	1883.40
2010	Average	119.00	893.38	764.02
	SD	99.03	682.74	578.56
	Minimum	10.83	34.06	30.49
	Maximum	484.64	2698.45	2146.57
2011	Average	120.76	882.43	872.35
	SD	100.51	671.82	636.21
	Minimum	10.20	33.38	32.59
	Maximum	488.41	2655.29	2255.03
All years	Average	122.57	971.51	469.02
	SD	122.82	759.94	420.96
	Minimum	9.97	33.38	13.3
	Maximum	1664.9	3558.55	2255.03

Note: a: The exchange rate was 1 Yuan = 0.154US$ in 2011

b: SD = Standard deviation

2.3 Result and discussion

The window DEA efficiency scores are computed by employing an input-oriented model since it is assumed that agricultural entities focusing on cost control have the possibility to adjust input usage, i.e., water usage. The window DEA allows one to evaluate the dynamic efficiency of the DMUs over time. The choice is based on the fact that agricultural entities may take more than one year to adjust the input given the output levels. As for a moving average approach, DMUs in different years are treated as if they were ‘‘different” DMUs. This approach allows one to compare the efficiency of a DMU with its own efficiency in other years as well as with the other DMUs’ efficiency.

To compute China agricultural water use dynamic efficiency scores during 1999 – 2011, the software package EMS (Efficiency Measurement System) are used. In what follows, presentation and discussion of each type of efficiency are undertaken and the results are summarized.

According to Cooper, *et al.* (2007), the following formulas can be used to study the properties of these window DEA analyses. Firstly, we introduce the following symbols

n = number of DMUs
k = number of periods
p = length of window (p ≤ k)
w = number of windows

$$p=\begin{cases}\dfrac{k+1}{2} & \text{when k is odd}\\[2mm] \dfrac{k+1}{2}\pm\dfrac{1}{2} & \text{when k is even}\end{cases} \tag{11}$$

Total number of “different” DMUs: $n(k-p+1)p$ .From these formulas the following is obtained: n=31, k=13, p=7. Then, total number of “different” DMUs = 1519. Thus, there are 1519 data points to which the DEA model is applied to compute the efficiency scores.

2.3.1 Overall Features of Agricultural Water Use Technical Efficiency

The agricultural water use technical efficiency (TE) scores were summarized in appendix Table A1 – A5. From those table, we could find the following:

(1) The TE of Hebei, Jiangsu, Hubei and Chongqing have been the benchmark for lying on the agricultural water use performance frontier.

(2) Beijing, Jilin, Shanghai, Jiangsu, Shandong, Chongqing and Xinjiang gain an

efficiency score above 0.65 for most years.

(3) Except for the regions above, Liaoning, Shanghai, Zhejiang, Shandong and Hainan have efficiencies that are above or close to 0.5 for most years during the study period.
(4) The efficiencies of the rest of the regions are below 0.6 for almost all years, and there are 3 regions (Tibet, Qinghai and Ningxia) that have the lowest efficiency scores below 0.5 for most year in the period from 1999 to 2011.

Furthermore, we illustrate the average agriculture water use TE of the 31 regions of china in Figure 2.3. Following results can be found from Figure 2.3.

(1) The average agricultural water use TE of China as a whole country is around 0.44 – 0.7 during 1999 – 2011, which is considered to not be high.
(2) 9 out of 31 regions (Beijing, Tianjin, Hebei, Jilin, Shanghai, Jiangsu, Shandong, Chongqing and Xinjiang) possess average TE score above 0.65.
(3) 9 out of 31 regions (Liaoning, Heilongjiang, Zhejiang, Fujian, Henan, Hubei, Hainan, Sichuan and Shaanxi) possess average TE score around 0.50 – 0.65
(4) 13 regions (Shanxi, Inner Mongolia, Anhui, Jiangxi, Hunan, Guangdong, Guangxi, Guizhou, Yunnan, Tibet, Gansu, Qinghai and Ningxia) are below 0.50.

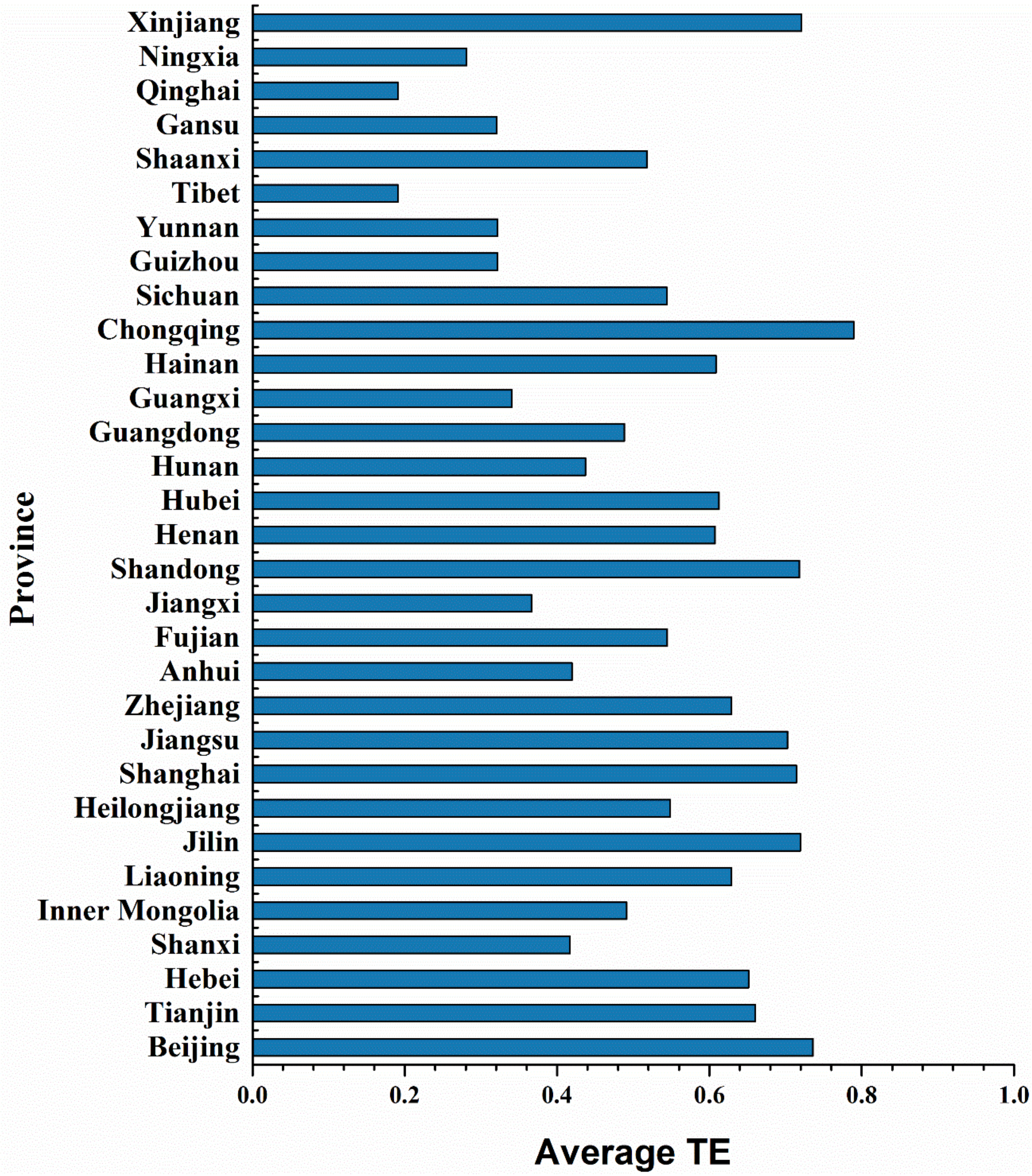

Figure 2.3 Average agricultural water use TE of China

2.3.2 Agricultural Water Use Technical Efficiency on Spatial Scale

In order to find out the relationship between water resource endowment and water use TE, 31 provinces are divided into three groups according to the Falkenmark indicator which is the most widely used measure of water stress. Falkenmark indicator defined as the fraction of the total annual runoff available for human use. Detailed information of the regions is shown in Table 2.5. Furthermore, we illustrate the average TE of 31 provinces of China in Figure 2.4 and the results shows the following:

(1) In abundant water resources area: only Chongqing and Xinjiang with relatively higher TE scores which is above 0.65. 4 provinces (Zhejiang, Fujian, Hainan and Sichuan) have average TE scores between 0.5 – 0.65. And 8 provinces (Jiangxi, Hunan, Guangdong, Guangxi, Guizhou, Yunnan, Tibet and Qinghai) are below 0.5, which is considered as low efficiency.
(2) In insufficient water resources area: just Jilin is highly efficient with average TE scores above 0.65, 4 provinces (Liaoning, Heilongjiang, Hubei and Shaanxi) have average TE scores around 0.5 – 0.65 and 3 provinces (Inner Mongolia, Anhui and Gansu) are inefficient with average TE scores below 0.5.
(3) In water resources scarcity area: 6 provinces (Beijing, Tianjin, Hebei, Shanghai, Jiangsu and Shandong) are highly efficient with average TE scores above 0.65, Henan has average TE scores around 0.5 – 0.65 and 2 provinces (Shanxi and Ningxia) are below 0.50, which is consider as relatively low efficiency.

Even though over 80% of the water resources concentrated locate in the southeastern part of China where the arable area is only 35% of the country's total arable area, which is 95 million hectares, the agricultural water use efficiency in the western and southern regions where are rich in water resources can be considered as low water use efficiency areas. It means that agricultural water use efficiency trend to be lower in the regions where the water resource is sufficient. This finding are as same as the previous studies which indicate the close correlation between water scarcity and water use efficiency (Molden, *et al.*, 2010; Garrido, 2011; Varghese, *et al.*, 2013).

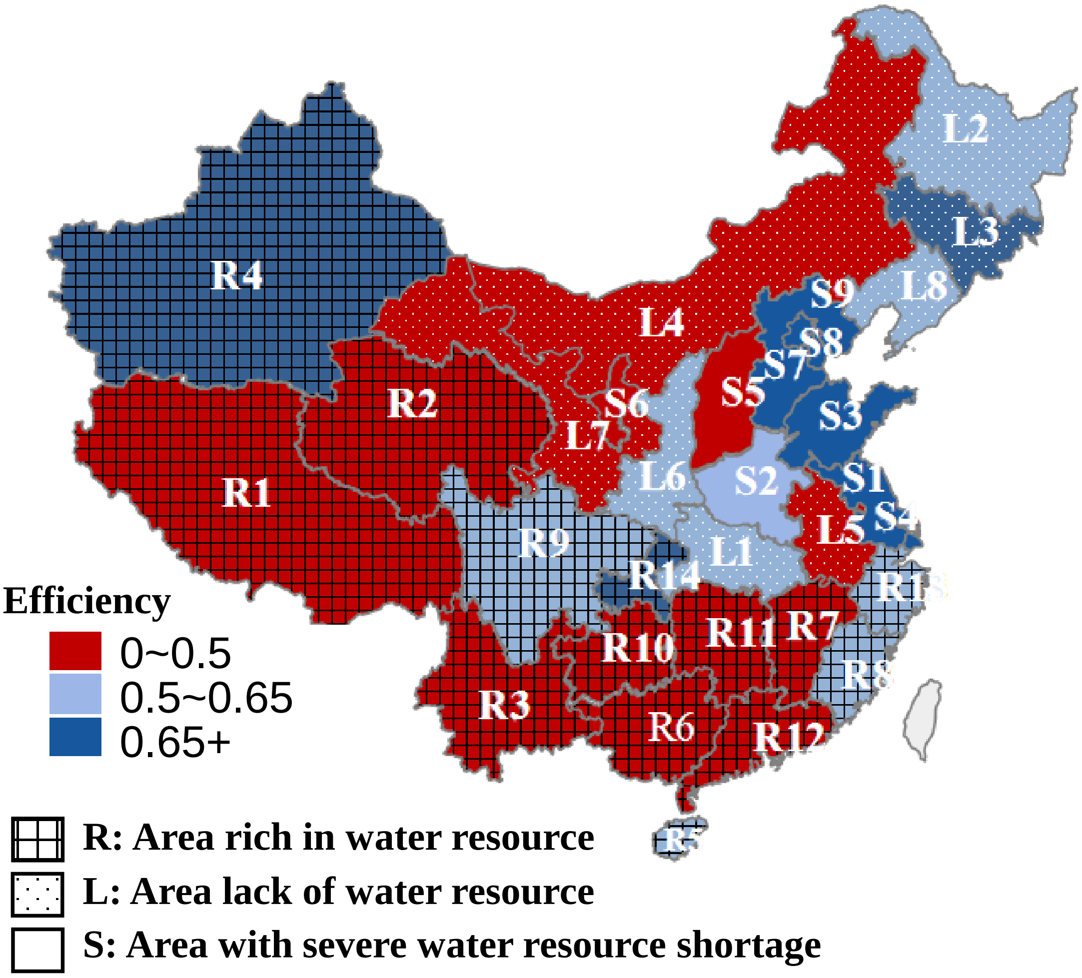

Figure 2.4 China agriculture water use TE performance during 1999 – 2011

Table 2.5 Group concept and their explanations (Based on Falkenmark indictor)

Definition	Areas
Area rich in water resource (1,700〜 m^3 per capita)[1)]	R1.Tibet, R2.Qinghai, R3.Yunnan, R4.Xinjiang, R5.Hainan, R6.Guangxi, R7.Jiangxi, R8.Fujian, F9.Sichuan, R10.Guizhou, R11.Hunan, R12.Guangdong, R13. Zhejiang, R14.Chongqing
Area lack of water resources (500〜1,700 m^3 per capita)[1)]	L1.Hubei, L2.Heilongjiang, L3.Jilin, L4.Inner Mongolia, L5.Anhui, L6.Shaanxi, L7.Gansu, L8.Liaoning,
Water scarcity area (〜500 m^3 per capita)[1)]	S1.Jiangsu, S2.Henan, S3.Shandong, S4.Shanghai, S5.Shanxi, S6.Ningxia, S7.Hebei, S8.Tianjin, S9.Beijing

Note: 1) average runoff per capita during 1999 – 2011 was used

2.3.3 Agricultural Water Use Technical Efficiency on Temporal Scale

We also divided 31 provinces into three major areas based on GDP per capital in order to identify the relationship between the economic grow and agricultural water use efficiency. As shown in Table 2.6, the developed area is constituted by 11 regions including eight coastal provinces (Hebei, Liaoning, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan) and three municipalities (Beijing, Tianjin, and Shanghai). This area has experienced the most rapid economic growth in China in the past 30 years and its average GDP output for our study period (1999–2011) is around half of Chinese total GDP output. Most light industries and quite a few heavy industries, as well as most service industries and foreign trades in China are located in the east area. Because of the convenient transportation system and developed infrastructure, this area has also attracted the most foreign investment and technology. Beijing and Shanghai are considered as the most economically and socially developed regions in China.

The developing area consists of 10 regions which are inland provinces: Heilongjiang, Jilin, Inner Mongolia, Henan, Shanxi, Anhui, Hubei, Hunan, Jiangxi, and Guangxi. This area has a large population and it is a home base for farming and related industries. The economy growth, attracted investments and technologies in this area are less than those of the developed area but more than those of the less developed area. There are also lots of heavy industries located in the northeast (Heilongjiang and Jilin) and central south (Hubei and Hunan) of this area, which are known as another two industrial centers of China. Inner Mongolia and Shanxi are the two largest energy industry regions of China.

The less developed area covers more than half of the territory in China, and includes one municipality of Chongqing and nine provinces, including Gansu, Guizhou, Ningxia, Qinghai, Shaanxi, Tibet, Yunnan, Xinjiang, and Sichuan. Compared to the other two areas, this area has low population density and high resource reserves as surface water, coal, oil, natural gas, and other minerals.

The result of average TE scores of three area and all of the provinces for each year from 1999 to 2011 are show in Figure 2.5.This figure indicates the following results:

(1) From an area perspective and in each year during our study period, the developed area exhibits the highest average TE score. The developing area has a better TE score than the less-developing area, but both of these are below the average TE score at the whole provinces level.

(2) All of the three areas have similar increase and decrease trends during the period of 1999 to 2011.

(3) In 1999, agricultural water use efficiency of China was 0.47, which slightly decreased

to 0.43 in 2002. After that, the efficiency continuously increased to the highest level of 0.70 in the last year of our study period.

In order to dynamically analyze the efficiency changes for each region during our study period and give a more detailed and clear demonstration, we illustrate 31 regions' agricultural water use TE for 1999, 2003, 2007 and 2011 in Figure 2.6. The following could be seen.

(1) About half of the 31 regions' efficiencies increased from 1999 through 2003, 2007 and 2011, and the most evident increases appeared in Hebei, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Jiangsu, Shandong, Hubei, Hunan, Shaanxi and Ningxia.

(2) Four out of 31 regions experienced an efficiency decrease process during 1999, 2003, 2007 and 2011, and the most evident decrease happened in Tibet.

(3) The efficiencies of the rest of the regions changed a little among these four time points.

In general, agriculture water use efficiency was presented a continuously increasing trend during the period 1999 to 2011, especially in the period of 2004 to 2011, in accordance with other studies (Xiao, *et al.*, 2013; Zhang, *et al.*, 2015; Long and Pijanowski, 2017). This may mainly be contributed by a series of water saving policies issued and carried out by the Chinese government in order to alleviate water shortages. Between 1990 and 2010, many water-related laws and regulations had been issued during this period, including the Law on Water and Soil Conservation (issued in 1991), Law on Prevention and Control of Water Pollution (issued in 1996), Flood Control Law (issued in 1997), and Water Law (revised in 2002)(Liu, et al., 2013). Building a water-saving society was first written in China's water law. Mu, *et al.* (2016) also indicate, the investment in water-related infrastructure for the municipal government increased during the period of 2004 to 2011. Moreover, those results indicate the TE score and economic growth has positive correlation. Chen, *et al.* (2014) concluded that adequate infrastructure was identified as one of the necessary prerequisite for the successful implementation of the water-saving mechanism. Due to the developed area (eastern area) has much superiority such as coastal location, level of economic development and market demand, which can be helpful to introduction of advanced technology and innovation, the developed areas has the higher TE score compared to the developing and less-developing areas. It means the developing level of the area affects the water use efficiency. The finding of Deng, et al. (2016) and Zhang, *et al.* (2016) also confirm the positive impact of economic level in improving agricultural water use efficiency. Therefore, economically backward regions should improve water use efficiency by learning water-saving technology from economically developed regions with higher water use.

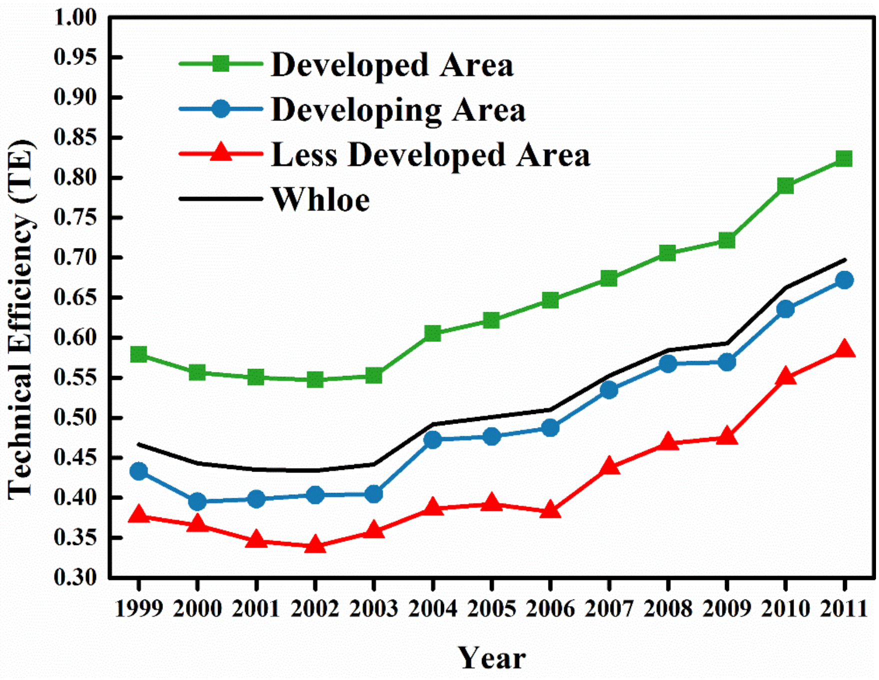

Figure 2.5 Average TE score of China and its three areas

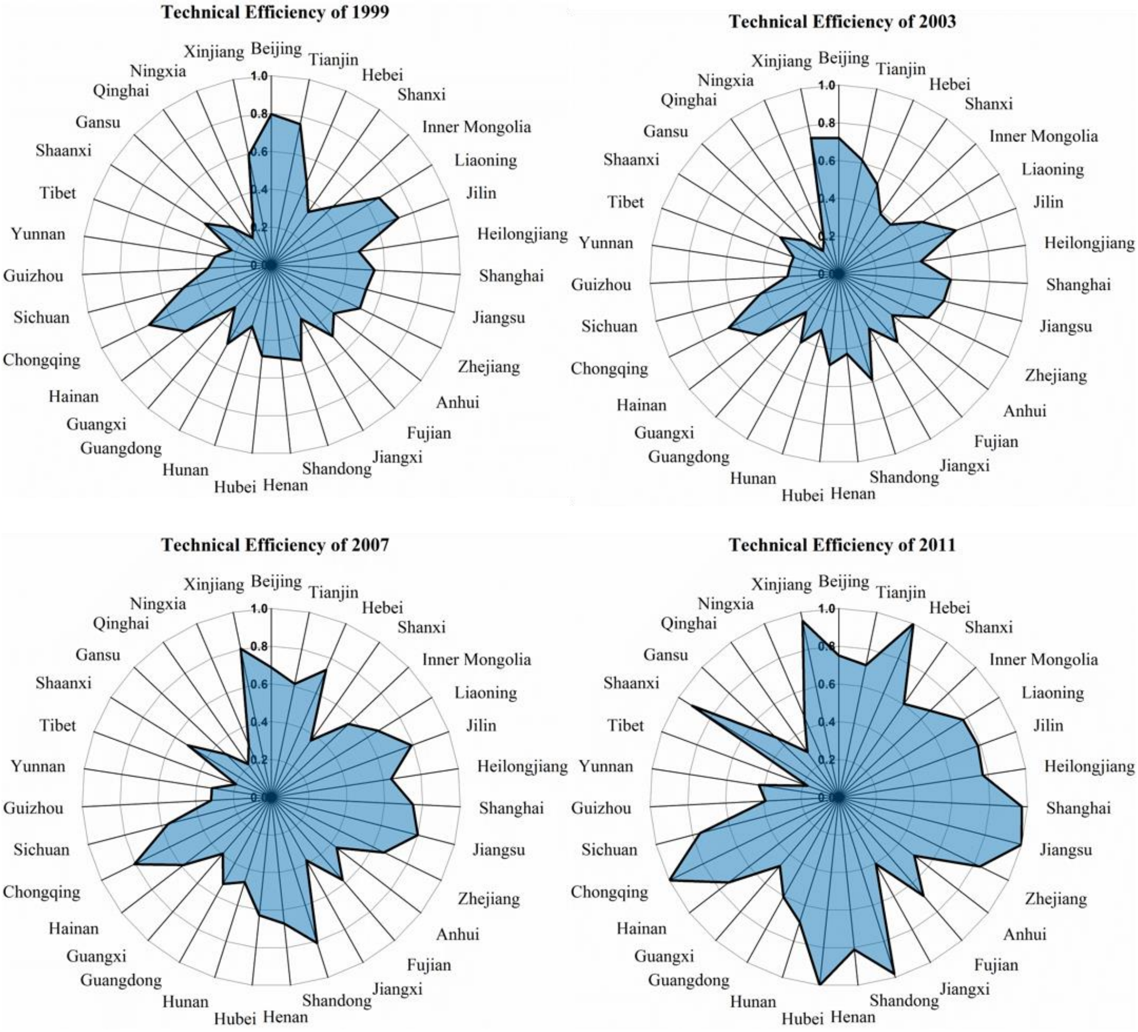

Figure 2.6 China’s regional agricultural water use TE changes

Table 2.6 Areas and regions in China

Areas	Regions (provinces, autonomous regions, and municipalities) included	Average GDP (RMB billion)
Developed Area	Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan	1,257
Developing Area	Inner Mongolia, Anhui, Jiangxi, Hunan, Guangxi, Heilongjiang, Henan, Hubei, Jilin, Shanxi	672
Less Developed Area	Sichuan, Shaanxi, Chongqing, Yunnan, Xinjiang, Guizhou, Gansu, Ningxia, Qinghai, Tibet	324
Whole country	31 regions	767

2.3.4 Agricultural Water Use Pure Technical and Scale Efficiency

For the purpose of exporting the primary sources of efficiency change, TE score was decomposed into PTE and SE (TE = PTE × SE) and the average scores during 1999 – 2001 5arized in Figure 2.7 and Table 2.7 (The efficiency score for each area are shown in Appendix Table A1 – A3). For a specific region, if the SE is greater than PTE, improvements should be carried out in management practices, such as adjusting irrigation water and labor. If the SE is smaller than PTE, the scale of production should be adjusted.

With respect to SE, it can be used to measure whether scale size is appropriate. The Figure 2.7 and Table 2.7 show the following:

(1) The average SE for agriculture water use was superior to PTE, although both exhibited upward trends.
(2) From 1999 to 2012, the average SE scores for agriculture water utilization in China was slightly improved, which was increased from 0.91 to 0.93
(3) The SE average scores reveals that Hebei was the best performer and Tibet was the worst.
(4) Only Tibet and Qinghai have a SE average scores below 0.4, which is consider as relatively low efficiency.
(5) The SE average scores of the rest of the regions are above 0.9 for most region
(6) There were 26 provinces for which the SE score was relatively high compared with the PTE value, accounting for 84 of provinces. These results clearly indicates that the scale size is appropriate for agriculture water use in China.

After discussing SE, what remains is PTE, which is an index for measuring how a firm utilizes its resources under exogenous environments. The results show that each of provinces effectively used its resources over the period 1999 – 2011. As show in Figure 2.7 and Table 2.7, it indicate the following result:

(1) Each of the province's PTE average scores is higher than TE average.
(2) Beijing was the best performer in term of PTE average scores and Gansu was the worst.
(3) 10 out of 31 regions (Beijing, Tianjin, Hebei, Jilin, Shanghai, Jiangsu, Shandong, Henan, Chongqing and Xinjiang) have average PTE scores above 0.65.
(4) 10 out of 31 regions (Liaoning, Heilongjiang, Zhejiang, Fujian, Hubei, Hainan, Sichuan, Tibet, Shaanxi and Qinghai) with average TE scores around 0.50 – 0.65
(5) 11 regions (Shanxi, Inner Mongolia, Anhui, Jiangxi, Hunan, Guangdong, Guangxi, Guizhou, Yunnan, Gansu and Ningxia) are below 0.50.

For the purpose of exporting the primary sources of efficiency change, TE score was decomposed into PTE and SE. The Figure 2.8 shown the relationships between TE, PTE and SE. In 1999 and 2012, the SE was distributed above the 45° diagonal, near the optimal level of effectiveness, and was not strongly correlated with TE. This indicates that the SE for agriculture water use did not determine the TE score. On the other hand, the relationship between PTE and TE shown that most samples fall on the periphery of the 45° line, suggesting that these two variables have a higher correlation than seen between SE and PTE. The correlation coefficient of PTE and TE was 0.82 in 1999, and 0.93 in 2011, showing that PTE has become an increasingly significant factor over the last 12 years. These results are consistent with the finding of Wang, *et al.* (2017). Moreover, in Table 2.7, the influence of PTE on TE is greater than that of SE for most of the provinces. Thus the PTE should be improved in order to achieve the efficient frontier, except Beijing, Tianjin, Shanghai and Tibet. Besides, in those provinces, the scale of production should be adjusted.

Based on above, we give some suggestions to improve China agricultural water use efficiency from PTE and SE aspects, as set out below.

A. Methods for improving PTE

There are several important ways of improving PTE for agricultural water use efficiency. An important aspect of improving the investment in water-related infrastructure, such as sprinkler irrigation, drip irrigation and underground pipe, which can conserve water over 30% by greatly reducing soil evaporation and maximizing crop water productivity (Blanke, *et al.*, 2007). While, the key economic barrier to implementing those technology is the high capital cost, the subsidy from government is necessary. Furtherly, for the farmer, adopting plastic mulch, surface pipe, which can conserve 23-35% of water, was potential way to save water (Jiang, 2013; Ingman, *et al.*, 2015). Moreover, as the irrigation water price is reality low in China, adopt of pricing mechanisms for water also a potential way to reduce water use. Farmers at this moment have little incentive to conserve water and to invest in new water saving technology. Huang, *et al.* (2010) indicate the pricing was a potential way to reduce water use, when the price of water is raised to a relatively high level. Additionally, Zhou, *et al.* (2015) indicated increasing irrigation water price may result in a further overexploitation of groundwater due to the unrestricted extraction of groundwater on existing wells. Therefore, the gradual introduction of water charges for this type of farmer is recommended, can probably be a trigger for more efficient water use. That means, the water charge should not exceed the tolerance for famers and the famer’ response should be fully considered.

B. Methods for improving SE

In order to improve the scales efficiency, the number of employee in agriculture should be guided by the optimum scale for maximum urban agricultural water use efficiency. As the result show in Table A5, policies should encourage the application of machine in order to reduce the redundant amounts of employee and improving the agricultural water use efficiency.

Furthermore, policy measures that encourage adoption of water-conserving irrigation technologies are widely believed to make more water available for cities and the environment. While, Ward and Pulido-Velazquez (2008) indicate the adoption of more efficient irrigation technologies reduces valuable return flows and limits aquifer recharge, these measures can actually increase water depletions. Therefore, the next step was to estimate the appropriate water saving leveling in each provinces.

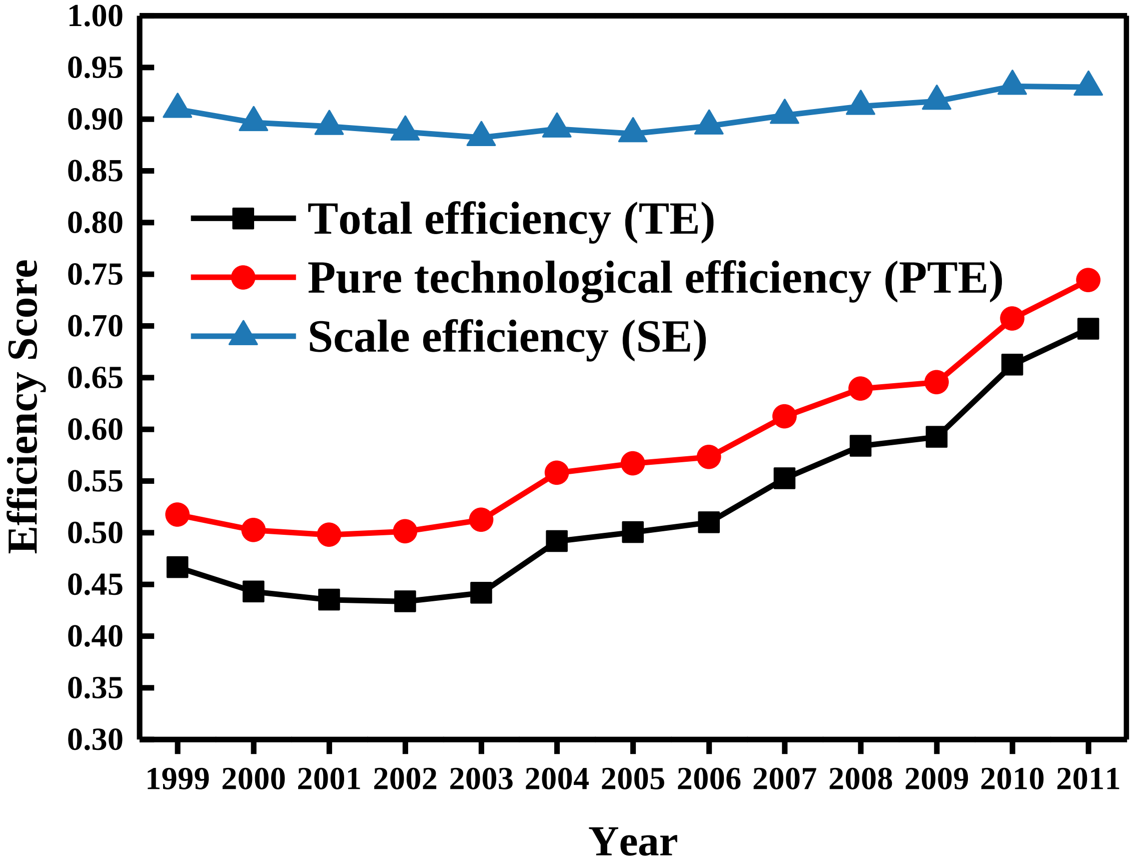

Figure 2.7 Average efficiency for agricultural water use in China from 1999 to 2012. Black, red, and blue lines indicate total efficiency (TE), pure technological efficiency (PTE), and scale efficiency (SE), respectively.

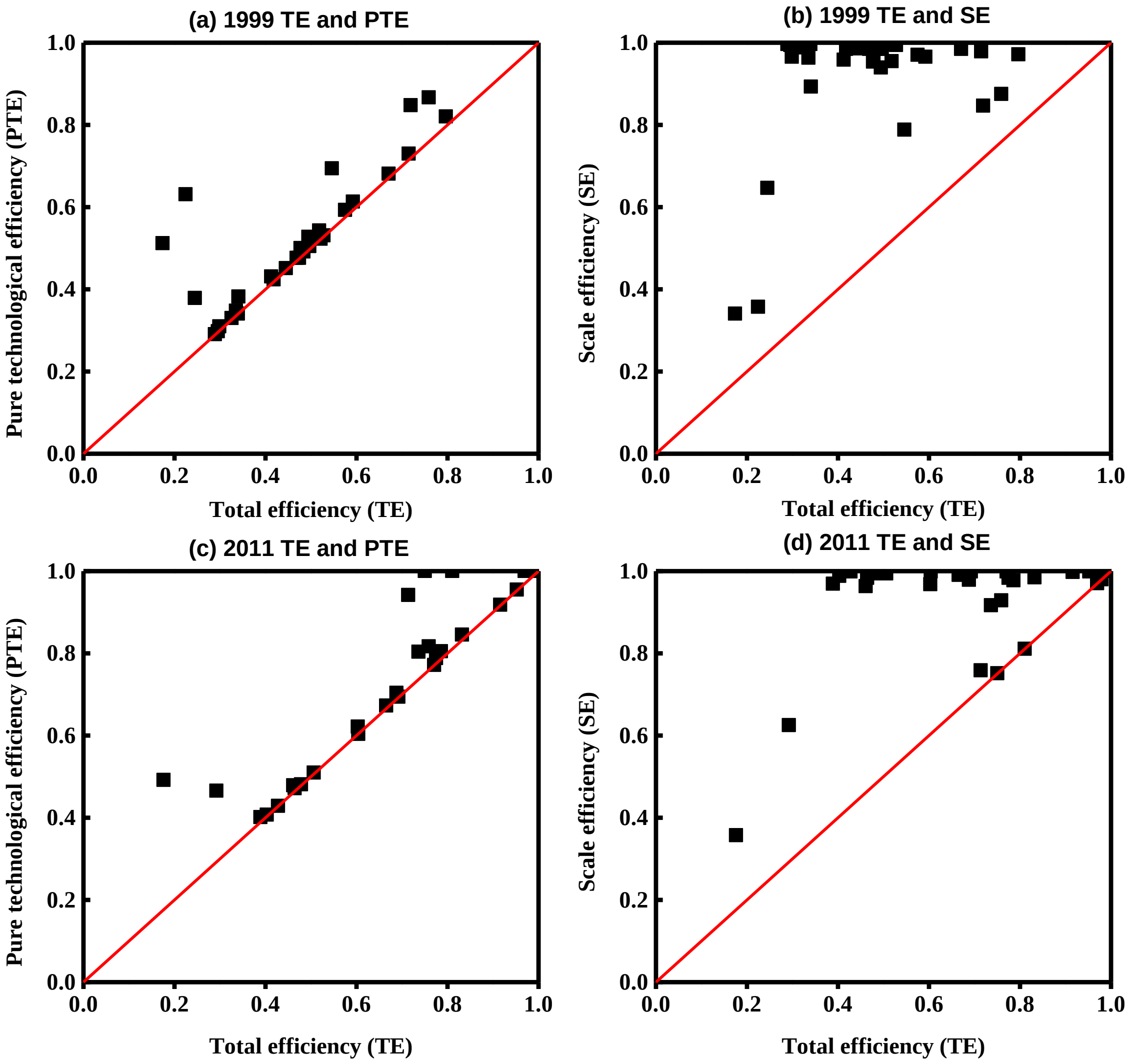

Figure 2.8 Relationship among total efficiency (TE), pure technological efficiency (PTE), and scale efficiency (SE) in 1999 and 2011, respectively.

Table 2.7 Agricultural water use efficiency: 1999 – 2011 averages

	TE (Technical Efficiency)	PTE(Pure Technical Efficiency)	SE (Scale Efficiency)	Return to scale
Beijing	0.736	0.932	0.792	IRS
Tianjin	0.660	0.900	0.733	IRS
Hebei	0.652	0.654	0.996	IRS
Shanxi	0.417	0.470	0.877	IRS
Inner Mongolia	0.491	0.497	0.988	IRS
Liaoning	0.629	0.638	0.985	IRS
Jilin	0.720	0.732	0.982	IRS
Heilongjiang	0.549	0.553	0.991	IRS
Shanghai	0.714	0.875	0.807	IRS
Jiangsu	0.702	0.709	0.988	DRS
Zhejiang	0.629	0.636	0.988	IRS
Anhui	0.420	0.427	0.982	IRS
Fujian	0.544	0.553	0.984	IRS
Jiangxi	0.366	0.371	0.985	IRS
Shandong	0.718	0.723	0.993	IRS
Henan	0.607	0.709	0.862	DRS
Hubei	0.612	0.618	0.991	IRS
Hunan	0.437	0.440	0.995	IRS
Guangdong	0.488	0.496	0.985	DRS
Guangxi	0.341	0.344	0.989	IRS
Hainan	0.609	0.642	0.946	IRS
Chongqing	0.790	0.881	0.888	IRS
Sichuan	0.544	0.570	0.961	DRS
Guizhou	0.322	0.347	0.921	IRS
Yunnan	0.322	0.333	0.964	IRS
Tibet	0.191	0.558	0.342	IRS
Shaanxi	0.518	0.539	0.954	IRS
Gansu	0.321	0.332	0.966	IRS
Qinghai	0.191	0.509	0.378	IRS
Ningxia	0.281	0.353	0.784	IRS
Xinjiang	0.721	0.731	0.985	IRS

2.3.5 Agricultural Water Consumption Redundancy Analysis

Because the TE is effected by PTE more than SE, we estimate the slack in each region to evaluate the adjust amount of inputs. The redundant amounts of inputs or shortfalls amounts of outputs can be calculated as the gap between their actual and target results, which is called slack. In other words, the value of slack expresses how much water or labor we can save when the DMU reaches the DEA efficient without reduce agricultural gross product.

Because in this study we just want to focus on the water use, the Figure 2.9 just shows the average slack value of the water withdrawal and indicate a men water excess of 182.8 billion m3/year. Considering that mean irrigation water consumption was 368.4 billion m3/year in study period, this infers that almost half of the water used “excess”.

Moreover, in order to understand the natural situation, the surface water resource per capita is also summarized in Figure 2.7. It illustrates that the top ten water saving potentiality provinces are 1).Xinjiang (279.7), 2).Guangxi (139.29), 3).Guangdong (122.67), 4).Hunan (115.33), 5).Heilongjiang (91.9), 6).Jiangxi (91.11), 7).Jiangsu (79.88), 8).Anhui (77.6), 9).Inner Mongolia (74.61), 10).Yunnan (72.5). And the top ten water endowment provinces are 1).Tibet (159547.6), 2).Qinghai (12215), 3).Yunnan (4660.8), 4).Xinjiang (4416.2), 5).Hainan (4318.3), 6).Guangxi (3822.5), 7).Jiangxi (3412.9), 8).Fujian (3237.3), 9).Sichuan (2972.5), 10).Guizhou (2655.2).

From the results, even though the water endowments in Jiangsu, Ningxia, Hebei, Heilongjiang, Hebei are less than other provinces, the water saving capacity are larger than most of the provinces. It indicates that the water transfer policy should not only consider the water endowment, but also think about the water saving capacity.

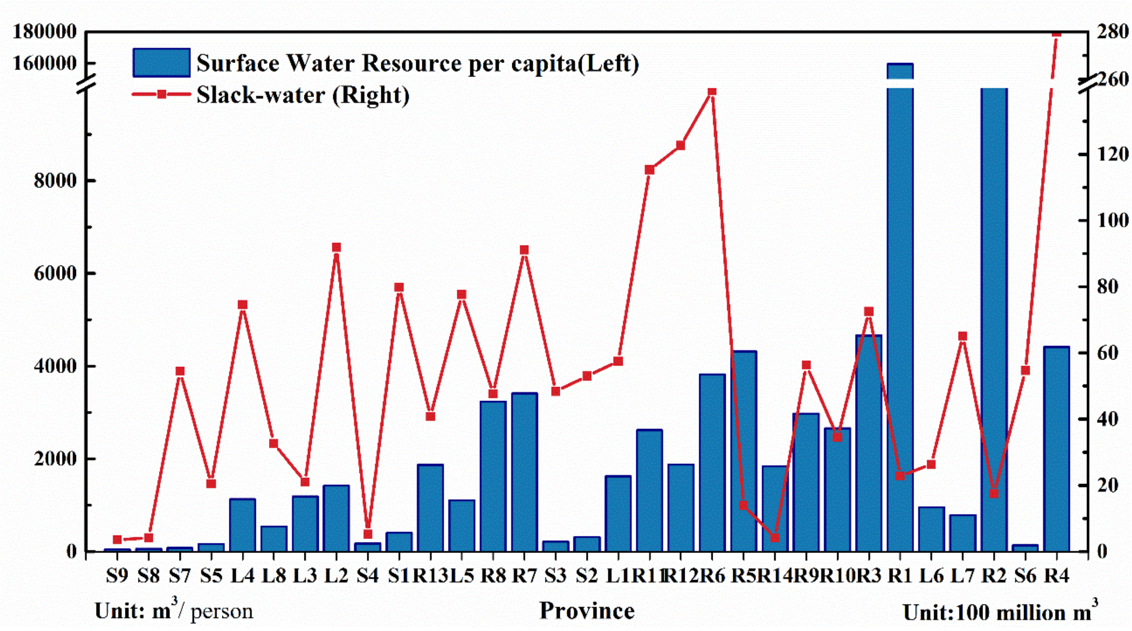

Figure 2.9 Average slack of input and surface water resource per capita

2.3.6 Consequence of Improving Agricultural Water Use Efficiency

I. Potential of improving agricultural water use efficiency to satisfy increasing water demand

For the purpose of clear the effect of alleviating water scarcity by increasing agricultural water use efficiency, a future agricultural water withdrawal was estimated under the following assumptions:

A. Yoshikawa, et al. (2014) indicate irrigation areas which is has a positive relationship with population. Due to the agricultural water withdrawal was related to the irrigation areas, we assumed the increase rate of agricultural water withdrawal as same as population growth rate. We used a future population growth rate of 0.9 % per year on a global scale according to the method of Shen, *et al.* (2008).

B. We assume all the providence attach the DEA efficiency by increasing water use efficiency. For example, the agricultural water withdrawal can be decrease from 10.2 to 7.66 without impact on the gross output of agriculture by increasing water use efficiency in Beijing. The adjusted agricultural water withdrawal in 2011 was used as baseline for projection of agricultural water withdrawal. Agricultural water withdrawal

C. Agricultural water withdrawal in 2011 was used as water supply. We assume the agricultural water supply (WS) will not change in the future.

Based on above assumption, agricultural water withdrawal was estimated as following:

$$\mathrm{WD} = WW_{2011} + WW_{2011} \times 0.9\% \times (T - 2011) \tag{11}$$

Where WW is agricultural water withdrawal, WW_{2011} is adjusted agricultural water withdrawal in 2011, T is year.

D. In this study, to examine whether the agricultural water demand can be satisfied by improving water use efficiency, we used one major criterion that whether the water resources in a given regions would be meet the demand of agricultural water. Here, the potential index was used to express the effect of alleviating water scarcity by increasing agricultural water use efficiency. In detail, P_i was defined as follows:

$$P_i = \frac{\mathrm{WD}}{\mathrm{WS}} \tag{12}$$

Where WW is agricultural water withdrawal ($10^8\mathrm{m}^3$), WS is agricultural water demand ($10^8\mathrm{m}^3$). When P_i exceeds the threshold value of 1, this suggests the water resources of the region is enough. Otherwise means the region is confronted with severe water stress.

Would regional water resource be sufficient for the rapid increase of population in each province? It depends on whether the agriculture water use stress can be alleviated over the period. Figure 2.10 compares the agricultural water supply, water demand, and the gap between those two factors during 2015 – 2030. The detail figures for each province was summarized in Table 2.7, which suggests that the annual maximum water saving potential should reach up to 119.1 billion m^3. For each province, the top ten water saving potentiality provinces are Xinjiang, Jiangxi, Guangxi, Guangdong, Anhui, Heilongjiang, Yunnan, Hunan, Gansu and Ningxia. Moreover, Table 2.8 summarizes the potential index in each provinces. From the simulation results, it indicates that most of the provinces has the enough water to meet the increase of agriculture water, especially in Tibet, Qinghai, Xinjiang, Ningxia and Guizhou. These results suggested that, improving agricultural water withdrawal is a useful way to alleviating water scarcity. While, due to the increasing of agricultural water withdrawal, the water scarcity was appear, such as Shanxi, Jiangsu, Shandong, Chongqing, Shaanxi.

Based on the abovementioned results, even though improving agricultural water withdrawal is a useful way to alleviating water scarcity in most provinces of China, the water scarcity will also appear in some province due to increasing demand of agricultural water. It indicates that the not only water management but also increasing water supply will also consider in order to deal with water scarcity.

II. Sensitive Analysis

The previous sections use the same technology level as 2011 to estimate potential water saving level. However, in reality, different technology level may significantly affect future simulation results; thus, we conduct a sensitive analysis based on different technology improve level (α) ranging from 0.2% to 1.7% per year.

Based on above assumption, agricultural water withdrawal was estimated as following:

$$\mathrm{WW} = WW_{2011} \times [1 - \alpha \times (T - 2011)] \times [(1 + 0.9\% \times (T - 2011)] \quad (13)$$

Where WW is agricultural water withdrawal, WW_{2011} is adjusted agricultural water withdrawal in 2011, T is year.

Figure 2.11 shows the results of the sensitive analysis. Under all conditions, a higher technology improve level decreases the number of regions which will meet to water scarcity due to the reduction in water using.

For the study periods, until the threshold of 0.6% per year, the data show that the number of regions under water scarcity slightly increasing. In line 5, technology improvement level was defined as 0.7 % per year, there was no change which maintained in 4 for the number of regions under water scarcity. In contrast, a large drop immediately appeared from 2020 to 2025 in line 6 due to technology improvement level was increased to 0.8% per year. Furtherly, there was no regions under water scarcity with the relatively high technology improvement level (0.9% per year). The results indicate the number of regions under water scarcity reductions by increase in agriculture technology improvement.

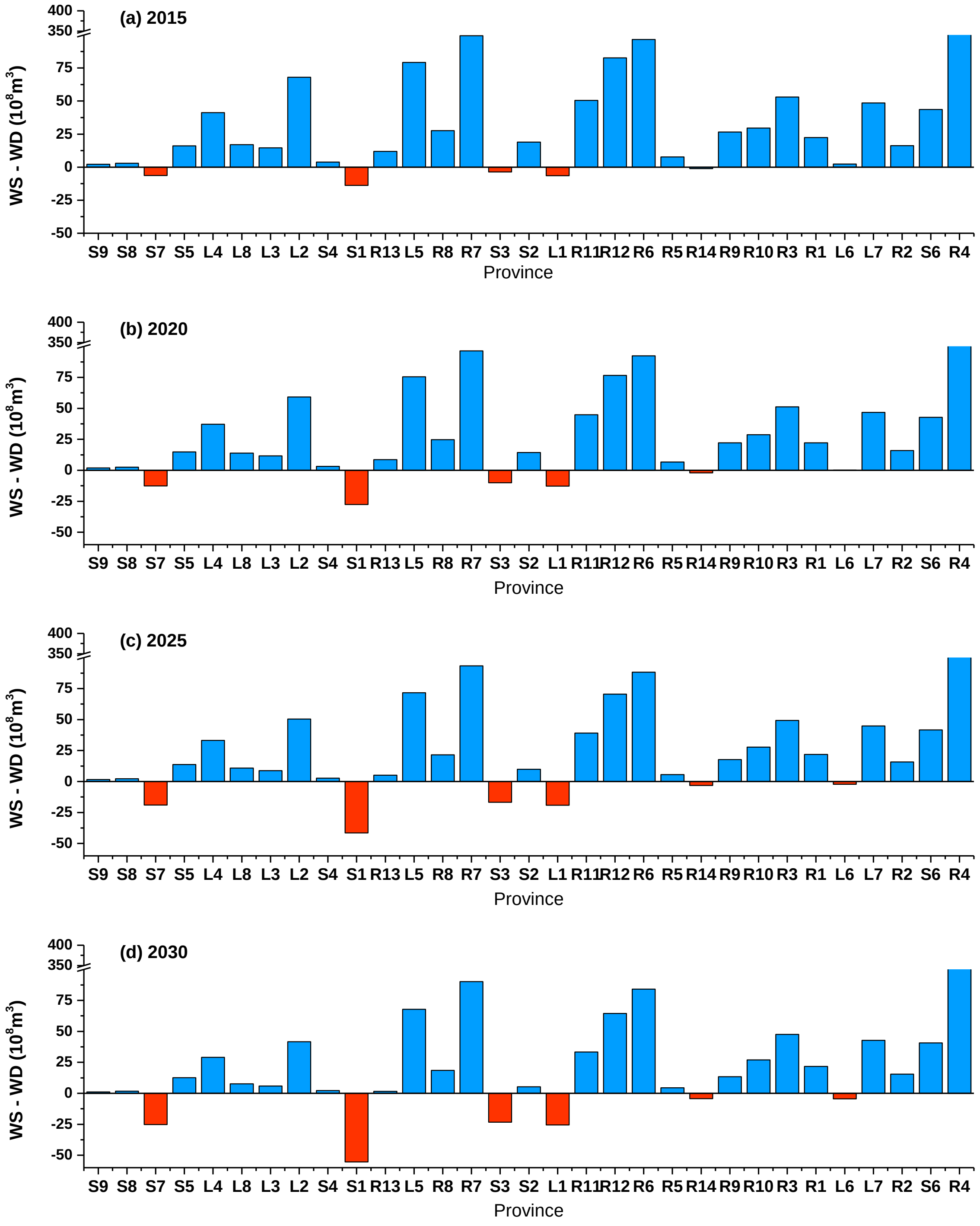

Figure 2.10 The different between agriculture water withdrawal and water supply during 2015 – 2030

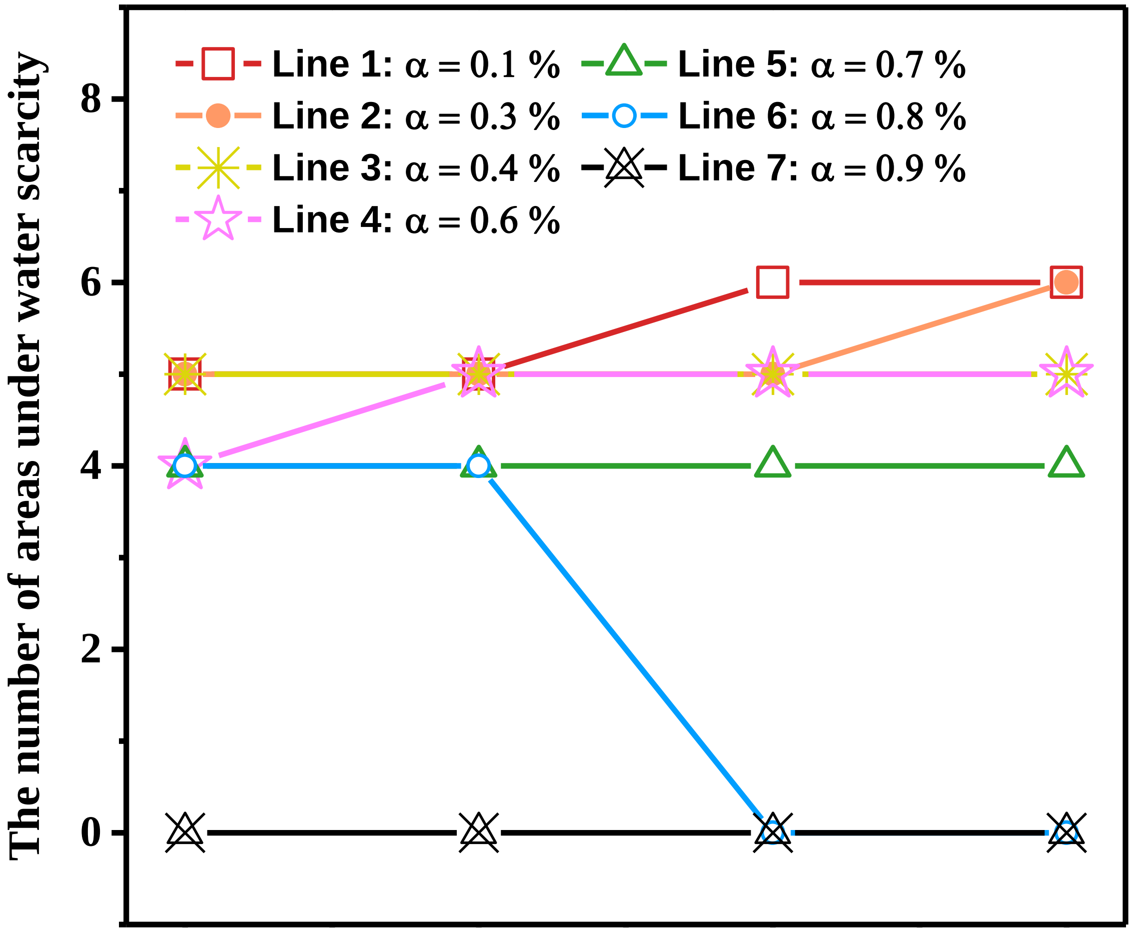

Figure 2.11 Sensitivity analysis of technology improvement level (α) with respect to the number of the regions under water scarcity. Red, orange, yellow, pink, green, blue, and black for technology improvement level in 0.1%, 0.3%, 0.4%, 0.6%, 0.7%, 0.8% and 0.9% per year, respectively.

Table 2.8 Agricultural water withdrawal, supply and the gap between those two factors during 2015 – 2030

	WS[a]	WD[b]				WS - WD			
	2011	2015	2020	2025	2030	2015	2020	2025	2030
Beijing	10.20	8.00	8.35	8.69	9.04	2.20	1.85	1.51	1.16
Tianjin	11.55	8.62	8.99	9.37	9.74	2.93	2.56	2.18	1.81
Hebei	140.49	146.81	153.13	159.46	165.78	-6.32	-12.64	-18.97	-25.29
Shanxi	43.40	27.33	28.50	29.68	30.86	16.07	14.90	13.72	12.54
Inner Mongolia	135.94	94.64	98.72	102.79	106.87	41.30	37.22	33.15	29.07
Liaoning	89.74	72.69	75.82	78.95	82.08	17.05	13.92	10.79	7.66
Jilin	81.64	67.09	69.98	72.87	75.76	14.55	11.66	8.77	5.88
Heilongjiang	272.26	204.28	213.08	221.88	230.68	67.98	59.18	50.38	41.58
Shanghai	16.47	12.67	13.21	13.76	14.30	3.80	3.26	2.71	2.17
Jiangsu	307.60	321.44	335.28	349.13	362.97	-13.84	-27.68	-41.53	-55.37
Zhejiang	92.07	80.07	83.52	86.97	90.42	12.00	8.55	5.10	1.65
Anhui	168.38	89.09	92.93	96.76	100.60	79.29	75.45	71.62	67.78
Fujian	98.62	70.92	73.97	77.03	80.08	27.70	24.65	21.59	18.54
Jiangxi	171.74	72.24	75.35	78.46	81.58	99.50	96.39	93.28	90.16
Shandong	148.92	152.48	159.05	165.61	172.18	-3.56	-10.13	-16.69	-23.26
Henan	124.60	105.63	110.18	114.73	119.28	18.97	14.42	9.87	5.32
Hubei	142.26	148.66	155.06	161.47	167.87	-6.40	-12.80	-19.21	-25.61
Hunan	183.12	132.58	138.29	144.00	149.71	50.54	44.83	39.12	33.41
Guangdong	224.16	141.44	147.53	153.62	159.71	82.72	76.63	70.54	64.45
Guangxi	193.21	96.63	100.79	104.95	109.11	96.58	92.42	88.26	84.10
Hainan	33.84	26.07	27.19	28.31	29.44	7.77	6.65	5.53	4.40
Chongqing	23.62	24.68	25.75	26.81	27.87	-1.06	-2.13	-3.19	-4.25
Sichuan	128.44	101.92	106.31	110.69	115.08	26.52	22.13	17.75	13.36
Guizhou	49.70	20.19	21.05	21.92	22.79	29.51	28.65	27.78	26.91
Yunnan	96.08	43.02	44.87	46.72	48.57	53.06	51.21	49.36	47.51
Tibet	27.37	5.03	5.24	5.46	5.67	22.34	22.13	21.91	21.70
Shaanxi	56.22	53.80	56.12	58.44	60.75	2.42	0.10	-2.22	-4.53
Gansu	93.84	45.20	47.14	49.09	51.04	48.64	46.70	44.75	42.81
Qinghai	23.48	7.16	7.46	7.77	8.08	16.32	16.02	15.71	15.40
Ningxia	66.12	22.47	23.44	24.41	25.38	43.65	42.68	41.71	40.74
Xinjiang	488.41	150.04	156.51	162.97	169.43	338.37	331.90	325.44	318.98
Total	3743.5	2552.9	2662.8	2772.8	2882.7	1190.6	1080.7	970.7	860.8

Note: a: WS= Agricultural Water Supply b: WD = Agricultural Water Demand

Table 2.9 Potential index (P_i) in 2015, 2020, 2025 and 2030. Red numbers indicate potential index lower than 1.

Province	P_i = WS / WD			
	2015	2020	2025	2030
Beijing	1.27	1.22	1.17	1.13
Tianjin	1.34	1.28	1.23	1.19
Hebei	0.96	0.92	0.88	0.85
Shanxi	1.59	1.52	1.46	1.41
Inner Mongolia	1.44	1.38	1.32	1.27
Liaoning	1.23	1.18	1.14	1.09
Jilin	1.22	1.17	1.12	1.08
Heilongjiang	1.33	1.28	1.23	1.18
Shanghai	1.30	1.25	1.20	1.15
Jiangsu	0.96	0.92	0.88	0.85
Zhejiang	1.15	1.10	1.06	1.02
Anhui	1.89	1.81	1.74	1.67
Fujian	1.39	1.33	1.28	1.23
Jiangxi	2.38	2.28	2.19	2.11
Shandong	0.98	0.94	0.90	0.86
Henan	1.18	1.13	1.09	1.04
Hubei	0.96	0.92	0.88	0.85
Hunan	1.38	1.32	1.27	1.22
Guangdong	1.58	1.52	1.46	1.40
Guangxi	2.00	1.92	1.84	1.77
Hainan	1.30	1.24	1.20	1.15
Chongqing	0.96	0.92	0.88	0.85
Sichuan	1.26	1.21	1.16	1.12
Guizhou	2.46	2.36	2.27	2.18
Yunnan	2.23	2.14	2.06	1.98
Tibet	5.45	5.22	5.01	4.82
Shaanxi	1.04	1.00	0.96	0.93
Gansu	2.08	1.99	1.91	1.84
Qinghai	3.28	3.15	3.02	2.91
Ningxia	2.94	2.82	2.71	2.61
Xinjiang	3.26	3.12	3.00	2.88

2.4 **Summary and Conclusions**

This chapter applies DEA window analysis to measure the dynamic agricultural water use efficiency of 31 provinces in China during 1999 – 2011, a period of rapid economic development and water resources consumption. To deal with panel data, this paper employs DEA window analysis to evaluate the efficiency scores.

In terms of the water use efficiency, several major findings were obtained. First, agricultural water use efficiency trends to be lower in the regions where the water resource is sufficient. Moreover, the developed area has higher TE score than the developing area and the efficiency of the less-developed area is the worst. It may be thought that the economic development mode of China causes the relatively low TE. In addition, the influence of PTE on TE is greater than that of SE in most provinces. Lastly, the water saving capacity is not based on the water endowment. Therefore, we give some suggestions to improve China agricultural water use efficiency. (1) The public awareness of water-saving should be enhanced in water abundant area. (2) Increasing the agricultural investment in the developing area and the less-developed area. (3) Improve the water management in most provinces, except Beijing, Tianjin, Shanghai and Tibet. Besides, in those provinces, the scale of production should be adjusted. (4) If a water transfer project is conducted, such as South-North water transfer project, not only local water endowment but also the water saving capacity should be considered in order to eliminate the impact on the agricultural production. (5) Improving agricultural water withdrawal is a useful way to alleviating water scarcity in most provinces of China, while the water scarcity will also appear in some province due to increasing demand of agricultural water. It indicates that the not only water management but also increasing water supply will also consider in order to deal with water scarcity.

Above all, the increasing water resource pressure in China has become a serious threat to economic development. Moreover, the water scarcity issue also has many adverse impacts on the environment. Jiang (2009) indicated water withdrawal rates in the North China can reach up to 90 percent which could increase the risk of negative environmental effects and undermining the capacity of water bodies to fulfill their ecological functions. Qin, *et al.* (2011)pointed out that the water scarcity enhanced exploitation of the wetlands and led to a continuous reduction in ecological functions, diminishing biodiversity, and increased ecosystem vulnerability of the river corridor. Shao, *et al.* (2017) found the water scarcity significantly affected the health development of ecological environment of slopes.

To deal with the challenges, one of the most effective strategies is a persistent efficiency improvement. While, although improving agricultural water withdrawal is a useful way to alleviating water scarcity in most provinces of China, the water scarcity will also appear in some province due to increasing demand of agricultural water. It indicates that the not only water management but also increasing water supply will also consider in order to deal with water scarcity. Therefore, we evaluation the feasibility of implement seawater desalination, which is a potential way to increase water supply, in the next chapter.

3. Economic and Environmental Feasibility Assessment of Seawater Desalination on a Global Scale to 2050

3.1 Introduction

3.1.1 Background

Water is a valuable basic natural resource, contributing to economic productivity and all societal activities. Its availability is today subject to shortages, given the effects of climate change, economic development, and population growth worldwide (Oki and Kanae, 2006; Kundzewicz Zbigniew and Gerten, 2015).

To address current and future water scarcity problems, many countries are already engaged in the search for various alternative countermeasures, such as such as the sea water desalination, wastewater reuse, groundwater exploiting and so on (Ghaffour, et al., 2013; Mays, 2013; Quist-Jensen, *et al.*, 2015). Groundwater is the most widely used, but the aquifers can be depleted without recharge and it will lead to seawater intrusion, land subsidence, and growing pumping costs (Budhu and Adiyaman, 2013; Fonseca, *et al.*, 2013; Green and MacQuarrie, 2014). Wastewater reclaim also a common way to expand the water supply which can directly or indirectly supply domestic water consumption. While, water reclaim comes with a “yuck” factor since much of the public were opposed to using the water associated with human waste (Nancarrow, *et al.*, 2009; Rozin, *et al.*, 2015). Lastly, desalination is a separation process which takes water with high salinity and removes the salt to make fresh water (Kesieme, et al., 2013). Due to the potentially climate-independent water resources with controlled quality of seawater and the unit production cost of desalinated water has decreased significantly due to technological progress, desalination has a strong potential as a reliable source of water to deal with water scarcity (Ziolkowska, 2016).

Numerous previous studies have assessed the future development of seawater desalination based on various scales. Bremere, *et al.* (2001) and Kirshen (2007) project the increasing desalinated water volume required for growing domestic or commercial needs to be 2025 year in 10 water-scarce countries and 2050 year in coastal nations, respectively. Additionally, Kim, *et al.* (2016) use an economic approach to predict the growth of total desalinated water as 2100 year at a basin scale. In view of the remarkable development of desalination, efforts have also been made to incorporate desalinated water into various hydrological models for global water resource assessments. For example, Wada, et al. (2011) incorporate desalinated water into their hydrological models by allocating its usage in seashore regions and assuming that its volume will increase with the population. Hanasaki, *et al.* (2016) propose a seawater desalination model to identify potential desalination areas and likely production volumes. These studies use reasonable assumptions to predict the development of seawater desalination over various spatial scales. However, little attention has been paid to the local economic conditions of the countries that would potentially use seawater desalination. Thus, further research is needed to examine whether seawater desalination is economically feasible given the specific circumstance of particular countries.

The main economic barrier to implementing seawater desalination derives from its high capital and operational and management (O&M) costs (Ziolkowska, 2015). These will eventually be converted into the price of desalinated water paid by consumers. It is evident that desalinated water will be incorporated as an integral part of a water portfolio once the cost of seawater desalination is reduced to the level that consumers can afford to pay for water resources. Therefore, the feasibility of seawater desalination for different countries is intertwined with two factors: the production cost of desalinated water and the water price, which may be a good proxy for the affordability of water resources. Using various empirical and computerized tools, several existing studies estimate the capital or O&M costs of desalination, as these will directly determine the threshold for building a desalination plant or the long-term operation of a desalination plant (Zhou and Tol, 2005; Ziolkowska, 2015; Caldera, *et al.*, 2016; Choi, *et al.*, 2016; Ali, *et al.*, 2017). However, few studies address the correlation between these two economic factors (i.e., the production cost and water price) when evaluating the development of seawater desalination in different countries.

In this study, we propose a methodology for evaluating the development of seawater desalination and assessing its economic feasibility for different countries over the long term. We develop a detailed feasibility index that involves comparing the water price with the production cost of desalination to determine the feasibility of seawater desalination for each country and to identify the countries that show the economic potential for seawater desalination. Herein, two statistical models for estimating the production cost and water price are outlined; they are discussed in terms of their historical validity (Section 3.2) as well as their subsequent application to future projections (Section 3.3). Based on these projections, we evaluate the feasibility of seawater desalination for different countries and assess the prospects of seawater desalination development in 140 coastal countries by 2050 (Section 3.3).

3.1.2 Desalination Technologies and Current Situation

With regard to the decreasing supply of conventional water resources and the increasing water demand, various non-conventional supply of sources have been considered to achieve this shortfall. In particular, many countries have adopted desalination water services as a response to their increasing water demand and stagnating or decreasing supply of the freshwater. For example, 100% of domestic and industry water supply are rely on desalination water in Qatar and Kuwait (Ghaffour, et al., 2013).

As a reason of the water scarcity, the capacity of desalination is rapidly increasing around the worldwide. Until 2013, the total global desalination source water is around 61.1 million m^3/day, in which is split with about 60% from seawater and 20.3% from brackish water resource, and the remaining percentage from river water, waste water, pure water and brine water (Figure 3.1). Of those, seawater desalination usually offers a seemingly unlimited, steady supply of high-quality water. Contrastively, the global water production by seawater desalination over 3.5×10^7 m^3/day in 2015, which is the seven times the rate of global water production by desalted seawater in 1995. To sum up, there has been rapid growth in the installation of seawater desalination facilities in the past two decades as a main scheme to augment water supply in those water-stressed countries.

Commonly, desalination can be accomplished by thermal and membranes process. In details, the thermal process mainly contains multi stage flash distillation (MSF), multiple effect distillation (MED), and vapor compression (VC), while the membranes process usually includes reverse osmosis (RO), electro dialysis (ED), electrode ionization (EDI) and nano-filtration (NF). As the oldest and most commonly process, the thermal desalination (distillation) has been used for hundreds of years to produce fresh water, and the first such type of desalination plant was built on Curacas, Netherlands Antilles, in 1928 with a capacity of 60 m^3/day (Ophir and Manor, 1987). MSF process was highly popular for producing fresh water since 1960s, and then member process began to enter the desalination market. Comparting with thermal process, RO membranes is a relatively new process and the first RO plants used seawater as the feed in the last 1960s. (Reddy and Ghaffour, 2007; Greenlee, *et al.*, 2009). There are several advantages by using RO process than other technologies, such as lower energy requirements, highly recovery rate and less surface for the same amount of water production and in consequence now RO process has gone through remarkable development and surpass thermal process in new plant installations (Dore, 2005). Comparing with the large energy consumption technology (MSF) which requires 5.5 – 16 kWh/m^3 electricity, RO just needs 4 – 6 kWh/m^3 electricity (Al-Sahali and Ettouney, 2007; Peñate and García-Rodríguez, 2012; Al-Karaghouli and Kazmerski, 2013; Ghaffour, et al., 2013; Schallenberg-Rodríguez, *et* *al.*, 2014; Miller, *et al.*, 2015). Miller, et al. (2015) indicate 65% of the total installed desalination capacity is produced by RO which is occupying the highest share compared with any other process. By 2015, RO technology achieved remarkable gains in the production of desalinated water from seawater (6.9 km^3 $year^{-1}$ of the 12.9 km^3 $year^{-1}$ total global desalinated water production from seawater reported in the DesalData database, Figure 3.2). As it currently dominates global seawater desalination, SWRO is expected to maintain its trend of growth and to play a greater role in increasing the availability of freshwater in the future.

In this study, we mainly focuses on the reverse osmosis desalination of seawater (SWRO) which accounts for a considerable proportion of the total desalination water to meet the rapidly growing of water demand.

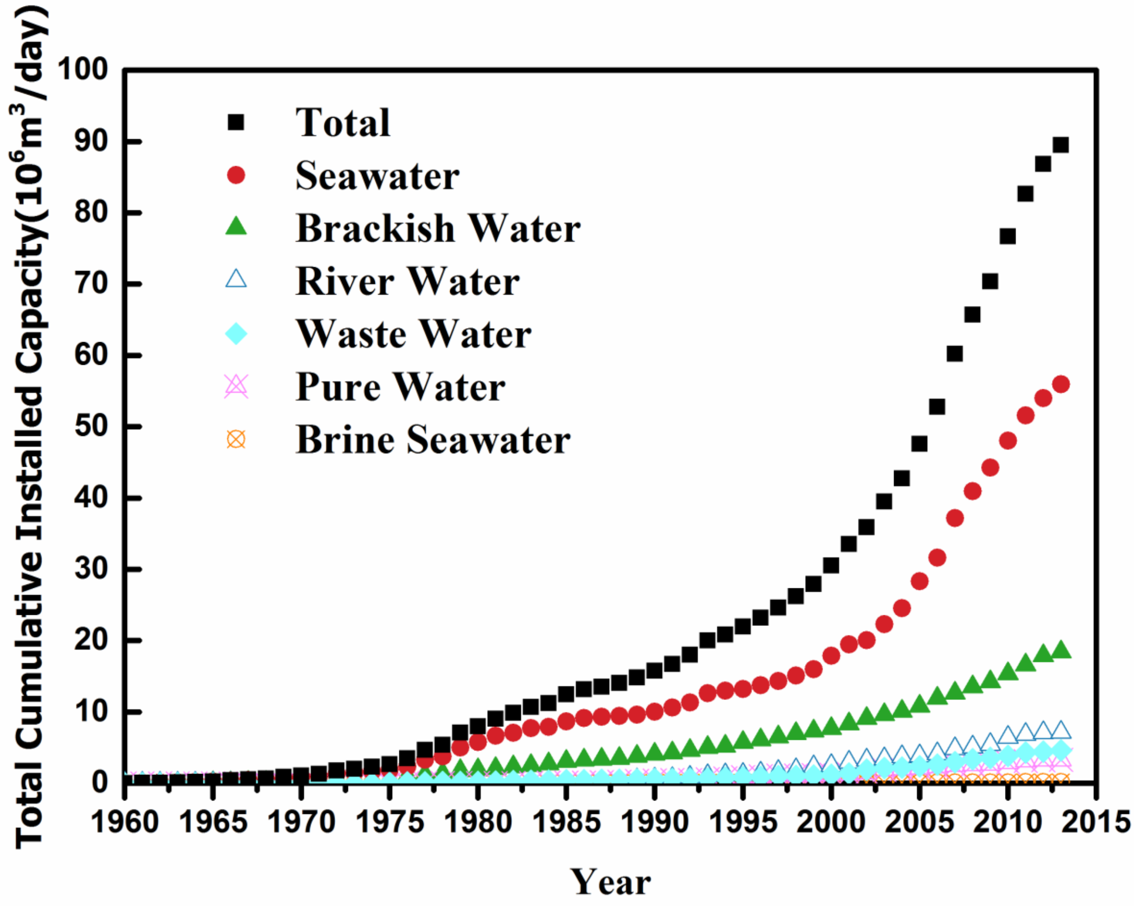

Figure 3.1 Total Cumulative Installed Capacity in the Worldwide

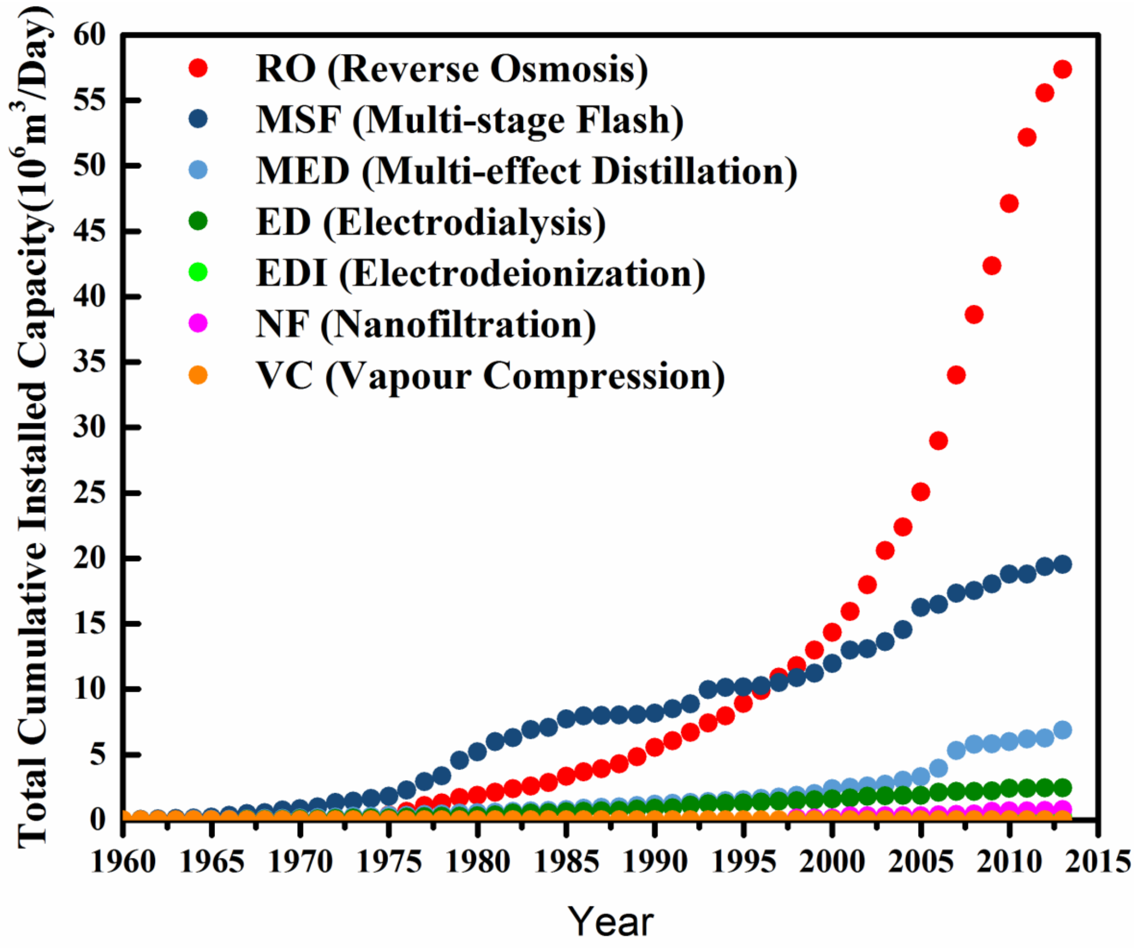

Figure 3.2 Total Cumulative Installed Capacity by technology in the Worldwide

3.1.3 Environmental Impact of Desalination

Although many governments and organizations are selecting SWRO as a solution to water scarcity, there are still several concerns with it because of the potential for directly or indirectly adverse environment impact. These are mainly attributed to the concentrate and chemical discharges, which may impair coastal water quality and affect marine life, and air pollutant emission attributed to the energy demand of the processes as shown in Table 3.1 and Figure 3.3.

(1) The indirect impact on the environment due to increase production electricity for desalination plants

Energy consumption on SWRO plants has improved with new technological advances in the process such as the energy recovery systems used. These SWRO plants require an external supply electrical energy mostly produced by thermal plants. To produce electricity it is necessary to burn fuels in a thermal plant, which produces the emission of air pollutants and greenhouse gases that further exacerbate climate change. Current state-of-the-art SWRO plants consume 3 – 4 kWh/m^3 and emit between 1.4 and 1.8 kg CO_2/m^3 of produced water (Elimelech and Phillip, 2011). To put this in perspective, in 2015, 51 billion kWh were required to produce desalinated seawater and the value of CO_2 emission was approximately 23 billion kg CO_2/Year in the worldwide. Increase capacity of desalination plants in the future need new electric infrastructure and, as a result, new thermal power station increase the amount of pollution by gas emission excepted if there was a replacement of conventional energies for renewable energies for the desalination industry.

(2) Impact on the marine environment as a result of returning the concentrated brine to the sea

Brine is an unavoidable by-product of desalination, which is most commonly discharged into the sea of the marine environment. In a typical SWRO plant, the discharge flow rate of brine is about 30 – 70% of the feed water flow, which means 1.3 – 1.7 times the seawater dispersion. Since the discharge of this highly concentrated salt solution, its environmental implication on local marine has been widely acknowledged. In other words, extensive brine discharge, which will give rise to a hypersaline layer that sinks towards the seabed due to it greater density, has the potential of heavily effect on local marine biota (Ahmed and Anwar, 2012). Generally, the level of the hazard of concentrates mainly lies on several factors, such as their temperature, total dissolved salts (TDS) and density, et al. The relations of these factors with their hazard are as follows: the higher the temperature of the concentrate, the less its impact; the higher the TDS and the density of the concentrate, the more its impact. To explain the reasons, if the density of concentrate is high, it will sink to the bottom of the sea and may thus harm the marine life, which is opposed to a low density where it will float and cause less damage. The temperature and density are related similarly. Recovery rate, which is defined as the ratio of the product of fresh water to the feed water, also affects the TDS of the concentrate, to which a higher recovery rate will lead to a higher TDS of the concentrate.

At present, most of the desalination plants discharge their waste streams of concentrate into the oceans. Indeed, this method of waste disposal currently represents the cheapest and most effective options for both small and larger desalination plants located near the coastal regions. However, more and more stringent environmental protection regulations has been organized in recent years, to which their promulgation will progressively reduce the discharge of the brine concentrate.

Regarding the disposal of the brine waste, its cost is still relatively high today, which ranges from 5% to 33% of total desalination cost, complicating the implementation of such activities (Morillo, *et al.*, 2014). Generally, the cost of brine disposal depends on several factors, including treatment level before disposal, the quality of the concentrate, disposal method, and the volume or quantity of concentrate (Arnal, *et al.*, 2005). As such, Laspidou, *et al.* (2010) once assessed the possibility of transferring brine from desalination plants to solar salt works for salt producing, and estimated the cost of transporting is ~ 4.7–106.1 USD/m^3 due to the varied shipping distance in Greece. For the others, Macedonio, *et al.* (2007) used four integrated systems to recover calcium sulphate, magnesium sulphate and sodium chloride by reaction with Na_2CO_3 to reduce the concentration of discharged liquid. Excluding the production cost, the net profit of salt recovery are ~ -0.077 – 0.68 \$/m^3.

To weaken the impacts of waste of high-salinity brines, on one hand, brine from the desalination plant may possibly be diluted with other waste streams (e.g., power plant cooling water and treated wastewater effluent), providing they are available (Elimelech and Phillip, 2011). As an example, the Carlsbad desalination plant have mixed its brine waste water with the cooling water from the adjacent Encina Power Station rather than directly discharging the brine into a lagoon that leads to the ocean (Cooley, *et al.*, 2013). On the other hand, one solution for the brine disposal may devote to evaporate water from the concentrate, which could thus obtain a salt residue for disposal or reuse in order to realize the purpose of zero liquid discharge.

(3) Impact of noise

Acoustic contamination on SWRO plants is important. High pressure pumps and energy recovery systems, such as turbines or similar, produce significant level of noise over 90dB. Therefore, they should be located far away from populated areas and equipped with appropriate acoustic technology to reduce noise level.

Table 3.1 The Principal Environment impact of Desalination for SWRO Plants

Aspect	Pollutant	Potential problems
Atmospheric Aspect	Energy use	Emission of air pollutants
Marine Aspect	Salinity	Implication on local water organisms
	Biocides	Impact on the life stages and species
	Heavy metals	Many benthic invertebrates feed on this suspended or deposited material, with the risk that metals are enriched in their bodies and passed on to higher trophic levels
	Antiscalants	As antiscalant have a low toxicity, the acute environmental risk associated with their release into the marine environment is relatively low. Due to a poor degradability, however, dispersal and relatively long residence times must be expected, during which interference with element cycles of trace metals is a possible risk.
	Coagulants	The chemicals themselves have a very low toxic potential. However, their discharge may cause an intense coloration of the reject stream if ferric salts are used ("red brines"), which may increase turbidity and reduce light penetration, or could bury sessile benthic organisms in the discharge site.
	Cleaning chemicals	Most of the named cleaning and disinfection chemicals may be hazardous to aquatic life
Social Aspect	Noise	High pressure pumps and energy recovery systems, such as turbines or similar, produce significant level of noise over 90dB

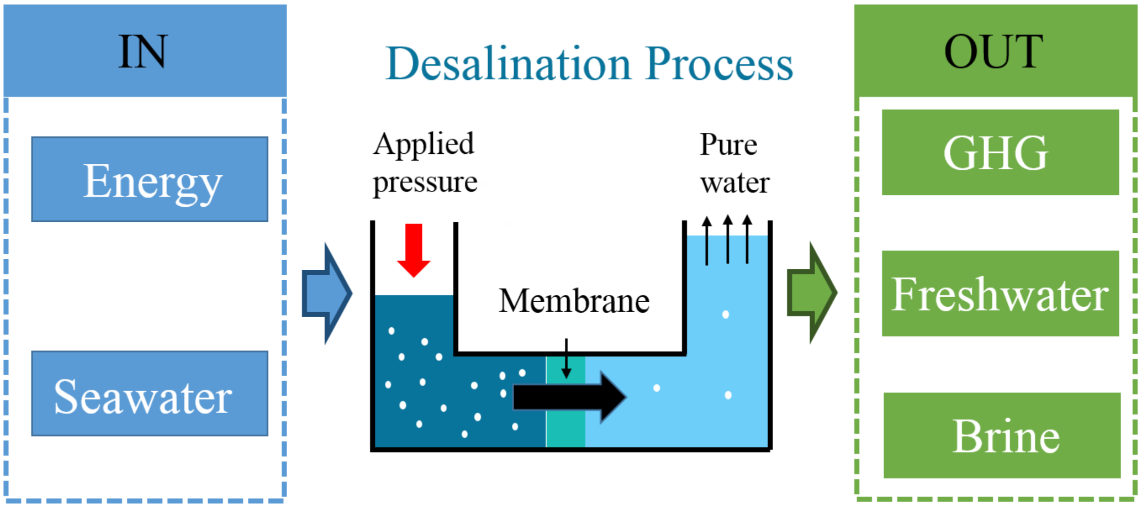

Figure 3.3 Schematic Diagram for the Desalination Process

3.2 Methods

3.2.1 Criteria for Feasibility Assessment of Seawater Desalination

A major criteria regarding the assessment of economic feasibility for implementing the SWRO was whether the cost of produced desalinated water in a given country would be affordable for consumers under local socioeconomic conditions. The conventional water price was decided by the political and social system to ensure cost recovery, equity and sustainability. Prices for conventional water resources are not determined solely by cost and it may or may not include subsidies. Since the cost of various conventional water supplies in different countries are impractical to calculate, it has identified that water price could be an integrated barometer to reflect all those cost and the payment for water resources in specify country. At present, approximately ~ 63% of desalinated water worldwide is used for municipal purposes, 26% is used for industrial purposes, and 6% is used in power stations for electricity generation (Ziolkowska, 2016). As municipalities are the main recipients of desalinated water, the municipal water price is treated as an indicator of the affordability of water resources for consumers.

In order to simply judge whether it is cost effective to adopt SWRO in different countries, the economic feasibility assessment would mainly depends on the trade-off between the production cost of SWRO and the water price in corresponding country. Moreover, Bhatia, *et al.* (1998) argued that sustainable and efficient use of water require the price to match not only costs of supply (i.e. O&M and capital costs), but also environmental externality costs. Here, the economic feasibility index (F_i) is appropriately used to express the cost effective level of implementing SWRO currently or in the future. In detail, the F_i was defined as the ratio of water price and production cost:

$$\mathrm{F}_i = \frac{W_p}{C_p} \tag{1}$$

Where W_p presents the unit water price ($/m^3) in a given country and C_p is the unit production cost ($/m^3) which included environment cost of a SWRO plant at a specific time. The above equivalent expresses as the annual value. When the F_i exceeds the threshold value of 1 in a country, this suggests high economic feasibility and great potential for developing SWRO in the given country because desalinated water from SWRO is expected to be affordable for consumers. Thus, to clarify the future market of SWRO, the condition of $F_i \geq 1$ can be used to identify the countries where SWRO is promising (i.e., a "country with the potential to develop seawater desalination" (CDSD)). Additionally, we also focus on the population most likely to use seawater desalination, defined as the population living within approximately 165 km of the seashore in each CDSD (hereafter, “desalination population”).

To calculate F_i and F_{ei}, three statistical models were developed to separately estimate the production cost (section 3.2.2), environmental cost (section 3.2.3) and water price (section 3.2.4) in different countries. For each model, a multiple regression method was used. Several parameters will influence the production cost, environmental cost and water prices, and an in-depth correlation of these parameters will lead to higher-accuracy estimations.

3.2.2 Estimation of Production Cost by Seawater Desalination

For a SWRO plant, the water production cost generally is influenced by numerous factors depending, which are listed in the Table 3.2. Here, the factors presented could be considered simply for the purposes of possible estimation only. Based on the principal factors presented in Table 3.2, production cost of a SWRO plant can be classified broadly into two major components: capital costs, and operation and management (O&M) costs. Regarding to the former, the annual amortized capital cost (C_a) can be determined by multiplying the capital cost with an annuity factor from the following equation:

$$\text{Capital cost} = \frac{C_a}{(1+i)^1} + \frac{C_a}{(1+i)^2} + \cdots + \frac{C_a}{(1+i)^n}$$

$$\text{Capital cost } \times (1+\text{i}) = C_a + \frac{C_a}{(1+i)^1} + \cdots + \frac{C_a}{(1+i)^{n-1}}$$

Therefore,

$$C_a = \mathit{Capital\ Cost} \times \frac{i \times (1+i)^n}{(1+i)^n - 1} \tag{2}$$

where C_a is the annual amortized capital cost, the *Capital Cost* is corresponding to the initial investment in the starting year, and i and n are the annual discount rate and the SWRO plant life, respectively. A discount rate of 8% and a 20-year plant life were used, as in previous study (Papapetrou, *et al.*, 2017).

Furthermore, the annual output of the SWRO plant (capacity) was used to shift annual amortized capital cost and annual O&M cost ($C_{a/O\&M}$) to a unit annual amortized capital cost (C_u) and unit annual O&M cost ($C_{O\&M}$), respectively. As a result, the unit water production cost (C_p, US \$/m^3) for producing 1 m^3 of desalted water can be calculated as follows:

$$C_p = C_u + C_{O\&M} = \frac{C_a}{Capacity} + \frac{C_{a/O\&M}}{Capacity} \tag{3}$$

Where C_p is the unit production cost in USD/m^3.

I. Capital Cost

(1) Multiple Regression Analysis

For the purpose of forecast the SWRO production cost, multiple regression analysis which is a statistical technique to analyze quantitative data to estimate model parameters and make forecasts was selected.

We denote the response (dependent) variable by Y and the set of predictor variables by X_1, X_2,… X_p, where p denotes the number of predictor (independent) variables. The relationship between Y and X can be approximated by the regression model:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_1 + \Lambda + \beta_n X_n + \varepsilon \tag{4}$$

Where β_0, β_1, β_2, ..., β_n, called coefficients, are unknown constants to be estimated from the data. The coefficients is estimated by ordinary least squares (OLS) with an aim of minimizing the difference between the observed and estimated variable value.

(2) Independent Variable

To estimate the capital cost of a SWRO plant, it is initially assumed that such a cost would potentially be correlated with four numerical variables (plant capacity, total installed capacity, GDP per capita, and Distance) and one dummy variable (Oil-exporting).

A) Plant Capacity (CAP)

Plant capacity directly reflects the size of equipment, construction size, etc., hence, it will affect the capital cost. Therefore, capacity of single plant was selected as independent variable (Zhou and Tol, 2005; Lamei, *et al.*, 2008; Loutatidou, *et al.*, 2014).

B) Total Cumulative Installed Capacity (TIC)

SWRO technology maturity is also expected to affect the capital cost. In this study, total cumulative installed capacity, which reflects the expansion of desalting plants over time, was used referred to technology maturity (Zhou and Tol, 2005; Loutatidou, et al., 2014).

C) Distance

In addition to plant capacity and cumulative capacity, Loutatidou, et al. (2014) added that whether the desalination plant was located in a country on the Gulf Cooperation Council also has a significant impact on capital cost. Consistent with the literature, the distance from the sea, which may change the investment in transportation, is also included. As the location of SWRO plant may change the investment of transportation, distance from sea was selected as independent variable.

D) GDP per capita

As the economic level will affect the labor costs, the GDP per capita is expected to change the capital cost

E) Oil-exporting

It is to be noted that the Oil-export countries was assumed to impact the capital cost due to their lower energy cost. In this study, ‘Oil-exporting’ is dummy variable, the variable assumes a value of “1” for the desalination plants located in the top 15 oil exported countries which include Saudi Arabia, Russia, Canada, UAE, Nigeria, Iraq, Kuwait, Angola, Kazakhstan, Venezuela, Iran, Qatar, Mexico, Norway and Algeria, otherwise is “0”

Before estimating the regression model, the preliminary step was to test the independent variables for multicollinearity. In statistics, multicollinearity is a phenomenon in which two or more predictor variables in a multiple regression model are highly correlated, meaning that one can be linearly predicted from the others with a substantial degree of accuracy. This phenomenon will increases the standard errors of the coefficients for predictor variables and makes those coefficients unreliable. Figure 3.4 indicate that the variables have little or no correlation with each other

(3) Statistic Model for Capital Cost

In this study, it has tried to develop the function for capital cost by referring the data of 631 desalting plants from 1990 to 2002, whereas the observed data consisting of 133 plants records from 2003 to 2014 were further applied to examine the accuracy and availability of our developed functions. In terms of the quantitative function of capital cost, those variables that result in an improvement in the model fit after their addition are deemed an integral part of the capital cost. We use Akaike’s information criterion (AIC) to check for model accuracy, and the value for each new regressor addition is shown in Tables 3.3 – 3.6. Considering the different characteristics of plants with various capacities, one uniform function may fail to fit all the observed data ideally. Considering the different characteristics of plants with various capacities, one uniform function may fail to fit all the observed data in an ideal manner. Thus, functions are developed based on the classification of plant capacity in the database, in terms of four groups: A (< 1,001 m^3/d), B (1,001 – 5,001 m^3/d), C (5,001 – 10,001 m^3/d), and D (10,001 – 900,000 m^3/d). Based on the linear regression analysis above, the functional equations for the different capacity groups were as follows:

$$Capital\ cost\ (A) = 2.9 \times 10^6 + 3.3 \times 10^3 \times CAP - 1.9 \times 10^5 \times \log(TIC) + 1.1 \times GDP\ per\ capita$$

T-statistic: (18.9) (156.3) (-18.9) (2.5)

R^2=0.98 (5)

$$Capital\ cost\ (B) = 2.1 \times 10^7 + 3.0 \times 10^3 \times CAP - 1.3 \times 10^6 \times \log(TIC)$$

T-statistic: (6.5) (29.3) (-6.5)

R^2=0.85 (6)

$$Capital\ cost\ (C) = 5.4 \times 10^7 + 2.5 \times 10^3 \times CAP - 3.3 \times 10^6 \times \log(TIC)$$

T-statistic: (4.8) (9.6) (-4.6)

R^2=0.77 (7)

$$Capital\ cost\ (B) = 2.9 \times 10^8 + 1.7 \times 10^3 \times CAP - 1.8 \times 10^7 \times \log(TIC)$$

T-statistic: (4.7) (11.9) (-4.4)

R^2=0.90 (8)

In Eqs. (5 – 8), *Capital Cost* and GDP *per capita* are in USD, *CAP* is the plant capacity (m^3/year), and *TIC* is the total cumulated installed capacity of all SWRO plants (m^3/year). The t-statistics show that CAP and TIC are significant at the 99% level and that the GDP per capita is significant at the 90% level.

Based on the regression results of Eqs. (5 – 8), the most statistically significant variables in capital cost estimation were CAP, TIC, and GDP. For the TIC variable, the results suggested decreased capital cost with an increase in the total installed capacity. Such a decline could be explained as ensuing from the technological development and experience gained, because TIC generally indicates the maturity of SWRO plants. In the case that capital cost decreases continually to an unexpected level over time with an increase in TIC, a minimum threshold vale of 0.15 $/$m^3$ was set, based on the present minimum value in DesalData.

Furthermore, to validate the functions developed in Eqs. (5 – 8), the function-predicted capital cost values were plotted against actual observed values, from 2003 to 2014, in Figure 3.5, with R^2 values for each capacity group of 0.98, 0.79, 0.99, and 0.84, respectively. These results suggested a good fit for the developed functions, and their satisfactory performance in predicting past capital costs.

(4) Statistic Model for Plant Capacity Selection

According to DesalData, even in the same year, there are many plants with different capacities installed in one and the same country. Because the variable of capacity plays a significant role in the estimation of unit capital cost, whereas various choices of capacity lead to different estimation results, it is necessary to clarify the capacity selection preference in different countries when a SWRO plant will be built. To that end, a decision-tree model with a Gini index algorithm is typically used to group the target capacity categories within the most homogeneous class. Here, plant capacity choice is classified into five groups: S (capacity of plants < 1,000 m^3/d), M (1,000 – 5,000 m^3/d), L (5,000 – 10,000 m^3/d), XL (10,000 – 50,000 m^3/d), and XXL (50,000 – 100,000 m^3/d). Then, each of these capacity groups is considered as the target category for selection under the splitting variables of GDP *per capita* and population, denoting the economic and water demand levels in different countries.

This study uses the 88 SWRO plants with the largest capacity installed in each country in different years to build the decision tree and assess its accuracy. As shown in Figure 3.6, the fitted decision tree includes eight nodes and summarizes the distribution of capacity within each group. For example, in node 3, the proportion of size L is 100%, suggesting that countries with a GDP per capita between 2,826 and 13,344 USD PPP/year are more likely to install a SWRO plant of size L. Based on the total distribution of the capacity in different nodes, the data show that countries with higher GDP per capita tend to install SWRO plants with larger capacities. However, when the GDP per capita is less than 2,826 USD PPP/year, it seems that the variable of population is more important than the GDP per capita in determining the capacity of a SWRO plant. Finally, to validate the decision tress, a simulated error matrix, described in Table 3.7, showed that the total accuracy of the decision process in correctly attributing locations to the respective capacity classes was 64%. It was found that success rate for each group has a contrary trend with its capacity volume, in which the accuracy for predicting S to XXL size was ranging 100% to 57%. For instance, among the 6 samples with M size capacity, 5 samples were correctly simulated for M size, while 1 for S size. The accuracy for predicting M was 83%. Among the 7 samples with XXL size, only 3 were correctly simulated into XXL, while 4 for XL. The accuracy for predicting XXL was 57%. The results suggested that the proposed decision tree model was appropriate for simulating capacity selection for countries, based on their income and population.

II. Operation and Maintenance (O&M) Cost

All water production facilities require operational attention and regular maintenance to ensure a long, productive and efficient plant. The O&M cost ($C_{\mathrm{O\&M}}$) was based on several economic parameters, including maintenance (M), labor (L), membrane exchange

(ME), chemical (CE), energy (E_T). These factors cover the general major cost of operating a desalination plant. As a result, the O&M cost can be calculated as follows:

$$C_{O\&M} = M + L + ME + CE + E_T \qquad (9)$$

To the abovementioned equation, as annual O&M cost is commonly excluded in DesalData, the values for economic parameters of *M*, *L*, *ME* and *CE* were carefully taken from literature reports (Table 3.8). Indeed, the only uncertain parameter in the O&M cost is the energy cost (E_T), which was suggested to be a significant variable in calculating production cost (Al-Karaghouli and Kazmerski, 2013; Miller, et al., 2015). Electricity is the general required form of energy used by a SWRO plant; thus, the final E_T depends on the electricity consumption (kWh/m^3) and price ($/kWh). Based on these results, energy cost is estimated as follows:

$$E_T = p_T \times f_e \qquad (10)$$

where E_T is the unit energy cost in US$/m^3, p_T is the price of electricity in each country (US$/kWh), f_e is the unit electricity consumption (kWh/m^3), and *T* is year.

Regarding energy consumption, due to the theoretical barrier, it cannot be reduced significantly even with the major changes. Semiat (2008) had indicated that it was a possible way to reduce the energy consumption by improving the RO membrane itself and this might result in an overall change on the order of just 15%. Therefore, the energy consumption can be assumed as some of uniformity over time, as shown in Table 3.8.

For the electricity price, we use the price from the national grid, as this is the source for desalination plants in most countries.

Finally, a historical simulation of production cost (C_p) was conducted to validate, by comparison with that from other previous simulation results (Figure 3.7) (Glueckstern, 1991; Al-Sahlawi and Abdulaziz, 1999; CDM, 2007; Lamei, et al., 2008; NWC, 2008; Zotalis, *et al.*, 2014). Production cost showed a range because plant capacity was selected as a capacity group from the decision tree. For example, if the XXL (50,000 m^3/d – 100,000 m^3/d) capacity group was selected, the left intercept (50,000 m^3/d) would give the maximum value of unit capital cost and the right side (100,000 m^3/d) would lead to the minimum value. A literature review on unit production cost over time was also conducted to validate these simulation results. Glueckstern (1991) evaluated production costs for 200,000 m^3/d capacity SWRO desalination plants and reported a range of 0.96 – 1.20$/m^3 in Israel. Al-Sahlawi and Abdulaziz (1999) reported a unit production cost of 1.03$/m^3 for SWRO plants in Saudi Arabia. In addition, Lamei, et al. (2008) estimated a value between 1.19 – 1.24$/m^3 for plants in Egypt. More recently, CDM (2007) reported the unit production cost of SWRO plants was between 1.12 – 1.19 $/m^3$ in USA. An even lower value was reported by NWC (2008), a value of 0.8 $/m^3$, for unit production costs, based on estimated results for SWRO plants with capacities of 208,000 m^3/d. Zotalis, et al. (2014) estimated the production cost for SWRO in Greece and reported a value of 1.21 $/m^3$. Our simulation results are fairly consistent with these previous published results for a number of regions and years (Figure 3.7). This indicates that our production cost model satisfactorily estimates the unit production costs of SWROs in different countries based on their individual socioeconomic conditions.

Table 3.2 The Principal Factors of Water Production Cost for SWRO Plants

Parameters	Explanation
Capital cost	Dependent on the capital cost and depreciation factor (determined from both plant life and financial parameters and consequently varying for each country).
O&M cost	Dependent on the operational (labor; consumption and cost of energy, related to the source employed and location selected; consumption and cost of chemicals used for pre- and post-treatment of water, especially in RO plants) and maintenance cost (the rate at which the membranes are to be replaced in a RO plants, facility upkeep cost; varying for each country).

Table 3.3 Model's parameters and performance results of capital cost (< 1,001 m^3/day)

	Dependent Variable: EPC cost (Capacity < 1,001 m^3/day)														
Variable	Model 1			Model 2			Model 3			Model 4			Model5		
Constant	**1.E+04**	(1.0)	**	**3.E+06**	(18.8)	***	**3.E+06**	(18.9)	***	**3.E+06**	(18.9)	***	**3.E+06**	(18.8)	***
Capacity	**3.E+03**	(114.0)	***	**3.E+03**	(155.3)	***	**3.E+03**	(156.3)	***	**3.E+03**	(155.1)	***	**3.E+03**	(155.2)	***
log(TIC)				**-2.E+05**	(-18.8)	***	**-2.E+05**	(-18.9)	***	**-2.E+05**	(-18.8)	***	**-2.E+05**	(-18.8)	***
Income							**1.E+00**	(2.50)	*						
Distance										**3.E+00**	(-0.2)				
Region													**-1.E+04**	(-1.4)	
AIC	**11,201**			**10,946**			**10,942**			**10,948**			**10,946**		
R^2	**0.97**			**0.98**			**0.98**			**0.98**			**0.98**		

***indicates a 99% significance level, ** indicates a 95% significance level,* indicates a 90% significance level

Akaike's Information Criterion (AIC) is a measure of the relative quality of a statistical method for a given set of data. A model having the lower AIC is considered to be the better model.

R^2 is a measure to evaluate how well the models fit the data. The higher value of R^2 shows that variables included in the line are good.

The t-value are in parentheses.

Table 3.4 Model’s parameters and performance results of capital cost (1,001-5,001 m^3/day)

	Dependent Variable: EPC cost (1,001 m^3/day< Capacity < 5,001 m^3/day)													
Variable	Model 1			Model 2			Model 3			Model 4			Model5		
Constant	**-3.E+04**	(-0.1)	***	**2.E+07**	(6.5)	***	**2.E+07**	(6.4)	***	**2.E+07**	(6.5)	***	**2.E+07**	(6.3)	***
Capacity	**3024.80**	(26.2)	***	**3.E+03**	(29.3)	***	**3.E+03**	(29.2)	***	**3.E+03**	(29.1)	***	**3.E+03**	(28.9)	***
log(TIC)				**-1.E+06**	(-6.5)	***	**-1.E+06**	(-6.4)	***	**-1.E+06**	(-6.5)	***	**-1.E+06**	(-6.3)	***
Income							**6.E+00**	(0.5)							
Distance										**2.E+02**	(0.3)				
Region													**-2.E+05**	(-0.8)	
AIC	**4,934**			**4,897**			**4,899**			**4,899**			**4,898**		
R^2	**0.81**			**0.85**			**0.85**			**0.85**			**0.85**		

***indicates a 99% significance level, ** indicates a 95% significance level,* indicates a 90% significance level

Akaike’s Information Criterion (AIC) is a measure of the relative quality of a statistical method for a given set of data. A model having the lower AIC is considered to be the better model.

R^2 is a measure to evaluate how well the models fit the data. The higher value of R^2 shows that variables included in the line are good.

The t-value are in parentheses.

Table 3.5 Model’s parameters and performance results of capital cost (5,001 m^3/day< Plant Capacity < 10,001 m^3/day)

	Dependent Variable: EPC cost (5,001 m^3/day< Capacity < 10,001 m^3/day)														
Variable	Model 1			Model 2			Model 3			Model 4			Model5		
Constant	**4.E+06**	(1.2)	*	**5.E+07**	(4.8)	***	**5.E+07**	(4.6)	***	**5.E+07**	(4.7)	***	**6.E+07**	(4.8)	***
Capacity	**2248.90**	(7.3)	***	**2.E+03**	(9.6)	***	**2.E+03**	(9.4)	***	**2.E+03**	(9.4)	***	**2.E+03**	(9.5)	***
log(TIC)				**-3.E+06**	(-4.6)	***	**-3.E+06**	(-4.4)	***	**-3.E+06**	(-4.5)	***	**-4.E+06**	(-4.6)	***
Income							**2.E+01**	(0.8)							
Distance										**2.E+02**	(1.1)				
Region													**8.E+05**	(0.8)	
AIC	**1,073**			**1,057**			**1,059**			**1,059**			**1,059**		
R^2	**0.62**			**0.77**			**0.77**			**0.76**			**0.77**		

***indicates a 99% significance level, ** indicates a 95% significance level,* indicates a 90% significance level

Akaike’s Information Criterion (AIC) is a measure of the relative quality of a statistical method for a given set of data. A model having the lower AIC is considered to be the better model.

R^2 is a measure to evaluate how well the models fit the data. The higher value of R^2 shows that variables included in the line are good.

The t-value are in parentheses.

Table 3.6 Model's parameters and performance results of capital cost (10,001 m^3/day< Plant Capacity < 90,000 m^3/day)

	Dependent Variable: EPC cost (10001 m^3/day< Capacity < 90000 m^3/day)														
Variable	Model 1			Model 2			Model 3			Model 4			Model5		
Constant	**2.E+07**	(2.5)	*	**3.E+08**	(4.7)	***	**3.E+08**	(4.7)	***	**3.E+08**	(4.4)	***	**3.E+08**	(4.8)	***
Capacity	**1818.00**	(9.3)	***	**2.E+03**	(11.9)	***	**2.E+03**	(10.9)	***	**2.E+03**	(11.0)	***	**2.E+03**	(10.7)	***
log(TIC)				**-2.E+07**	(-4.4)	***	**-2.E+07**	(-4.4)	***	**-2.E+07**	(-4.2)	***	**-2.E+07**	(-4.5)	***
Income							**-2.E+02**	(-0.7)							
Distance										**-4.E+04**	(-0.3)				
Region													**7.E+06**		
AIC	**802**			**788**			**790**			**790**			**789**		
R^2	**0.80**			**0.90**			**0.90**			**0.89**			**0.90**		

***indicates a 99% significance level, ** indicates a 95% significance level,* indicates a 90% significance level

Akaike's Information Criterion (AIC) is a measure of the relative quality of a statistical method for a given set of data. A model having the lower AIC is considered to be the better model.

R^2 is a measure to evaluate how well the models fit the data. The higher value of R^2 shows that variables included in the line are good.

The t-value are in parentheses.

Table 3.7 Error matrix for capacity predictions of SWRO desalination plant

	S	M	L	XL	XXL	Total sample	Accuracy (%)
S	3	0	0	0	0	3	100
M	1	5	0	0	0	6	83
L	1	1	3	0	0	5	60
XL	0	0	0	7	5	12	58
XXL	0	0	0	4	3	7	57
Total accuracy(%): 64							

Table 3.8 Values assigned to economic parameters in order to estimate the O&M cost

Cost Association	Parameters	Values	Ref
Operation Cost	Labor cost	0.1 US $/m^3$	Ziolkowska (2015)
	Chemical cost (water treatment)	0.07 US $/m^3$	Ziolkowska (2015)
	Membranes exchange cost	0.03 US $/m^3$	Ziolkowska (2015)
	Energy consumption	4 kWh/m^3	Schallenberg-Rodríguez, et al. (2014)
Maintenance Cost	Instruments, Facility upkeep, Minor equipment replacement, Associated cleaning	2% of capital cost	Kesieme, et al. (2013)

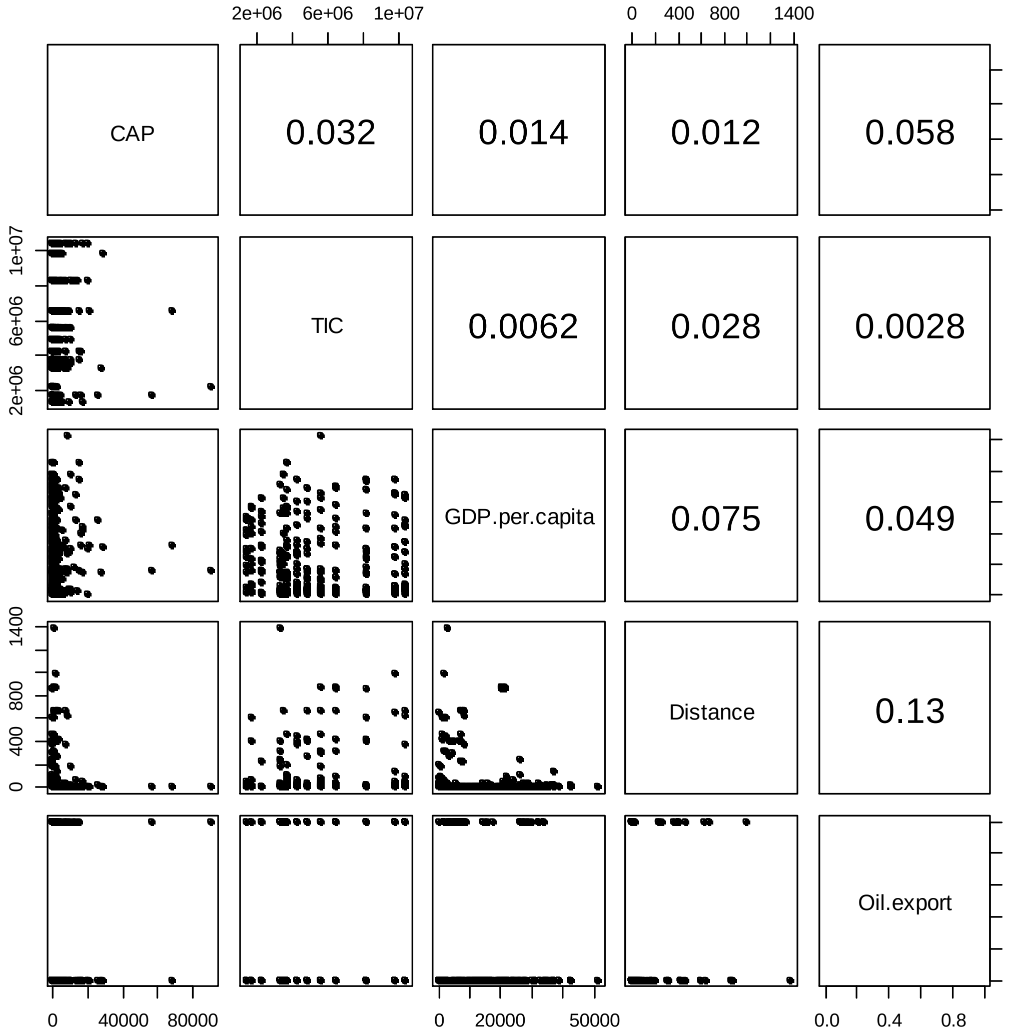

Figure 3.4 Correlation coefficients between various principle variables to estimate the capital cost. The lower/left panels show pairwise scatterplots between each variable, and the upper/right panels contain correlation coefficients.

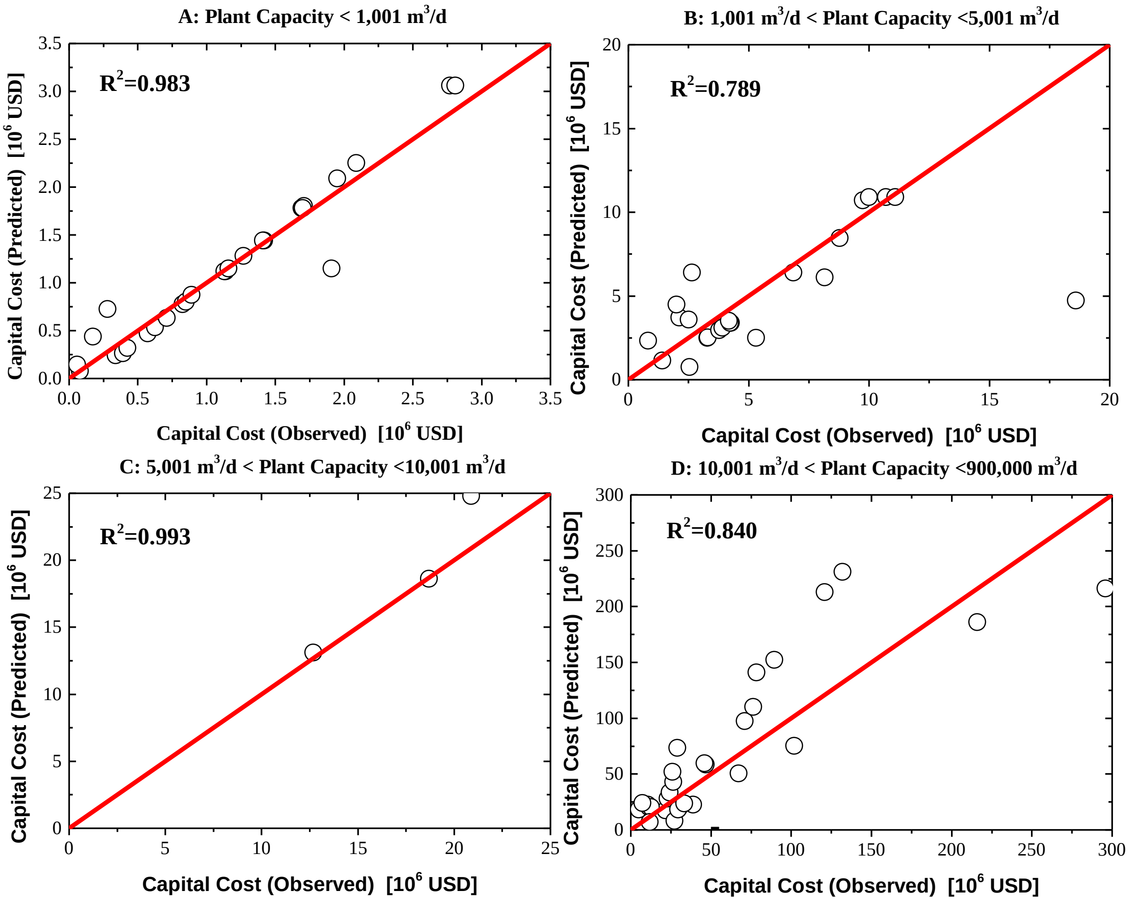

Figure 3.5 Plotting the function-predicted capital cost values against with the actual observed values ranging from 2003 to 2014. R^2 is a measure to evaluate how well the models fit the data. The higher value of R^2 shows that variables included in the line are good.

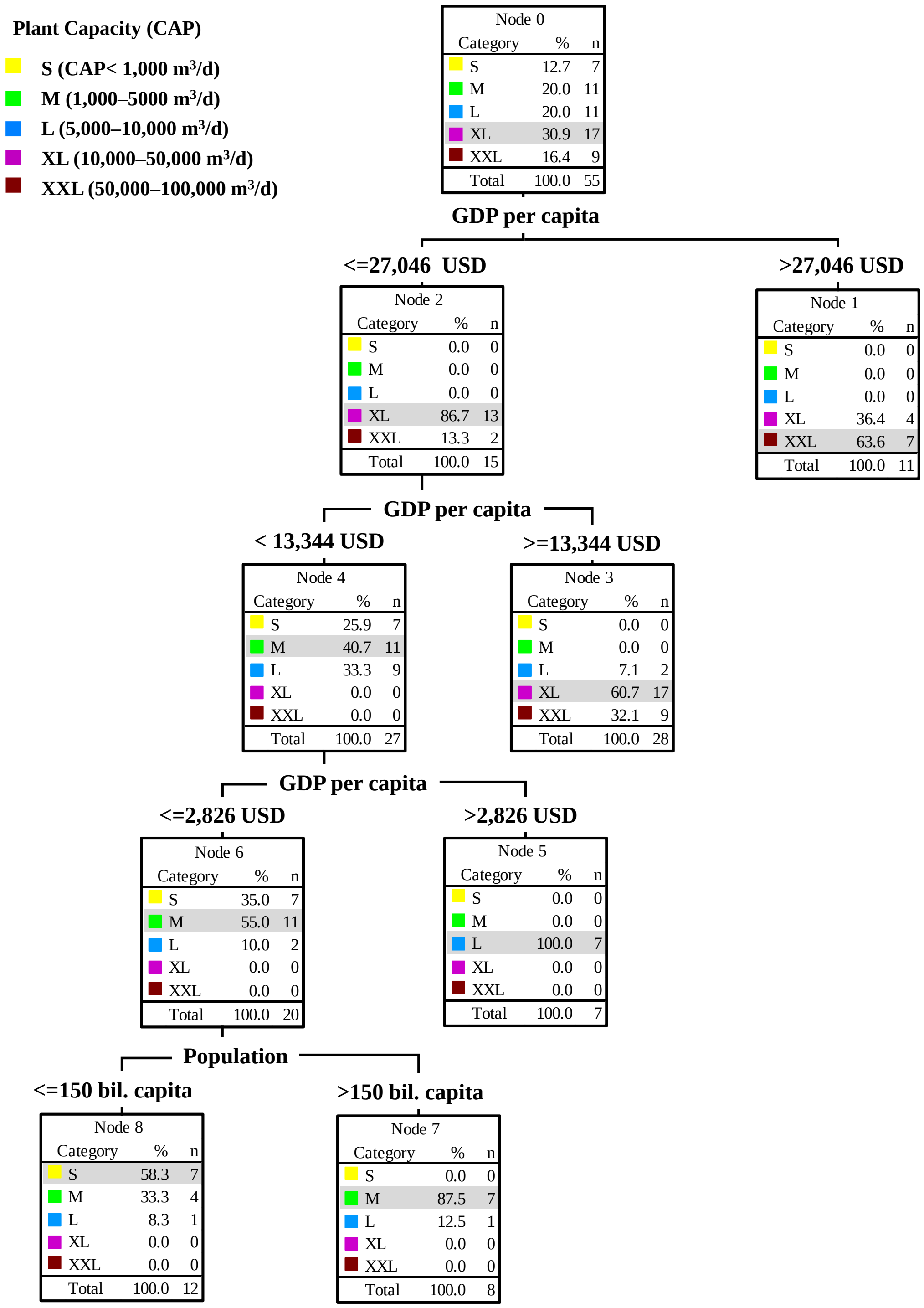

Figure 3.6 Decision tree of capacity selection preference for SWRO plants. Each square is a node, labeled by a node number. In each parent node, a peak and its threshold peak height, used to divide the node into two daughter nodes, are stated. For example, in node 1, the peak 13,344 USD/year of income was selected. The number (n) of cases in a node and their percentage distribution in same capacity group are shown in each node frame.

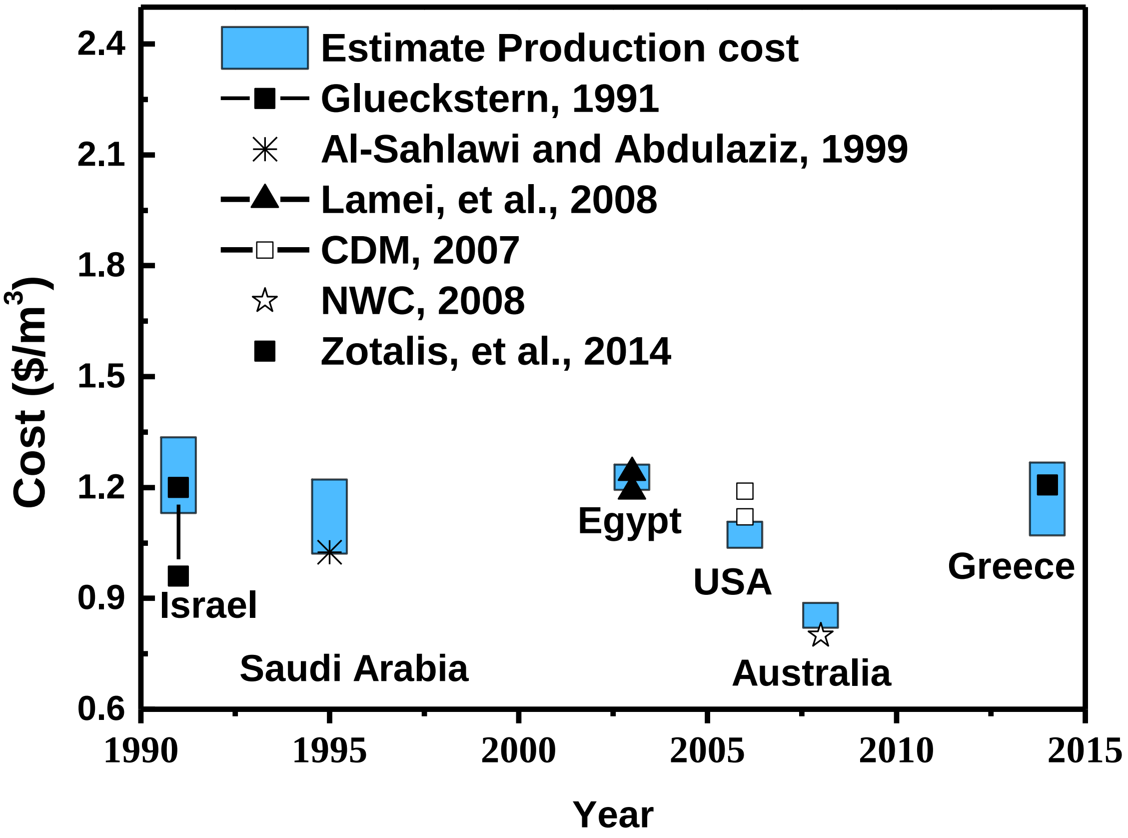

Figure 3.7 Showed the simulated annual productionl costs (maximum and minimum values) for target countries during the period 1990 – 2014. The disperse points are values of unit production costs from previous studies (Glueckstern, 1991, Al-Sahlawi et al., 1999, CDM, 2007, NWC, 2008, Lamei et al., 2008 and Zotalis et al., 2014).

3.2.3 Estimation of Environmental Cost by seawater Desalination

At present, seawater desalination process are positively contributing to solving the problem of water shortage but, at the same time, they cause locally same negative impacts on the environment. There are mainly attributed to the brine and gas emission. Due to the limitation of brine dispose data, we assume the cost of operating a discharge desalination on plants is offset by the profits realized from selling the extra salt produced by the desalination effluent brine. Therefore, this study concentrate on the emission cost which was consider as the environment cost by SWRO.

The emission cost due to increase production electricity for desalination plants

In agreement with the Kyoto Protocol about the climate change, most of the industrialized countries must reduce gas discharges that can contribute to the global warming. During the first commitment period, the objective of Kyoto Protocol is to reduce global greenhouse gas emission by at least 5% against 1990 levels. During the second commitment period, parties committed to reduce greenhouse gas emissions by at least 18% below 1990 levels in the period from 2013 to 2020.

To achieve greenhouse gas reduction targets, many country put a price on carbon pollution as a means of bringing down emissions and drive investment into cleaner options. Therefore, the volume and environmental impact cost for carbon emission could be estimated by carbon tax as follows:

$$\text{Carbon emission} = \sum_i EC_i \frac{G_i}{G_{Total}} \qquad i \in E \tag{11}$$

$$C_{carbon} = C_{\text{carbon tax}} \times f_e \times \text{Carbon emission} \tag{12}$$

Where C_{carbon} is the unit carbon cost in US$/m^3, $C_{carbon\ tax}$ is the carbon tax in each country (US$/kg CO_2), f_e is the unit electricity consumption (kWh/m^3), EC_i is the unit carbon emission (kg CO_2/kWh) for specified energy sources i, G_i is the energy generation for specified energy sources i (kWh/year), G_i is the total energy generation (kWh/year), $i \in E$ is a set of energy sources which include coal, oil, natural gas, hydro, nuclear, SPV, wind, geothermal, bioenergy and others(kWh/year).

3.2.4 Estimation of Conventional Water Resources Cost with Water Price

Generally speaking, the main purpose of water pricing is cost recovery. Depending on the extant policies and socioeconomic conditions, different patterns of water pricing, such as decreasing block tariffs and increasing block tariffs, may be adopted in different countries or areas. For example, a program of decreasing block tariffs, which involves a decrease in the water price as water use increases, is employed only in countries with an abundant water supply, such as Canada (McKenzie and Ray, 2009). In such countries, water can be considered an economic good, and its price decreases with more consumption due to economies of scales. In contrast, a program of increasing block tariffs, which serves as an incentive for conserving water, is often applied in countries characterized by water scarcity, such as China, India, and Spain (McKenzie and Ray, 2009; Loutatidou, et al., 2014; Li, *et al.*, 2017). Therefore, considering the possible differences in the water pricing patterns of countries with different water scarcity indices, all studied countries are divided into two groups: low water-scarcity countries (water scarcity index > 0.8) and high water-scarcity countries (water scarcity index < 0.8). In this study, the water scarcity index which is defined by (Hanasaki, et al., 2013) was picked and it was defined as following:

$$\text{Water Scarcity Index} = \frac{\sum_{DOY=1}^{365} a_{DOY}}{\sum_{DOY=1}^{365} d_{DOY}} \tag{13}$$

Where a_{DOY} and b_{DOY} denote the simulated daily water abstraction from a river and the daily consumption-based potential water demand for a day of the year (DOY), respectively.

For the purpose of making sure the tendency of water price so as to forecast and complete the unclear case, these data in this study were mainly drawn from some reports (Gleick and Michael, 2009) and the IBNET tariff database. Moreover, domestic water price will be primarily discussed. In same year and country, mean value is carefully used for the tap water price in some country.

(1) Multiple Regression Analysis

For the purpose of forecast the SWRO production cost, multiple regression analysis which is a statistical technique to analyze quantitative data to estimate model parameters and make forecasts was selected.

We denote the response (dependent) variable by Y and the set of predictor variables by X_1, X_2, …, X_p, where p denotes the number of predictor (independent) variables. The relationship between Y and X can be approximated by the regression model:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_1 + \Lambda + \beta_n X_n + \varepsilon \tag{14}$$

Where β_0, β_1, β_2, …, β_n, called coefficients, are unknown constants to be estimated from the data. The coefficients is estimated by ordinary least squares (OLS) with an aim of minimizing the difference between the observed and estimated variable value.

(2) Independent Variable

In this study, the water price for each group is assumed to correlate with four independent variables: GDP *per capita*, energy price (electricity price, P_T), population density (PD), and water withdrawal per capita (W_pc). The rationale for the selection of these variables is as follows.

A) GDP per capita

Generally speaking, the main purpose of water price is for cost recovery. As the economic level affects the labor costs in the water supply sector (Alexander, *et al.*, 2014), the GDP per capita is used as a main economic parameter to calculate the water price.

B) Energy Price

Commonly, it will require massive energy consumption to extract the groundwater and treat the raw water in conventional water supply. As energy costs account for a significant fraction of all operational costs, an increase in energy prices leads to an increase in the production cost of water, which, in turn, leads to an increase in the water price (Linda, 2013). Thus, the price of electricity is treated as a key factor in the study

C) Population Density

Population density is assumed to affect the water price because it can determine the water supply per person, which translates into the average cost for the water supply (Piper, 2003).

D) Domestic Water Scarcity per capita

Finally, domestic water withdrawal per capita represents the water demand and further reflects the water stress level; hence, it is expected to change the water price

(Zachariadis, 2010).

Before estimating the regression model, the preliminary step was to test the independent variables for multicollinearity. In statistics, multicollinearity is a phenomenon in which two or more predictor variables in a multiple regression model are highly correlated, meaning that one can be linearly predicted from the others with a substantial degree of accuracy. This phenomenon will increases the standard errors of the coefficients for predictor variables and makes those coefficients unreliable. Figure 3.8 shows a matrices for original data set of independent variables. Because correlation coefficients whose magnitude were between 0.01 and 0.43 indicate variables which can be considered low correlated, there were no problems with multicollinearity.

(3) Statistic Model for Conventional Water Price

Regarding to the estimation in a linear regression analysis, a data set of water prices we use 105 observed data points representing the water prices in various countries from 1990 to 2010 to establish the function, and the observed data from 2011 to 2014, which include 78 data points, are used to assess the accuracy of the model. The Table 3.9 and Table 3.10 gives the results of the regression coefficients, the AIC and R^2 values of the different models. According to the regression results, for the low water scarcity countries, the variables of domestic water withdrawal *per capita* and population density were excluded as possible regressors because adding them did not improve function accuracy and model 2 which include GDP *per capita* and Energy price is the best fitted one due to the lowest AIC value. The values of R^2 was 0.67 which it indicates GDP *per capita* and Energy price explains 67% of the variation between water price and the basically model fitted observation data. Moreover, for the high water scarcity countries, the variables of domestic water energy price and population density were excluded as possible regressors because adding them did not improve function accuracy and model 3 which include GDP *per capita* and domestic water withdrawal *per capita* is the best fitted one due to the lowest AIC value. The values of R^2 was 0.64 which it indicates the satisfactory good fit of model 3 which include GDP *per capita* and domestic water withdrawal *per capita* to the observation data.

The following function is the result of the linear regression modeling:

$$W_p\,(\text{Low water scarcity countries}) = -0.41 + 5.1 \times 10^{-5} \times GDP\ per\ capita + 8.1 \times P_T$$

T-statistic: (-1.7) (9.8) (3.7)

R^2=0.67 (15)

$$W_p\,(\text{High water scarcity countries}) = \text{-}0.06 + 2.7\times10^{-5}\times \mathit{GDP\ per\ capita} + 4.4\times10^{-3}\times W_{pc}$$

T-statistic: (-0.4) (2.7) (1.7)

R^2=0.64 (16)

In Eqs. (15–16), GDP *per capita* is in USD PPP person^{-1} year^{-1}, and W_{pc} is the domestic water withdrawal per capita in each country, m^3/person. The t-statistics show that GDP per capita and Energy are significant at the 99% level, and W_{pc} is significant at the 90% level.

To validate these equations, the function-predicted water price, based on the regression analysis, is plotted against the observed actual water price in different countries (Figure 3.9). The high values of R^2 (0.95 and 0.84) indicate the satisfactory performance of the statistical water price model for the estimation of the water price in each country.

Table 3.9 Model’s parameters and performance results of conventional water price (Low water scarcity: water scarcity index > 0.8)

	Dependent Variable:Conventional water price (water scarcity index > 0.8)														
Variable	Model 1			Model 2			Model 3			Model 4			Model 5		
Constant	**2.9E-01**	**(1.8)**	·	**-4.1E-01**	**(-1.7)**	·	**4.1E-01**	**(2.4)**	*	**-3.0E-01**	**(-1.1)**		**-4.8E-01**	**(-1.8)**	·
Income	**5.1E-05**	**(8.9)**	***	**5.1E-05**	**(9.8)**	***	**5.6E-05**	**(8.9)**	***	**5.3E-05**	**(9.0)**	***	**5.2E-05**	**(9.3)**	***
Energy price				**8.0E+00**	**(3.7)**	***				**7.3E+00**	**(3.1)**	**	**7.9E+00**	**(3.6)**	**
W_{pc}							**-2.7E-03**	**(-1.9)**	·	**-1.2E-03**	**(-0.9)**				
PD													**7.2E-05**	**(0.6)**	
AIC	**88.47**			**86.73**			**77.79**			**78.97**			**79.45**		
R^2	**0.59**			**0.67**			**0.61**			**0.67**			**0.67**		

***indicates a 99% significance level, ** indicates a 95% significance level,* indicates a 90% significance level

Akaike’s Information Criterion (AIC) is a measure of the relative quality of a statistical method for a given set of data. A model having the lower AIC is considered to be the better model.

R^2 is a measure to evaluate how well the models fit the data. The higher value of R^2 shows that variables included in the line are good.

The t-value are in parentheses.

Table 3.10 Model’s parameters and performance results of conventional water price (High water scarcity: water scarcity index < 0.8)

	Dependent Variable: Conventional water price (water scarcity index < 0.8)														
Variable	Model 1			Model 2			Model 3			Model 4			Model 5		
Constant	**1.1E-01**	**(0.9)**		**1.6E-01**	**(-0.9)**	·	**-6.1E-02**	**(-0.4)**		**-3.1E-02**	**(-0.2)**		**2.2E-01**	**(1.0)**	·
Income	**4.2E-05**	**(8.5)**	***	**4.2E-05**	**(8.4)**	***	**2.7E-05**	**(2.7)**	***	**2.8E-05**	**(2.7)**	**	**4.1E-05**	**(6.6)**	***
Energy price				**-5.5E-01**	**(-0.4)**					**-3.0E-01**	**(-0.2)**		**-4.9E-01**	**(-0.4)**	
W_{pc}							**4.4E-03**	**(1.7)**	·	**4.3E-03**	**(1.6)**				
PD													**-3.8E-05**	**(-0.4)**	
AIC	**56.51**			**58.30**			55.5567			**57.49**			**60.10**		
R^2	**0.61**			**0.61**			**0.64**			**0.63**			**0.61**		

***indicates a 99% significance level, ** indicates a 95% significance level,* indicates a 90% significance level

Akaike’s Information Criterion (AIC) is a measure of the relative quality of a statistical method for a given set of data. A model having the lower AIC is considered to be the better model.

R^2 is a measure to evaluate how well the models fit the data. The higher value of R^2 shows that variables included in the line are good.

The t-value are in parentheses.

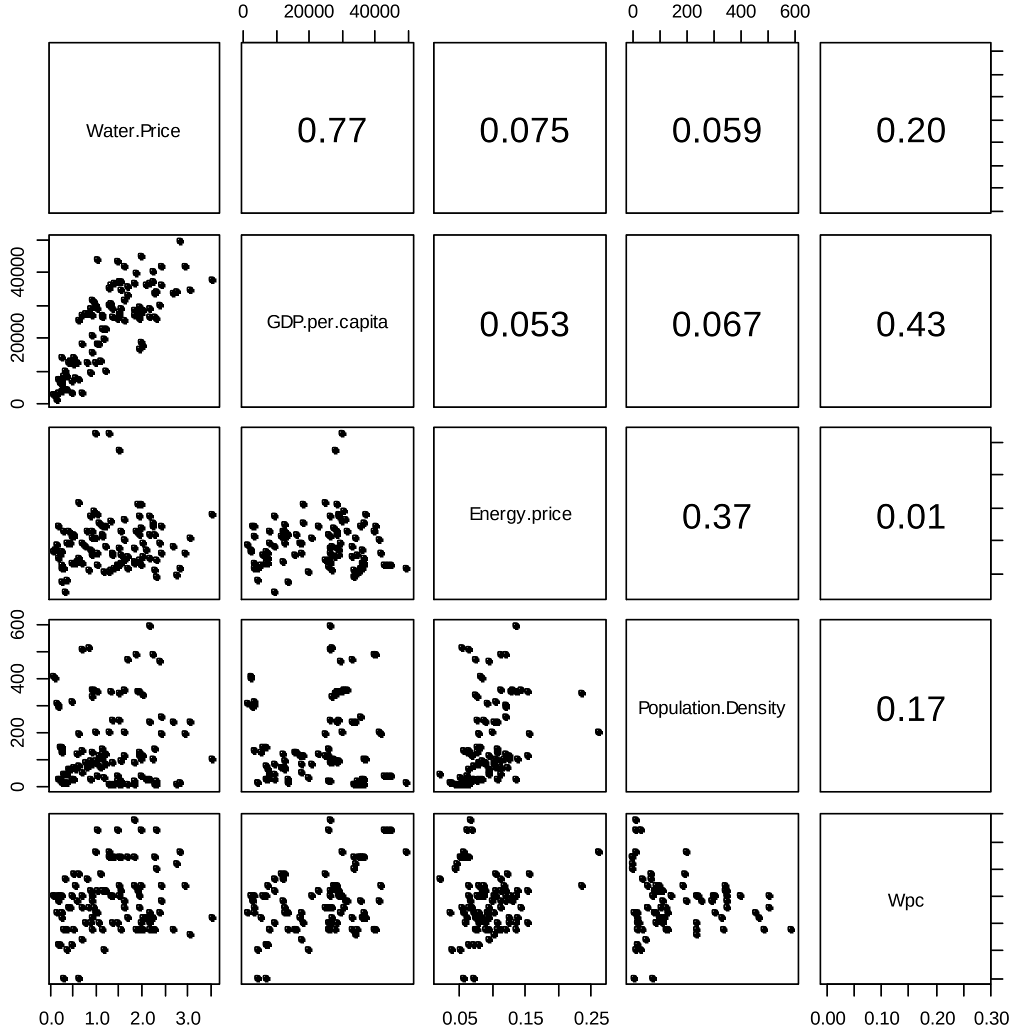

Figure 3.8 Correlation coefficients between various principle variables to estimate the capital cost. The lower/left panels show pairwise scatterplots between each variable, and the upper/right panels contain correlation coefficients.

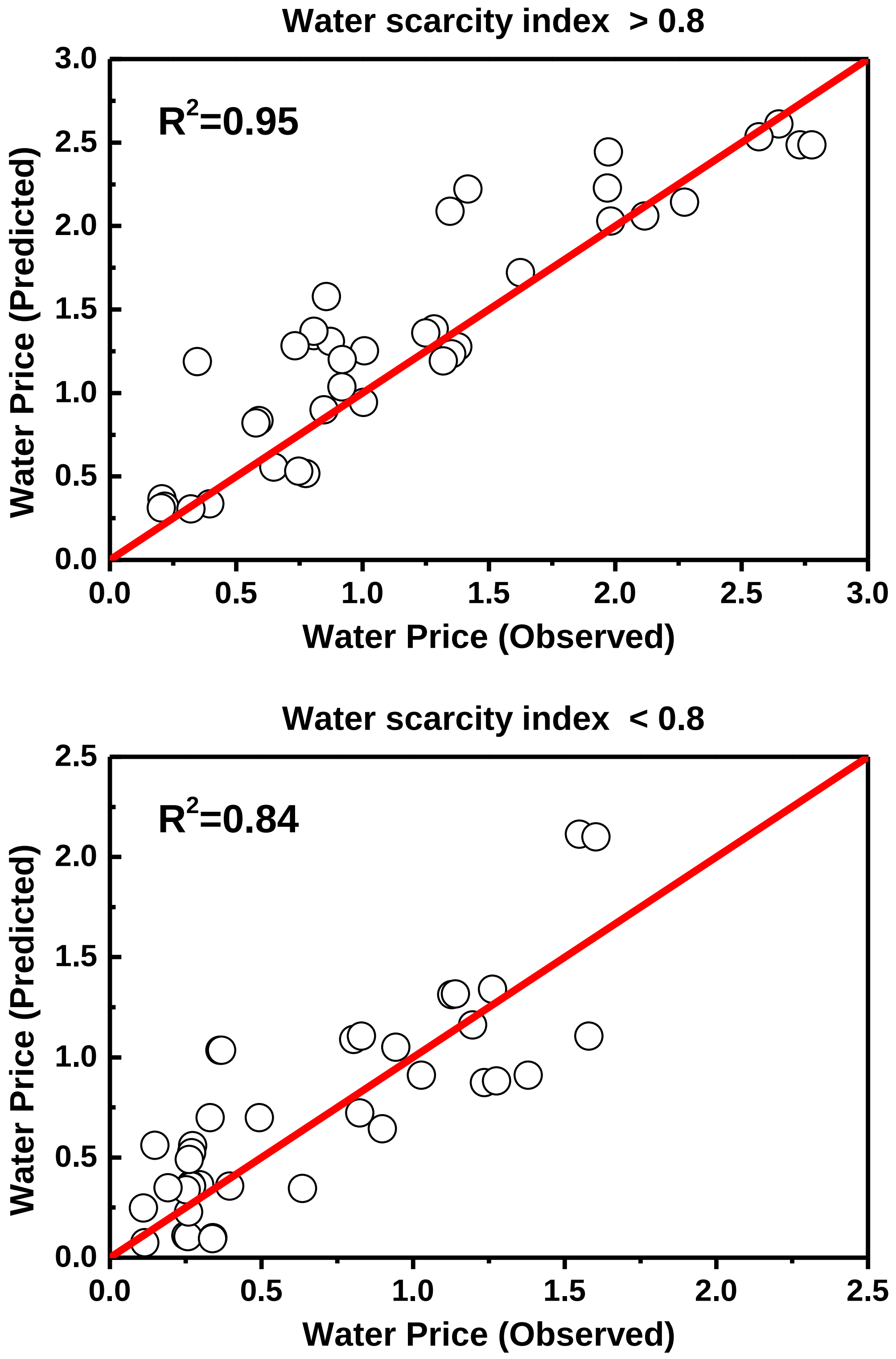

Figure 3.9 Plotting the predicted water price by the best model values against with the actual observed values from 2011 to 2014. R^2 is a measure to evaluate how well the models fit the data. The higher value of R^2 shows that variables included in the line are good.

3.2.5 Future Simulations with the Models Developed for the Feasibility Assessment of SWRO

In section 3.2.2 - 3.2.4, the three models developed were shown to be useful for estimating the production cost of SWRO plants, the environmental cost and the conventional water price in each country, respectively. Next, these developed models were applied to project the production cost, environmental cost and conventional water price in different countries on a global scale under three shared socioeconomic pathways (SSP1, SSP2, SSP3), assuming that the trends observed over the modeling period (1990 – 2014) would continue into the next several decades (2015 – 2050). Attention was focused on the following:

I. Assumption

A. Capital cost: as mentioned, the capital cost was estimated using Eqs. (5 – 8). In the equations, plant capacity selection for each country was based on the results of the decision trees. For the total installed capacity, Ghaffour, et al. (2013) estimated the current growth rate would be ~55%; here, that same past growth rate was used for the future simulations. Additionally, as same as past simulation, a discount rate of 8% and a 20-year plant life were also used in the future periods (Papapetrou, et al., 2017).

O&M cost: in both the past and future periods, the O&M cost ($C_{O\&M}$) was based on several economic parameters, including maintenance (M), labor (L), membrane exchange (ME), chemical (CE) and energy (E_T) costs. For the future simulation, environment costs (carbon costs) is added and Eqs. 16 were used to calculate the O&M cost, as follows:

$$C_{O\&M} = (p_T + C_{carbon\ tax}) \times f_e + M + L + ME + CE \qquad (16)$$

where p_T is the comprehensive electricity price which include coal, oil, natural gas, hydro, nuclear, SPV, wind, geothermal, bioenergy and others (US \$/kWh), $C_{carbon\ tax}$ is the carbon tax in each country (US \$/kWh), f is the unit electricity consumption (kWh/m^3; Table 3.5), maintenance (M), labor (L), membrane exchange (ME), chemical (CE) were assumed to be constant, as summarized in Table 3.8.

B. Water price: the water price is estimated using Eqs. 15 and 16 for the two scenarios. First, these functions are used to simulate the change in the water price in each country during different years. In our long-term future simulation, the future projected water price is assumed to change uniformly every year. Second, the function, developed based on data from 56 countries, is applied to compute the deficient water price in the other 84 countries that were not included in the observed dataset. For domestic water withdrawal per capita, Hanasaki, et al. (2013) estimate that the growth rate would be ~7.3×10^{-4} m^3 $person^{-1}$ $year^{-1}$; here, that same past growth rate is used for the future simulations.

Finally, by combining the results for the production cost (capital and O&M costs) and water price simulation, the economic feasibility of adopting seawater desalination in different countries on a global scale can be discussed in detail.

II. Scenario

A. Climate mitigation scenario

As mentioned above, energy cost is an integral part of the unit production cost. This may be greatly affected by future climate policies, as different policies lead to different energy prices (Fujimori, *et al.*, 2017). In the present study, to clarify the effect of climate policy on future SWRO diffusion, future simulations of production cost and water price models are carried out under the following four climate policy scenarios (van Vuuren, *et al.*, 2011) (Figure 3.10):

1. BUS (Business as Usual) with no constraint on greenhouse gas (GHG) emissions;
2. RCP (Representative Concentration Pathways) 6.0 is developed by National Institute for Environmental Studies in Japan. The radiative forcing is stabilized 6.0 W/m^2 at 2100, which is consistent with the application of a range of technologies strategies for reducing greenhouse gas emissions;
3. RCP 4.5 is developed by the Pacific Northwest National Laboratory in the US. Here radiative forcing without overshoot pathway to 4.5 W/m^2 at stabilization after 2100, consistent with a future with relatively ambitious emissions reductions;
4. RCP 2.6 is developed by PBL Netherlands Environmental Assessment Agency. Here radiative forcing reaches 3.1 W/m^2 before it returns to 2.6 W/m^2 by 2100. In order to reach such forcing levels, ambitious greenhouse gas emissions reductions would be required over time. This is a strict climate scenario to keep global mean temperature increase below 2℃.

B. Socioeconomic scenarios

Regarding the socioeconomic dimension, we adopted the SSPs (Shared Socioeconomic Pathways) concept. SSPs consist of narrative storylines and quantitative information about plausible future world states. SSPs comprise five representative scenarios and we focus on SSP1 – 3 for socioeconomic scenarios (Figure 3.11):

1. SSP1 reveals a sustainability scenario. Such scenario has the characteristic of relatively rapid income growth and smaller populations, thus the sustainability is achieved at least in part through quick technological change and high levels of international cooperation.
2. SSP2 is a middle road scenario which continues current trend with moderate progress made in terms of income convergence. For instance, per-capita income levels of this scenario grow at a medium pace on the global average, with slowly converging income levels between developing and industrialized countries. Others like educational investments, which are not high enough to rapidly slow population growth, particularly in those low-income countries.
3. SSP3 is defined as fragmented world which is distinguished for lacking of international cooperation, slow technological progress, low education levels and high population growth.

Generally, the SSPs would not include any climate policy effect. While, as mentioned before, energy costs may be an important part of the unit production cost, while it might be affected greatly by future climate policies, as varied policies would lead to different energy prices. Kriegler, *et al.* (2012) proposed scenarios relating to climate policy for SSPs, called the shared climate policy assumptions. Hanasaki, et al. (2013) also sought to relate SSP1 – 3 with three climate policies: RCP2.6, RCP4.5 and RCP6.0, respectively. These settings are based on a straightforward interpretation of the mitigation challenge of SSPs (the vertical axis of Figure 3.12). Because the SSP1 is less challenging to mitigate, the RCP2.6 was selected for it. In contrast, the SSP3 is indicated as more challenging, so we choose RCP6.0 for it. In the present study, it attempted to clarify the effect of climate policy on production cost by used in a manner similar to Hanasaki, et al. (2013).

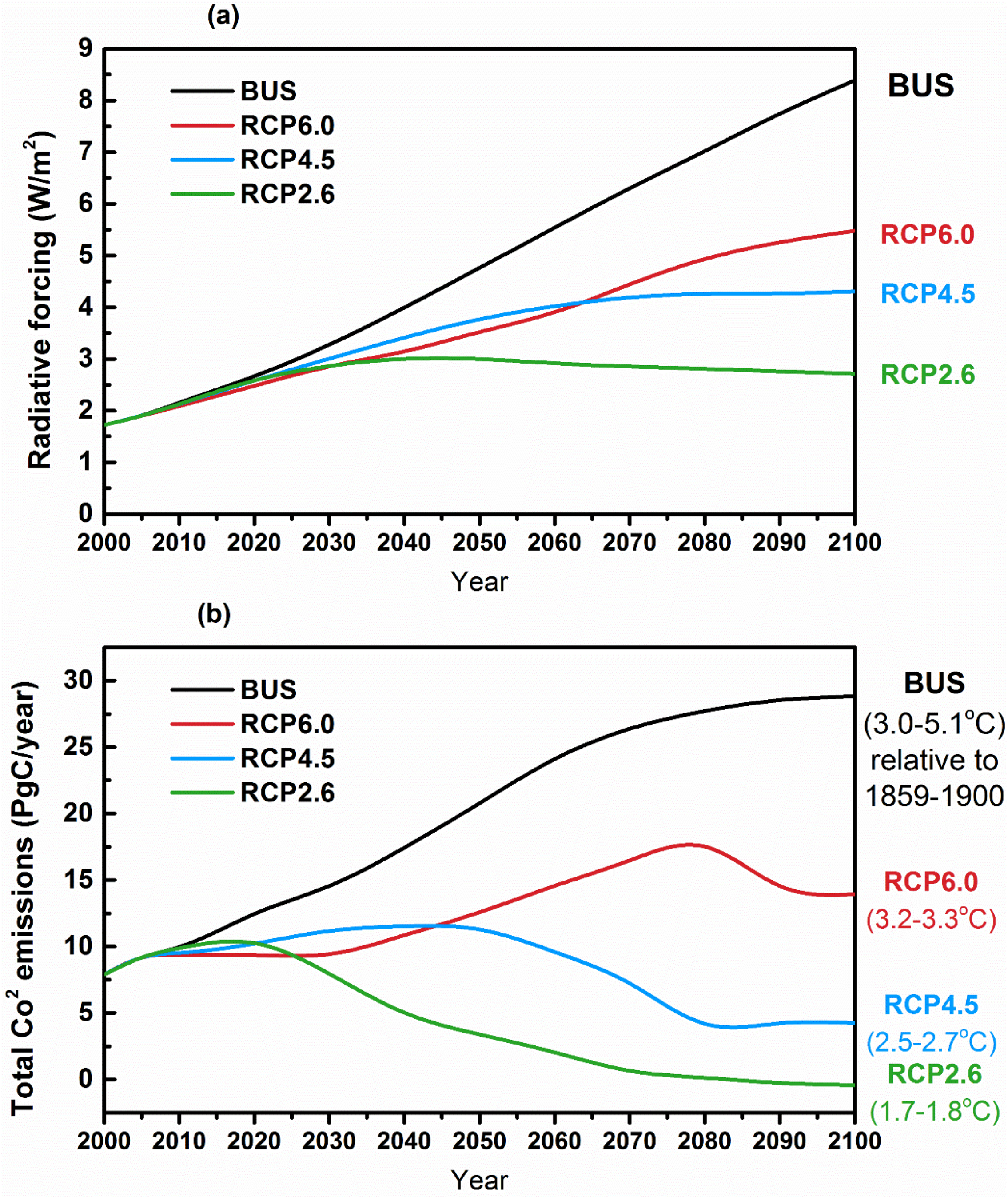

Figure 3.10 Radiative forcing levels and corresponding total CO_2 emissions in each scenarios. (a) Radiative forcing. (b) CO_2 emissions, global mean temperature change is relative to a reference period of 1859 – 1900.

(Data source: RCP database and SSPs database which is provided by IIASA)

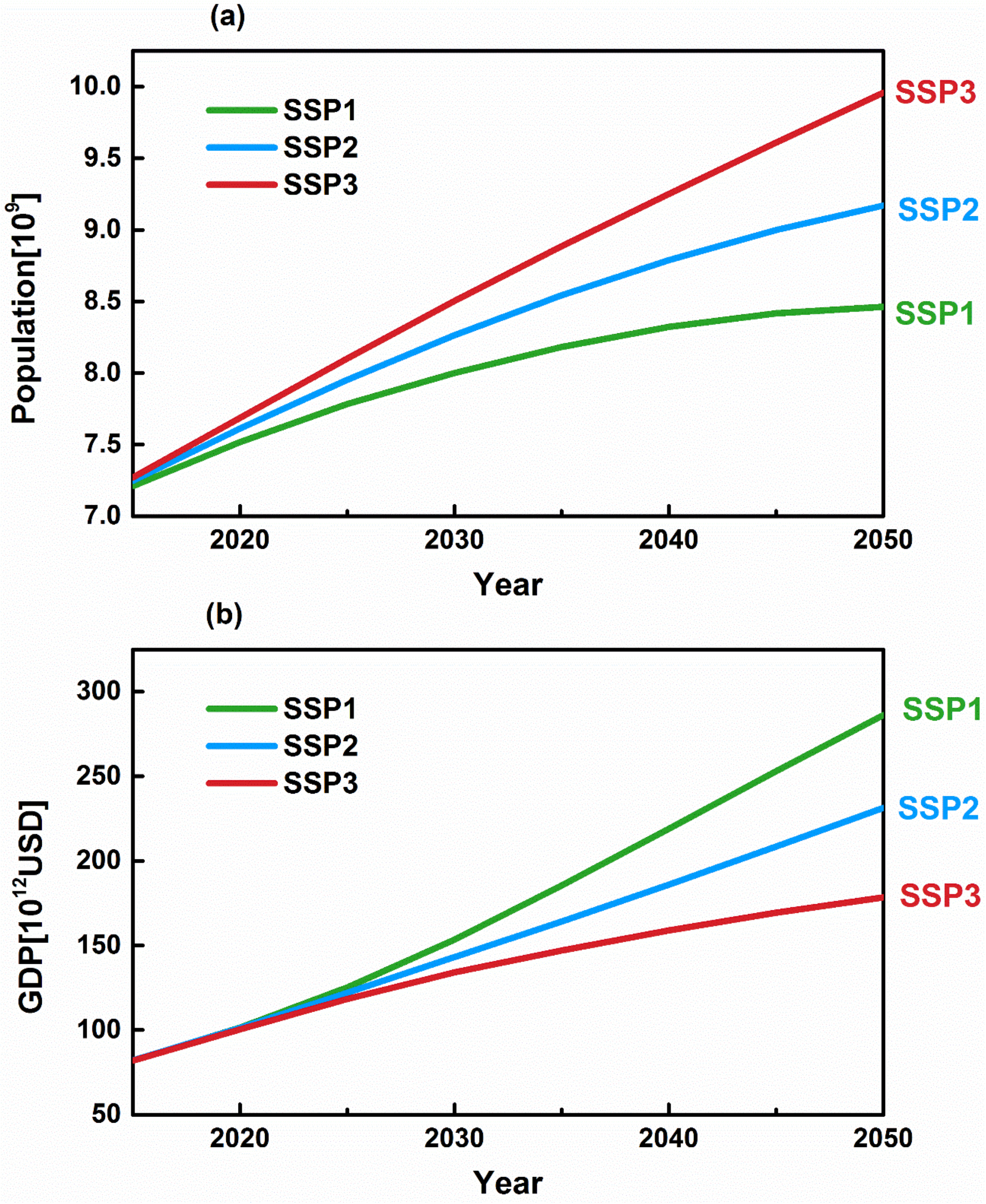

Figure 3.11 Socio-economic factors. (a) Population. (b) GDP

(Data source: RCP database and SSPs database which is provided by IIASA)

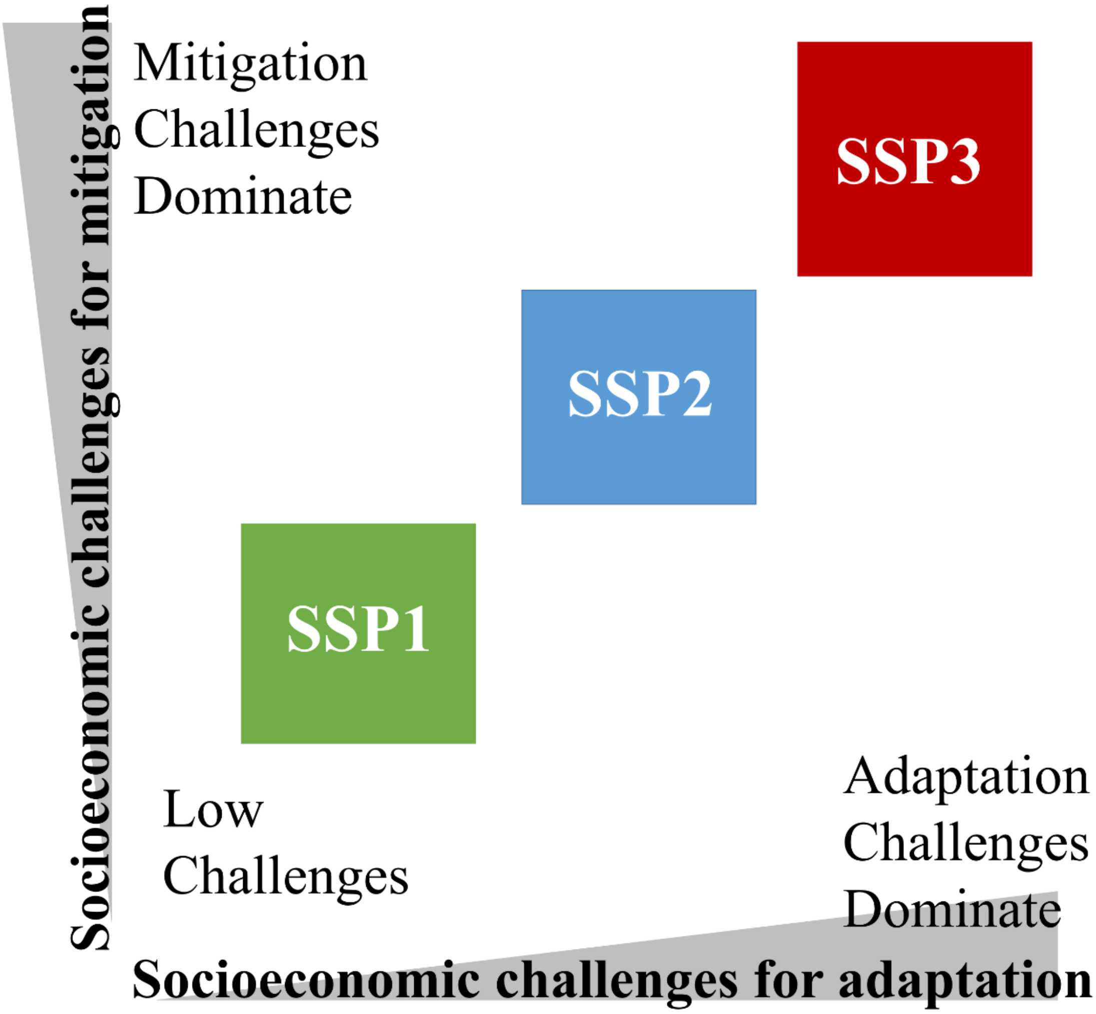

Figure 3.12 The three SSPs in a conceptual space of adaptation and mitigation challenges.

3.2.6 Data Collection

Parameters adopted in simulations for models establishing are shown in Table 3.11. First, desalination data were gathered. To analyze present desalination capacity, DesalData (2014) were primarily used. As of 2014, DesalData covered records for more than 17, 000 desalination plants. In total, information for the period 1990 to 2014, involving 56 countries, about 764 SWRO plants, including data on capital cost (EPC-type contracts), plant capacity, location, and contract award year, is analyzed (the detailed criteria was summarized in Table 3.12).

Second, we use socioeconomic data (1990–2014) for the historical simulations based on our models. Socioeconomic data, including the gross domestic product (GDP) and population, are from the database of the World Bank (2016) . GDP is analyzed in terms of purchasing power parity (PPP) in 2005 US Dollars. Additionally, the electricity prices for individual countries from 1990 to 2014 are from the IEA database (2017) . The municipal water prices for 56 countries from 1990 to 2014 are primarily from Gleick and Michael (2009) and the IBNET tariff database (2017) . Nationwide water-use data, including water withdrawal and water demand from 1990 to 2000, are from Yoshikawa, et al. (2014).

Finally, socioeconomic data from 2015 to 2050 are used for future simulations. As seawater is used as the water resource for SWRO plants, 140 countries, none of which is landlocked, are considered. For the simulation parameters of the GDP (in constant 2005 PPP US Dollars) in these countries, the Shared Socioeconomic Pathway (SSP) Database (2016) covering the period of 2015 – 2050, provided by IIASA, is used. The population is taken from Murakami and Yamagata (2016) . Given that different climate policies may impact future energy prices, electricity price data for two climate policies are used. These are from Fujimori, et al. (2017). For the purpose of comparison, all cost figures in this paper are given in 2005 US Dollars, calculated based on the United States Consumer Price Index (CPI).

Table 3.11 Socioeconomic parameters and data used in the simulation.

Parameter	Data	Year	Ref
Capital cost	56 countries (764 plants)	1990 – 2014	DesalData (2014)
Population	56 countries	1990 – 2014	World Bank (2016)
GDP	56 countries	1990 – 2014	World Bank (2016)
Electricity	56 countries	1990 – 2014	IEA (2017)
Water price	56 countries	1990 – 2014	Gleick and Michael (2009), IBNET tariff database (2017)
Water withdrawal	56 countries	1990 – 2014	Yoshikawa, et al. (2014)
Water demand	56 countries	1990 – 2014	Yoshikawa, et al. (2014)
For the future period			
Population	140 countries	2015 – 2050	Murakami and Yamagata (2016)
GDP	140 countries	2015 – 2050	SSP Database (2016)
Electricity	17 Regions	2015 – 2050	Fujimori, et al. (2017)

Table 3.12 Data items and selection criteria

Items	Options	Selection
Plant status	Online	Included
	Construction, Planned, Cancelled, On hold, Offline, Unknown	
Water type	Seawater (TDS 20,000 ppm-5,000ppm)	Included
	Brine of concentrated seawater (TDS > 50,000 ppm)	Excluded
	Brackish water or inland water (TDS 3,000 ppm - < 20,000 ppm)	
	River water or low concentrated saline water (TDS 500 ppm - < 3,000 ppm)	
	Pure water or tap water (TDS < 500 ppm)	
	Waste water, Unknown	
User category	Municipalities as drinking water (TDS 10 ppm - < 1,000 ppm)	Included
	Tourist facilities as drinking water (TDS 10 ppm - < 1,000 ppm)	
	Industry (TDS < 10 ppm)	
	Military purposes (TSD 10 ppm - < 1,000 ppm)	
	Power stations (TDS < 10 ppm)	
	Irrigation (TDS < 1,000 ppm)	
	Demonstration, Discharge, Process, Water injection, Unknown	
Plant size	Extra-large (Capacity ≻= 50,000 m^3/d)	Included
	Large (50,000 > Capacity ≻= 10,000 m^3/d)	
	Medium (10,000 > Capacity ≻= 1,000 m^3/d)	
	Small (1,000 m^3/d > Capacity)	
Private finance	EPC	Included
	BOT, DB, DBO, IWP	Excluded
Selected countries	Algeria, Australia, Belgium, Brazil, Canada, Chile, China, Colombia, Cuba, Cyprus, Denmark, Ecuador, Egypt, Fiji, Finland, France, Germany, Greece, Honduras, India, Israel, Italy, Jamaica, Japan, Jordan, Kazakhstan, Kenya, Kuwait, Libya, Malaysia, Mexico, Morocco, Netherlands, Nigeria, Norway, Oman, Pakistan, Peru, Philippines, Portugal, Russia, Saudi Arabia, South Africa, South Korea, Spain, Sweden, Thailand, Tunisia, Turkey, United Arab Emirates, United Kingdom, United States of America, Venezuela, Vietnam	Included

Note: BOT (Build-Operate-Transfer), DB (Design-Build), DBO (Design-Build-Operate), IWP (International Water Project)

3.3 Results and Discussions

3.3.1 Prediction of Production Cost with Future Simulation

This section focuses on the projection of future unit production costs, under three shared socio-economic pathways (SSP1, SSP2, and SSP3) with climate policies (RCP2.6, RCP4.5 and RCP6.0). Figure. 3.13 shows the projected unit production cost (C_u), unit capital cost (C_p) and unit energy cost (E_T) as average values for all countries studied in 2015-2050 under the different SSPs.

Overall, for three SSP scenarios, the unit capital cost showed a decreasing trend which could be reasonably explained as a result of the technology progress and economies of scale, as the increasing of GDP per capita would make it easier to build a SWRO plant with a larger capacity in more countries. Whereas, contrary was true to the unit energy cost because of the increasing of electricity price under the progressively changed climate policy within the studied period.

In each scenarios, the decrease in unit capital cost was high in SSP1, medium in SSP2, and low in SSP3, which can be explained as that the higher share of the high-income counties in SSP1 than in the other scenarios would make it easier to build a SWRO plant with a larger capacity. As evidence, Figure. 3.14 shows that the number of countries that could install SWRO plants with the maximum capacity increased over time under the three socioeconomic scenarios, while the proportion of these countries was highest in SSP1. In contrast, for the unit energy cost, its increases in SSP2 were somewhat limited, compared with SSP1 and SSP3. This can be primarily attributed to the increase in electricity prices induced by the climate policies within the studied period. Finally, based on the contradictory contributions of unit capital cost and energy cost to the unit production cost in Figure 3.13, the projected average unit production costs over the period of 2015 – 2050 are expected to be within the ranges of 1.30 – 0.98, 1.30 – 0.97 and 1.31 – 1.09 USD/m^3 under the SSP1, SSP2, and SSP3 scenarios, respectively. The projected production costs are industry-wide average projections rather than those at the single-plant level. According to our projections, although unit production costs of SWRO are expected to continue their downward trend, which matched well with an earlier estimate of unit production costs (Dore, 2005), the variation in SSP3 was relatively limited versus that in SSP1 and SSP2 because the increase in energy costs in SSP3 was larger than SSP2 and the decrease in capital costs in SSP3 was lower than that under the other two scenarios.

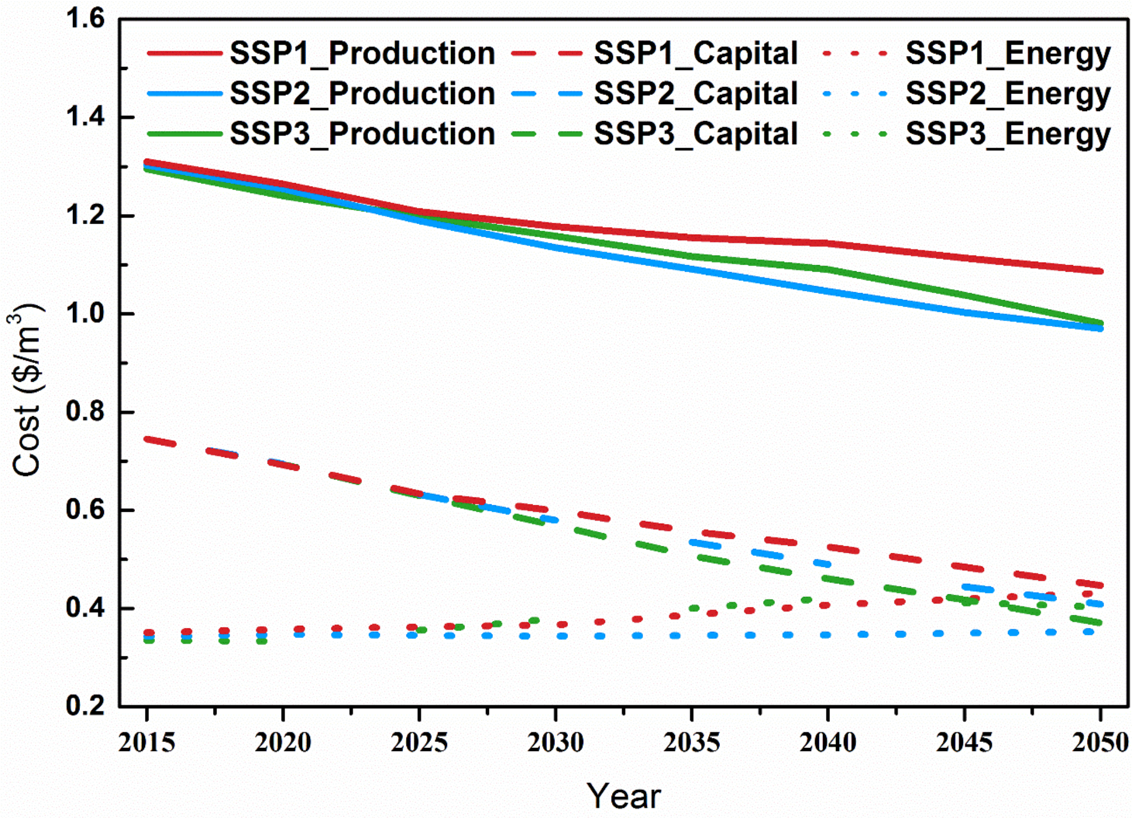

Figure 3.13 Future projections of averaged unit production (C_P), capital (C_u), and energy (E_T) costs of SWRO plant for 140 countries under three SSPs. Green, blue, and red lines indicate SSP1, SSP2, and SSP3, respectively. Solid, dash, and dot lines indicate production cost, capital cost and energy cost, respectively.

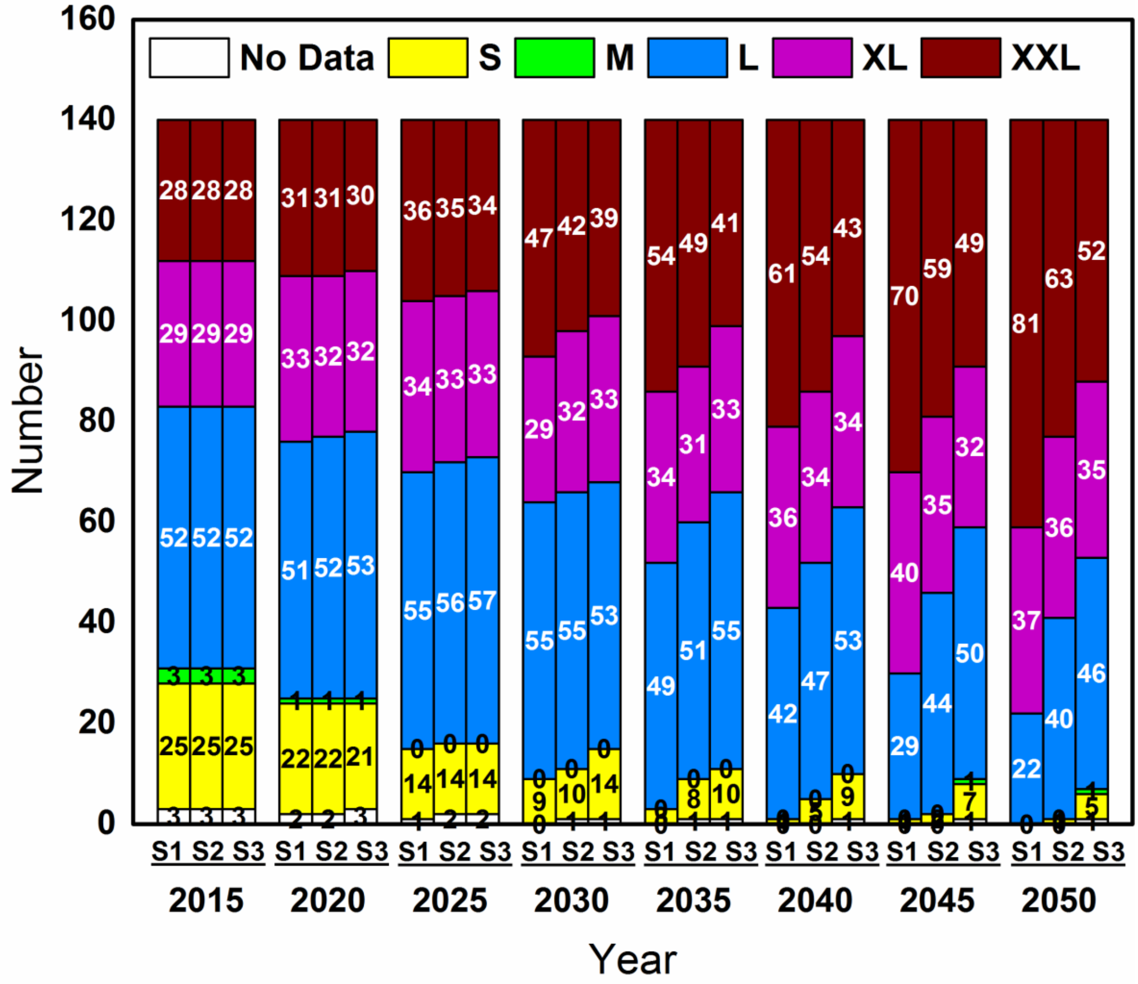

Figure 3.14 Future projections of plant capacity of SWRO desalination plants under three socioeconomic scenarios: SSP1 (S1), SSP2 (S2), and SSP3 (S3). Yellow, green, blue, pink, and red bars indicate S (capacity of plants < 1,000 m^3/d), M (1,000 – 5,000 m^3/d), L (5,000 – 10,000 m^3/d), XL (10,000 – 50,000 m^3/d), and XXL (50,000 – 100,000 m^3/d) plants. The countries with the GDP per capita lower than 800 UDS is defined as no data. The value on each stack bar indicates the number of countries that are likely to install a SWRO plant with the corresponding capacity.

3.3.2 Prediction of Water Price with Future Simulation

After completing the projection of the unit production cost, the next concern was owned to the projection of water price in 140 countries over the period 2015–2050. On the temporal-scale, as shown in Figure. 3.15, for three SSP scenarios, the unit water price was further averaged among all the countries to determine its trend with time (The water price for each country is shown in Appendix B1). Under all SSP scenarios to 2050, the projected average water price in different countries will increase markedly compared with the 2015 figures, although at different degrees.

The increase in water price can be explained primarily by the income growth in each country, whereas potential changes in the electricity price due to different climate policies probably play a marginal role. In SSP1, the unit water price showed the largest increase globally. In SSP2 and SSP3, although increase pattern was similar to SSP1, the water price value was lower in same predicted period. On the spatial-scale, a complete illustration of the projected unit water price in each country by a world map was shown in Figure 3.16. Basically, the unit water price for the spatial coverage in the baseline year of 2015 was considered to be high over the areas in U.S., Canada, Europe, and Australia; medium over the countries around Mediterranean belt, South America, China, and Russia; low over the South-east Asia and Africa. For all SSPs scenarios in 2050, the projected water price in different countries would extensively increase compared to the 2015 figures, though at different levels. The increase of water price could be primarily explained by growth of income in each country and the potential energy cost change due to different climate policy would play a marginal role.

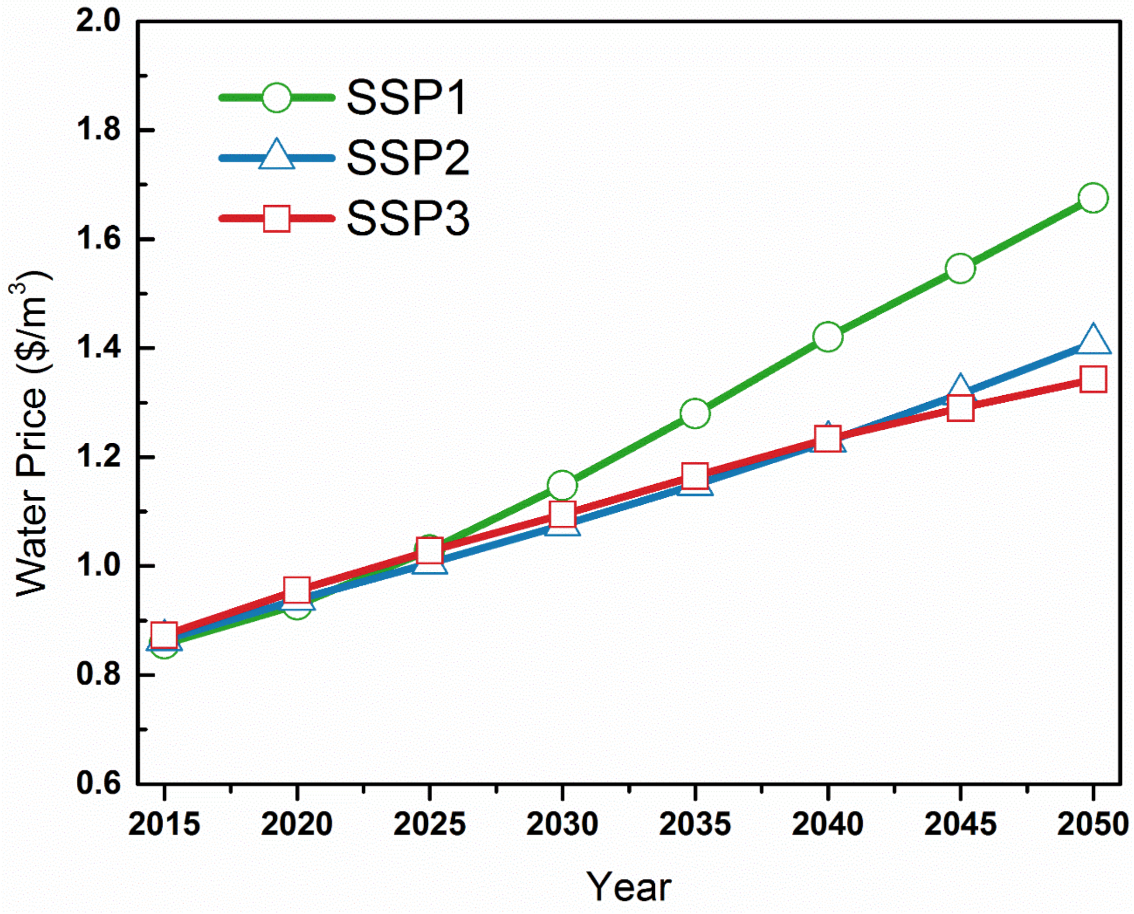

Figure 3.15 Future projections of averaged unit water prices for 140 countries under three SSPs. Green, blue, and red lines indicate SSP1, SSP2, and SSP3, respectively.

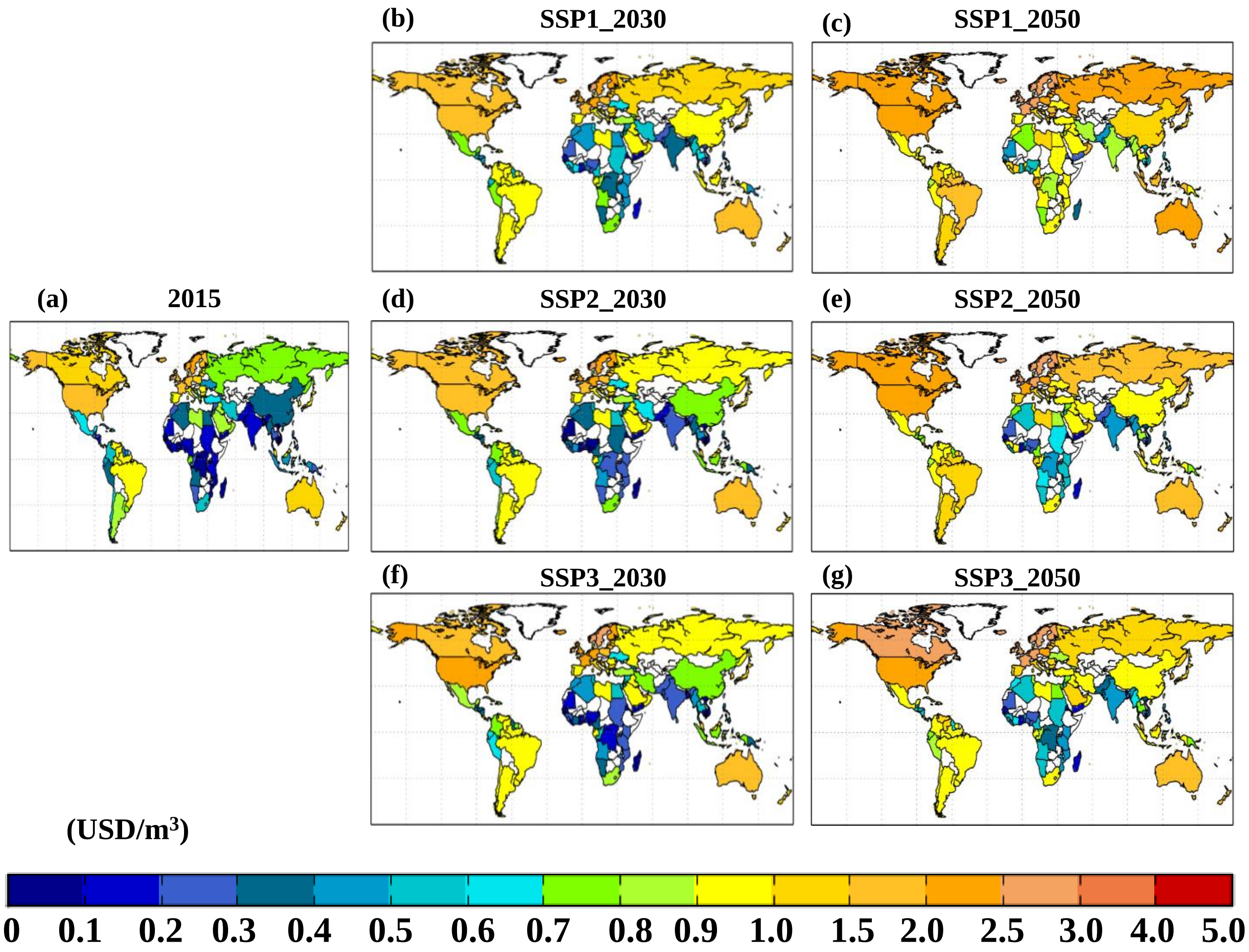

Figure 3.16 A world map of the projected water prices for different countries in the years 2015, 2030, and 2050 under the SSP1 – 3 scenarios. Colors change at national boundaries.

3.3.3 Economic Feasibility Evaluation of Seawater Desalination on Global Scale

I. Simulation of Feasibility with Historical Validation

First, we perform a historical simulation to validate the feasibility index (F_i) by correlating it with the actual SWRO development in the nine countries (United Arab Emirates, Saudi Arabia, Spain, Kuwait, Israel, Qatar, Bahrain, Oman, and Libya) that dominate global water desalination in terms of reported volume of desalination production (Hanasaki, et al., 2016). Validation was performed by comparison with DesalData within two aspects: on spatial-scale, we examine whether the F_i for these major countries is consistently higher than its value for the 131 other countries; on the temporal scale, we check whether there is significant long-term consistency between the F_i and TIC for each of these major countries within the studied period.

In Figure 3.17 and Table 3.13, we summarize the F_i derived from our historical simulation and the TIC in each 5-year interval from 1990 to 2015. Notably, some missing data in each panel are attributed primarily to the limited data for these countries in specific years. As a result, the calculated F_i values for these nine countries range from 0.76 to 4.14 for 2015; these are indeed significantly higher than the values for most of the other countries that account for a negligible proportion of the total global water desalination production (Table C1 in Appendix C). Moreover, for the nine major countries, the data reflect a significant increase in F_i during 1990 – 2015. This is consistent with the corresponding increase in TIC in these specific years in each of these countries. As a result, the performance of F_i on the spatial and temporal scales suggests that it can be a promising way for assessing the feasibility of desalination because its variability is consistent with the actual historical development of SWRO in major countries. It should be noted that the threshold of the F_i for the application of desalination can be varied for different countries, whereas a standard theoretical value of 1 can contribute to the establishment of a threshold value for the development of SWRO in various countries and thus be used to identify these potential SWRO countries.

Furthermore, based on the projected production costs and water prices, the next step was to apply these simulated data to evaluate the economic feasibility of SWRO in 140 countries for the period 2015 – 2050 under the SSP1 – 3 scenarios. Specifically, we identify the countries with the potential to develop seawater desalination (CDSDs) and estimate the corresponding desalination population.

II. Assessment using the water price in 2015

To clarify the effects of production cost alone on the future diffusion of SWRO in different countries, a constant water price in baseline year 2015 was first used to calculate F_i. CDSD levels are illustrated in Figure 3.18 and detailed percentages for the countries in each feasibility index class are summarized in Table 3.14 (F_i for each country was summarized in Table C1 in Appendix C). The results in Table 3.14 indicated that ~24% of countries were CDSD in 2015. As expected (Figure 3.18), the 'best' areas were primarily in the developed and oil-exporting countries, especially in North America, Europe, Australia, and Mediterranean countries. For the cases examined, the CDSD expanded slightly from 2015 to 2050, to 36%, 36%, and 34% under the SSP1 – 3 scenarios, respectively (Table 3.13).

Moreover, based on the condition of $F_i \geq 1$, Figure 3.19 shows the global distribution of the predicted CDSDs and desalination population in each CDSD in different years and under different projection conditions (desalination population for each country was summarized in Table C2 in Appendix C). Table 3.15 summarizes the total desalination populations in CDSDs for each F_i class. The simulation results identify ~ 5.7% of global population as the desalination population in 2015. In the case of the three scenarios, our data show that the total desalination population in all CDSDs increases slightly from 2015 to 2050, to 9.4%, 7.7%% and 6.4% of the global population under the SSP1 – 3 scenarios, respectively (Table 3.15).

This slight increase in the CDSD percentages and desalination population under the three SSPs indicated that, without considering the change in water prices, the decline in capital costs contributes to a diminishing unit production cost, rendering the introduction of SWRO in more countries and its application to a greater number of people feasible. Although the number of CDSD cases and desalination population all increased until 2050, different patterns were found among the three SSPs. In SSP3, the increased number was less than that in SSP1 and SSP2 which was primarily attributed to a higher capital cost and a higher energy costs.

III. Assessment incorporating changes in water prices

Furtherly, the change of F_i in 140 countries is estimated based on the binary projected unit production cost and the water price to clarify their synergistic effects on future SWRO development. Figure 3.20 and Table 3.16 showed the global distributions of potential CDSD and their percentage in each feasibility index class in the year of 2015, 2030, and 2050 under SSP1 – 3 scenarios, respectively (F_i for each country was summarized in Table C3 in Appendix C). Additionally, Figure 3.21 and Table 3.17 show the global distribution of predicted CDSDs and the total desalination population in CDSDs in each feasibility index class, respectively (desalination population for each country was summarized in Table C4 in Appendix C). These results highlights two points. First, according to Table 3.16, for all the cases in 2050, the number of CDSD has increased significantly to 98, 78, and 69 compared to 34 in the baseline year of 2015, corresponding to 70%, 56%, and 49% of total 140 countries in SSP1 – 3 scenarios, respectively. As expected in Figure 3.20, the spatial coverage over the diffused countries were primarily including China, Egypt, Russia, south Africa, some countries in south America and eastern Europe, showing up as the very promising areas for SWRO in near future. Second, Table 3.17 show that the total global desalination population in 2050 increases to 1,600 – 1,900 million against 4,500 million in 2015, corresponding to 14.4% – 21% of the global population. Previously, Hanasaki, et al. (2016) set an economic threshold for when the national average GDP per capita exceeds 14,000 USD PPP $\text{person}^{-1}\text{year}^{-1}$ to estimate the spatial extent of where seawater desalination is likely to be used. Their study indicates that the geographical extent of seawater desalination will expand considerably into more non-oil-producing countries, such as Algeria, northern China, and southeastern India, which is consistent with the distribution presented here. Nevertheless, comparison of the populations of these regions that will adopt desalination shows that the criterion of GDP per capita exceeds 14,000 USD PPP $\text{person}^{-1}\text{year}^{-1}$ finally leads to a population change from 700 million in 2015 to 1,900 – 2,900 million in 2050, which obviously exceeds the population change from 4.6 to 1,600 – 1,900 million by the criterion of $F_\mathrm{i} \geq 1$ used in this study (Figure 3.22). This distinction in population is mainly attributed to the fact that our assessment of the future development of SWRO emphasizes its economic feasibility. This involves not only whether building a SWRO plant would be beneficial under local economic conditions but also whether desalinated water would be competitive with other conventional water resources (i.e., whether desalinated water is affordable for consumers).

Obviously, there were two reasons for such considerable diffusion of SWRO. One was due to the diminishing production cost in Figure 3.13, the other was attributed to the increasing of water price in Figure 3.15. However, comparing the significant diffusion of CDSD in Figure 3.20 originated from the effect of both two factors with the slight diffusion of CDSD in Figure 3.18 leaded by single factor of production cost, it clearly suggested the water price overwhelmed the production cost to be the main barrier for successful diffusion of SWRO under the investigated period. In addition, it was found that the diffusion of CDSD in SSP2 and SSP3 were relatively limited compared to that in SSP1 due to the water price levels in these scenarios were lower than in SPP1. Since all SSPs scenarios projected significant income growth for most developing countries over the global scale, which subsequently leaded their increase of water price (Figure 3.15), the CDSD were expected to diffuse into more developing countries and non-oil export countries globally by 2050 (Figure 3.20 and Figure 3.21).

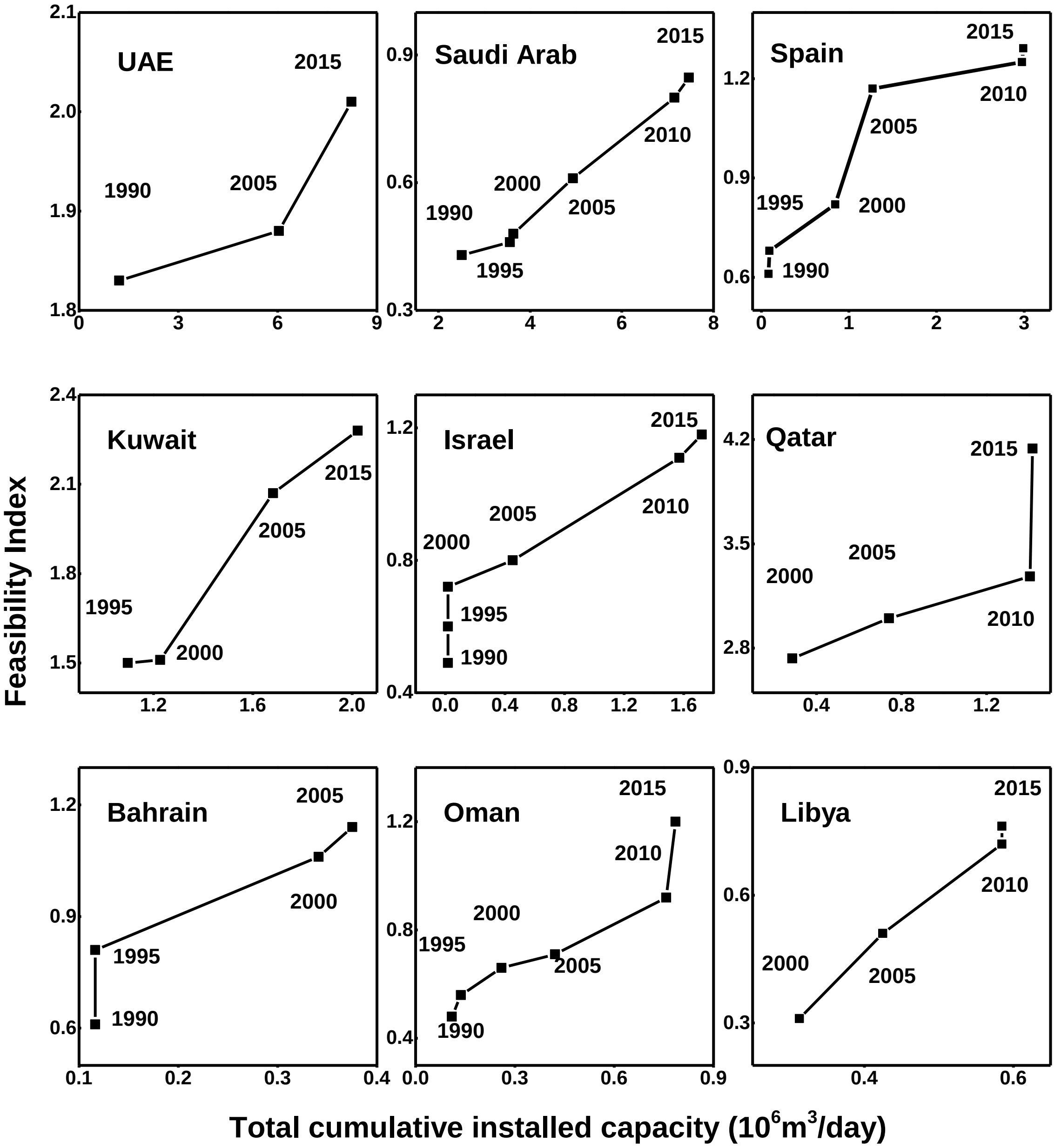

Figure 3.17 The feasibility index (*F*i) and total cumulative installed capacity (TIC) in major SWRO countries. The value in each point show the specific year of the data.

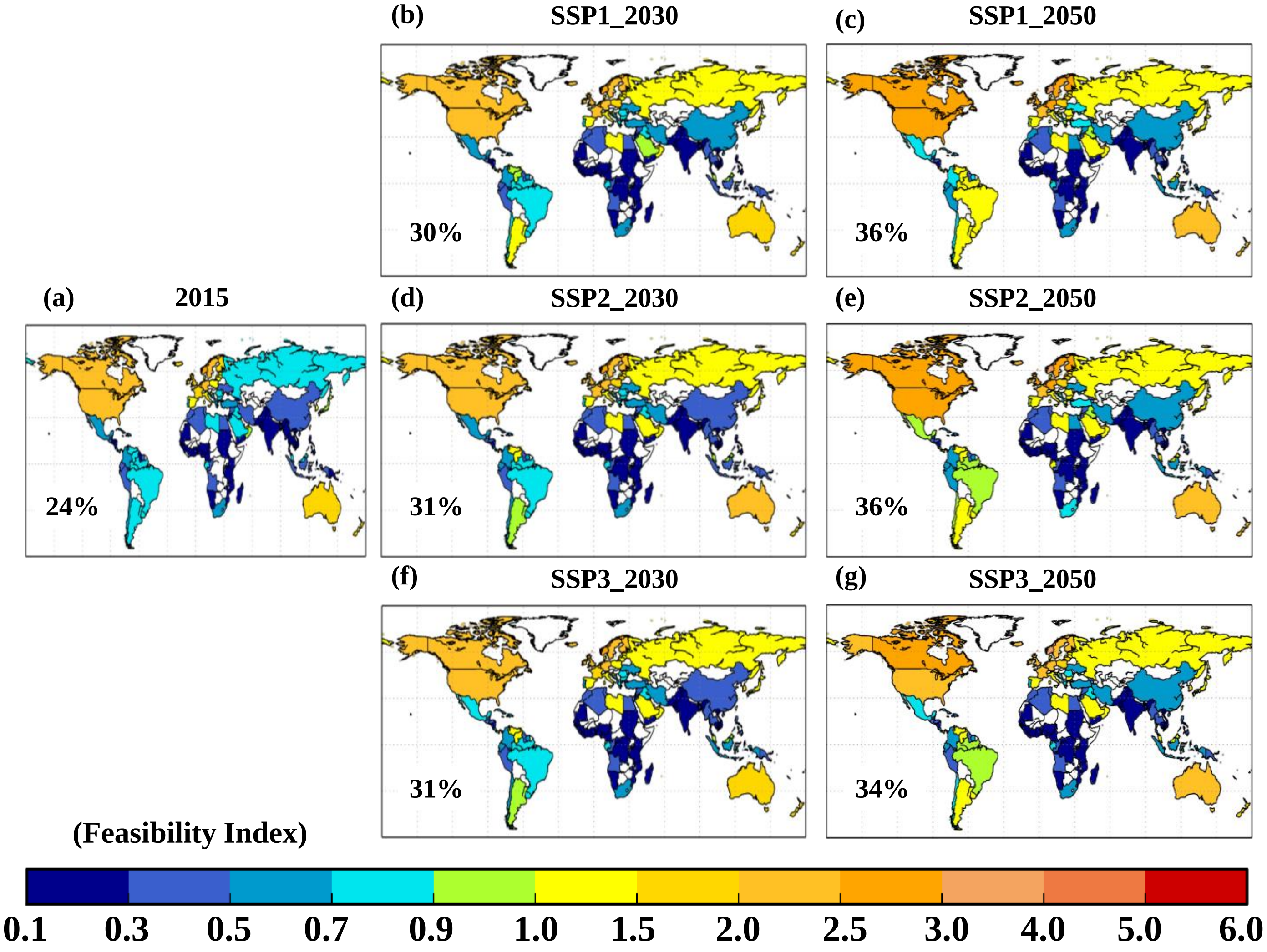

Figure 3.18 Global distributions of CDSD in (a) 2015, (b) SSP1 in 2030, (c) SSP1 in 2050, (d) SSP2 in 2030, (e) SSP2 in 2050, (f) SSP3 in 2030, (g) SSP3 in 2050. ($F_i = W_{p\text{-}2015}/C_p$; the values in (a) – (g) show the percentages of countries which $F_i \geq 1$).

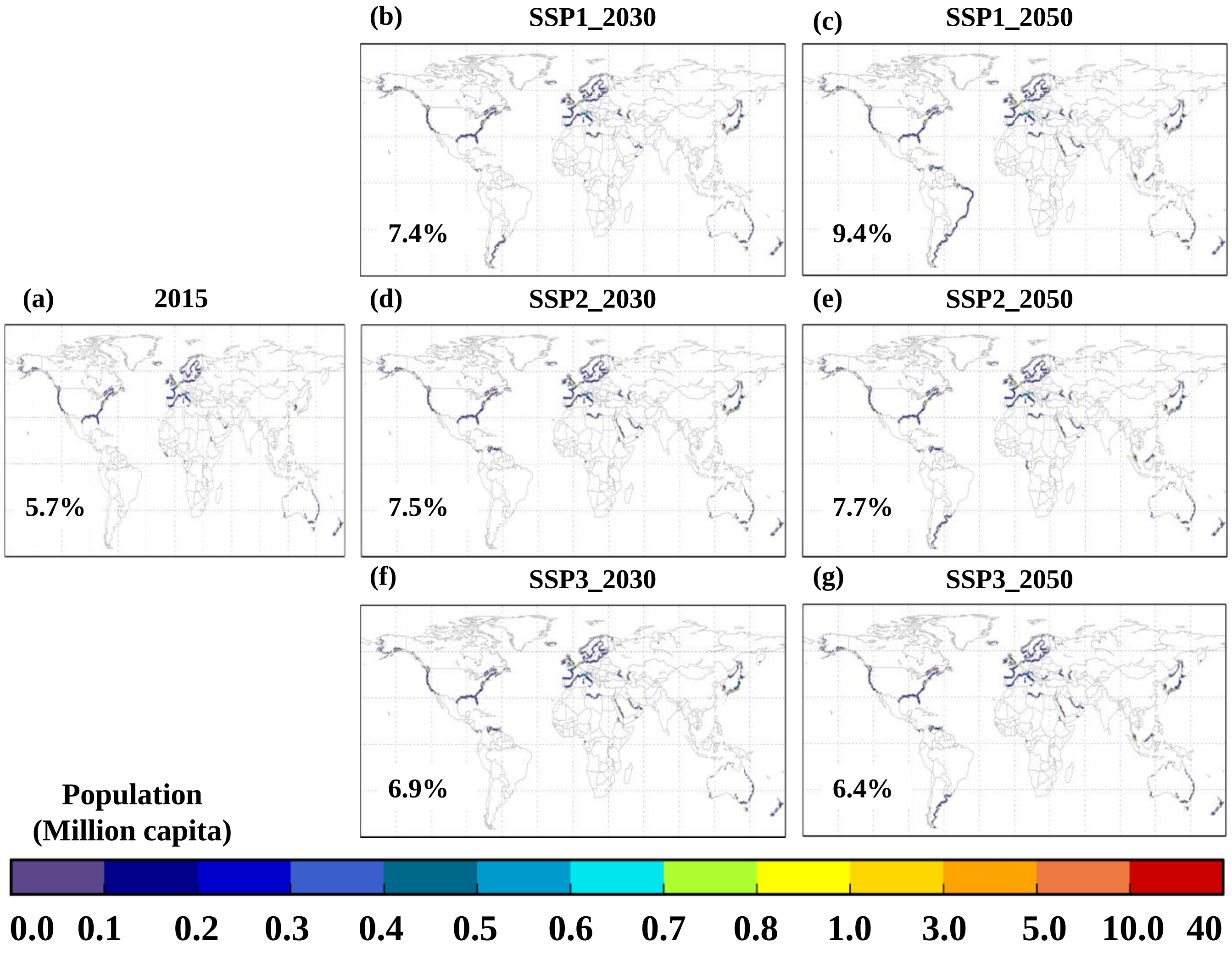

Figure 3.19 Global distributions of population in each CDSD (a) 2015, (b) SSP1 in 2030, (c) SSP1 in 2050, (d) SSP2 in 2030, (e) SSP2 in 2050, (f) SSP3 in 2030, (g) SSP3 in 2050. ($F_i = W_{p\text{-}2015}/C_p$; the values in (a) – (g) ratio of the total global desalination populations in all CDSDs to the global population.)

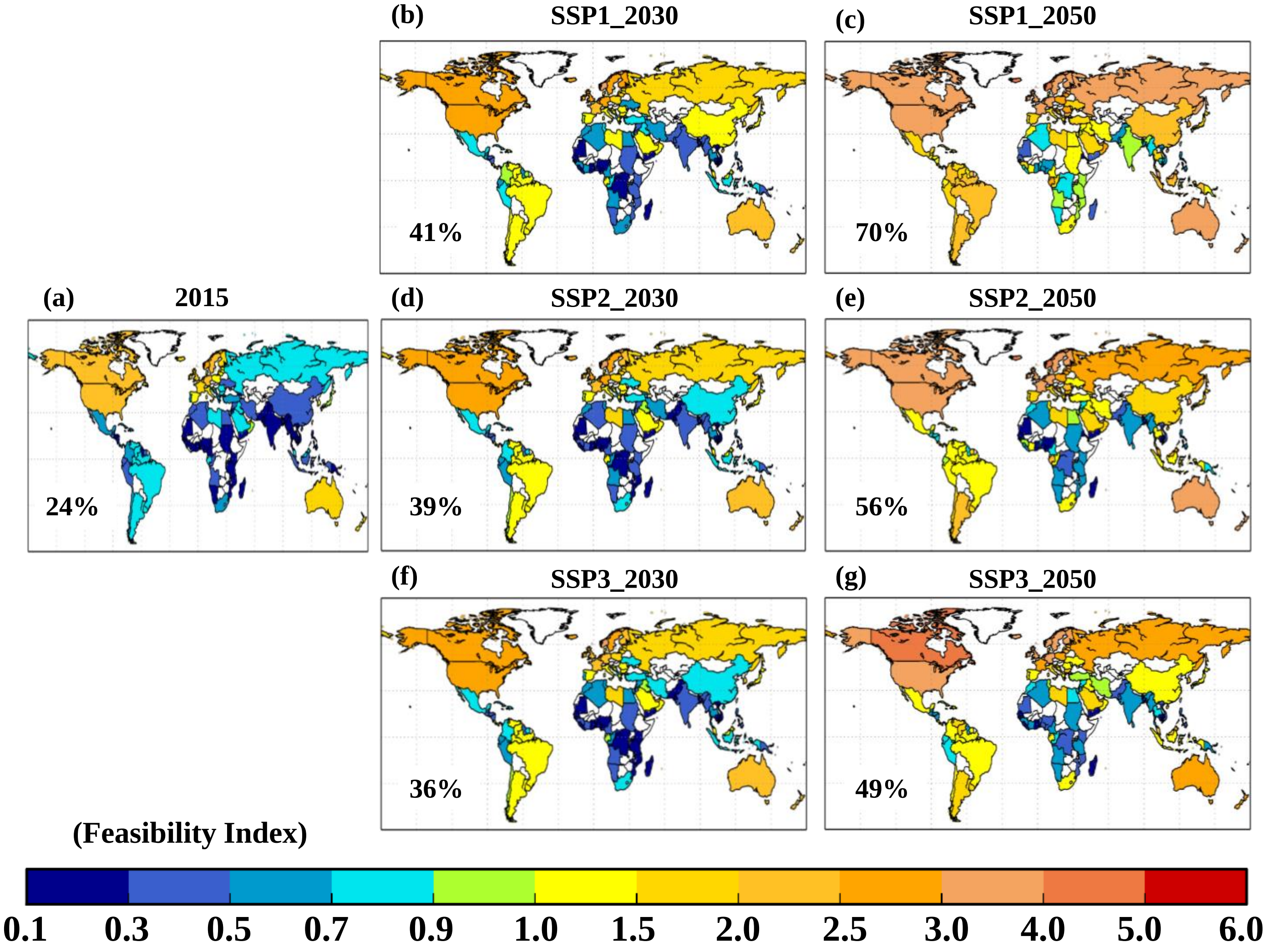

Figure 3.20 Global distributions of CDSD in (a) 2015, (b) SSP1 in 2030, (c) SSP1 in 2050, (d) SSP2 in 2030, (e) SSP2 in 2050, (f) SSP3 in 2030, (g) SSP3 in 2050. ($F_i = W_p/C_p$, the values in (a) – (g) show the percentages of countries which $F_i \geq 1$).

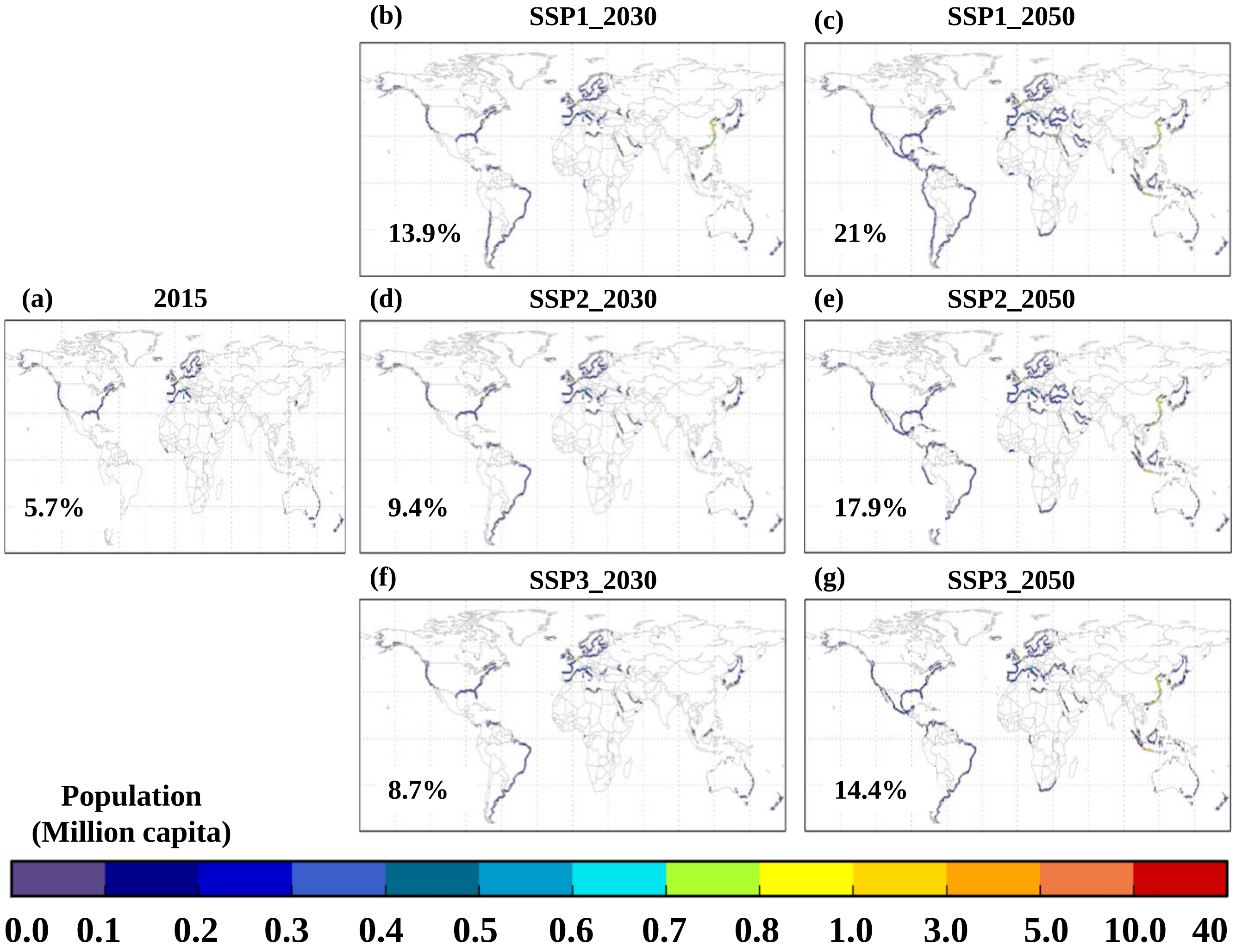

Figure 3.21 Global distributions of population in each CDSD (a) 2015, (b) SSP1 in 2030, (c) SSP1 in 2050, (d) SSP2 in 2030, (e) SSP2 in 2050, (f) SSP3 in 2030, (g) SSP3 in 2050. ($F_i = W_p/C_p$; the values in (a) – (g) ratio of the total global desalination populations in all CDSDs to the global population.)

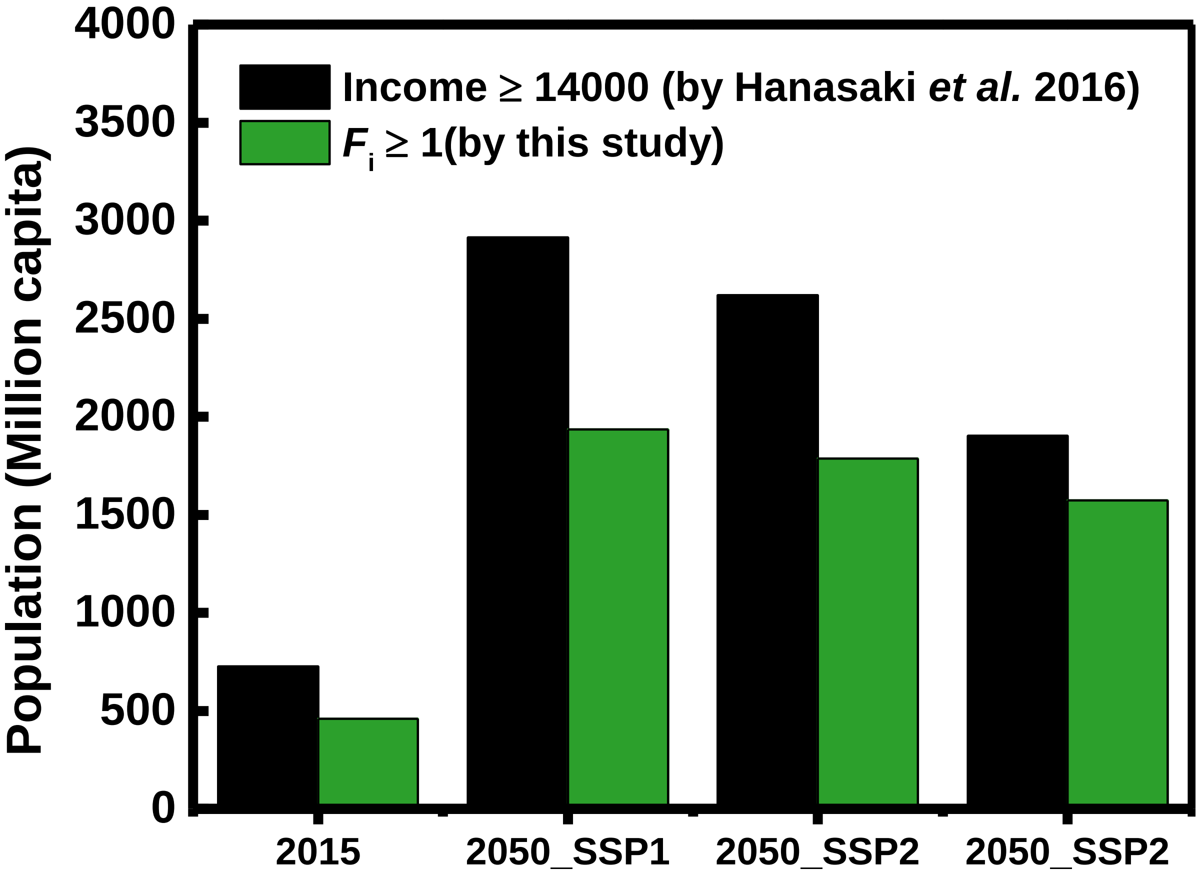

Figure 3.22 Population using desalination under different criterions

Table 3.13 The feasibility index (F_i) and TIC in major SWRO countries.

Country	1990		1995		2000		2005		2010		2015	
	F_i	$TIC^{1)}$	F_i	TIC	F_i	TIC	F_i	TIC	F_i	TIC	F_i	TIC
UAE$^{2)}$	1.83	1.21	NA$^{3)}$	1.97	NA$^{3)}$	3.54	1.88	6.04	NA$^{3)}$	8.10	2.01	8.23
Saudi Arabia	0.43	2.51	0.46	3.56	0.48	3.64	0.61	4.93	0.80	7.15	0.85	7.46
Spain	0.61	0.08	0.68	0.09	0.82	0.84	1.17	1.27	1.25	2.98	1.29	2.99
Kuwait	NA$^{3)}$	0.97	1.50	1.10	1.51	1.23	2.07	1.68	NA$^{3)}$	2.02	2.28	2.02
Israel	0.49	0.02	0.60	0.02	0.72	0.02	0.80	0.45	1.11	1.57	1.18	1.72
Qatar	NA$^{3)}$	0.14	NA$^{3)}$	0.29	2.73	0.29	3.00	0.74	3.28	1.40	4.14	1.42
Bahrain	0.61	0.12	0.81	0.12	1.06	0.34	1.14	0.38	NA$^{3)}$	0.88	NA$^{3)}$	0.88
Oman	0.48	0.11	0.56	0.14	0.66	0.26	0.71	0.42	0.92	0.76	1.20	0.78
Libya	NA$^{3)}$	0.16	NA$^{3)}$	0.23	0.31	0.31	0.51	0.42	0.72	0.58	0.76	0.58
Average	0.74	0.59	0.77	0.83	1.04	1.16	1.32	1.82	1.35	2.83	1.71	2.90

Note: 1) TIC: Total cumulative installed capacity ($10^6 m^3$/day) 2) United Arab Emirates (UAE) 3) NA: No data

Table 3.14 Numbers and percentages of countries in each feasibility index class for 2015, 2030, and 2050 under the three SSPs ($F_i = W_{p\text{-}2015}/C_p$)

			SSP1				SSP2				SSP3			
	2015		2030		2050		2030		2050		2030		2050	
Class	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent
1 ($F_i < 0.5$)	74	53%	68	49%	58	41%	66	47%	61	44%	67	48%	63	45%
2 ($0.5 < F_i < 1$)	32	23%	30	21%	32	23%	30	21%	29	21%	29	21%	29	21%
3 ($1 < F_i < 2$)	22	16%	25	18%	29	21%	26	19%	28	20%	29	21%	31	22%
4 ($2 < F_i < 4$)	12	9%	17	12%	19	14%	18	13%	20	14%	15	11%	17	12%
5 ($4 < F_i < 8$)	0	0%	0	0%	2	1%	0	0%	2	1%	0	0%	0	0%
Total	140	100%	140	100%	140	100%	140	100%	140	100%	140	100%	140	100%
Class > 2	34	24%	42	30%	50	36%	44	31%	50	36%	44	31%	48	34%

Table 3.15 Total global desalination population and percentages of global population in each feasibility index class for 2015, 2030, and 2050 under the three SSPs ($F_i = W_{p\text{-}2015}/C_p$)

			SSP1				SSP2				SSP3			
	($F_i = W_{p\text{-}2015}/C_p$)		($F_i = \mathrm{W}_{p\text{-}2015}/C_p$)				($F_i = W_{p\text{-}2015}/C_p$)				($F_i = W_{p\text{-}2015}/C_p$)			
	2015		**2030**		**2050**		**2030**		**2050**		**2030**		**2050**	
Class	Pop$^{(1}$	%$^{(2}$	Pop$^{(1}$	%$^{(2}$	Pop$^{(1}$	%$^{(2}$	Pop$^{(1}$	%$^{(2}$	Pop$^{(1}$	%$^{(2}$	Pop$^{(1}$	%$^{(2}$	Pop$^{(1}$	%$^{(2}$
1 (F_i <0.5)	1793.1	23%	1608.3	18%	1378.9	15%	2021.3	22%	1622.2	16%	1883.3	20%	1944.2	18%
2 (0.5< F_i <1)	486.3	6%	760.5	9%	920.9	10%	409.4	5%	1002.1	10%	651.2	7%	994.4	9%
3 (1< F_i <2)	269.7	3%	349.3	4%	496.3	5%	352.9	4%	404.6	4%	389.2	4%	395.3	4%
4 (2< F_i <4)	177.2	2%	297.8	3%	371.7	4%	318.9	4%	364.5	4%	251.5	3%	295.3	3%
5 (4< F_i <7)	0.0	0%	0.0	0%	2.9	0.0%	0.0	0%	3.1	0%	0.0	0%	0.0	0%
Global total Population	7811.3		8704.9		9228.5		8993.4		10003		9258.3		10867	
Class > 2	446.8	5.7%	647.1	7.4%	870.9	9.4%	671.9	7.5%	772.2	7.7%	640.71	6.9%	690.57	6.4%

Note: 1) Pop: Population (Million capita) 2) %: percent

Table 3.16 Numbers and percentages of countries in each feasibility index class for 2015, 2030, and 2050 under the three SSPs ($F_i = W_p/C_p$).

			SSP1				SSP2				SSP3			
	2015		2030		2050		2030		2050		2030		2050	
Class	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent
1 (F_i <0.5)	74	53%	45	32%	11	8%	54	39%	25	18%	51	36%	31	22%
2 (0.5<F_i<1)	32	23%	38	27%	31	22%	32	23%	37	26%	38	27%	40	29%
3 (1< F_i <2)	22	16%	33	24%	48	34%	30	21%	38	27%	28	20%	35	25%
4 (2< F_i <4)	12	9%	23	16%	44	31%	23	16%	34	24%	22	16%	32	23%
5 (4< F_i <8)	0	0%	1	1%	6	4%	1	1%	6	4%	1	1%	2	1%
Total	140	100%	140	100%	140	100%	140	100%	140	100%	140	100%	140	100%
Class > 2	34	24%	57	41%	98	70%	54	39%	78	56%	51	36%	69	49%

Table 3.17 Total global desalination population and percentages of global population in each feasibility index class for 2015, 2030, and 2050 under the three SSPs ($F_i = W_p/C_p$)

			SSP1				**SSP2**				**SSP3**			
	($F_i = W_p/C_p$)		($F_i = W_p/C_p$)				($F_i = W_p/C_p$)				($F_i = W_p/C_p$)			
	2015		**2030**		**2050**		**2030**		**2050**		**2030**		**2050**	
Class	Pop(1	%(2	Pop(1	%(2	Pop(1	%(2	Pop(1	%(2	Pop(1	%(2	Pop(1	%(2	Pop(1	%(2
1 (F_i <0.5)	1793.1	23%	1127.5	13%	84.0	1%	1282.6	14%	580.0	6%	1281.4	14%	828.1	8%
2 (0.5<F_i<1)	486.3	6%	682.2	8%	1150.8	12%	978.7	11%	1030.0	10%	1092.9	12%	1240.0	11%
3 (1< F_i <2)	269.7	3%	869.5	10%	742.0	8%	460.0	5%	1265.2	13%	442.8	5%	1128.9	10%
4 (2< F_i <4)	177.2	2%	334.3	4%	1180.1	13%	378.8	4%	512.2	5%	355.9	4%	417.66	4%
5 (4< F_i <7)	0.0	0.0%	2.4	0.0%	13.7	0.1%	2.4	0.0%	9.0	0.1%	2.2	0.0%	14.48	0.1%
Global total Population	7811.3		8704.9		9228.5		8993.4		10003		9258.3		10867	
Class > 2	446.8	5.7%	1206.2	13.9%	1935.9	21.0%	841.3	9.4%	1786.5	17.9%	800.88	8.7%	1561.0	14.4%

Note: 1) Pop: Population (Million capita) 2) %: percent

3.3.4 Impact factor on future diffusion of seawater desalination

I. Impact of climate policy on future diffusion of seawater desalination

To clarify the effects of climate policy on the future diffusion of SWRO among different countries, the proportion of potential SWRO countries during 2015 – 2050 in three socioeconomic under each climate policy are illustrated in Figure 3.23(a) – (c). Additionally, based on the condition of $F_{\mathrm{i}} \geq 1$, Figure 3.23(d) – (f) shows the global desalination population during 2015 – 2050 in three socioeconomic under each climate policy. The results in Figure 3.23(a) – (c) indicated that ~24% of 140 countries were recognized as CDSD in 2015. For the cases examined, the CDSD expanded slightly from 2015 to 2050, 36% – 39%, 35% – 36% and 33% – 34% under SSP1, SSP2 and SSP3, respectively. Similarly, the global desalination population is also increasing during 2015 – 2050. The simulation results identify that the total global desalination population is 430 million in 2015. In the case of the three scenarios, our data show that the total desalination population in all CDSDs increases slightly from 2015 to 2050, to 870 – 880, 770 – 780 and 670 – 700 million under the SSP1 – 3 scenarios, respectively.

In SSP1 and SSP2 under RCP2.6 scenario, the increased number was less than that in other scenario which the increase number are similarity, which was primarily attributed to a higher energy costs under such stricter climate policy, causing higher production costs of SWRO, and restricting the diffusion. As Fujimori, et al. (2017) and Riahi, *et al.* (2017) the world under SSP3 scenario cannot achieve the long-term mitigation target of RCP2.6, there for, just BUS, RCP4.5 and RCP6.0 are included in SSP3. In SSP3 under RCP 4.5 scenario, different with SSP1 and SSP2, the increased number was less than that in other scenario.

These results suggest that, without considering the change in water prices, the decline in capital costs contributes to a diminishing unit production cost, rendering the introduction of SWRO in more countries and its application to a greater number of people feasible. The Paris Agreement sets out an action plan for mitigating global warming below 1.5 ℃ to reduce the risks of climate change; this is a more stringent target than that included in RCP2.6 in this study. Based on the abovementioned results, it is expected that the Paris Agreement will, to some extent, limit the future diffusion of SWRO.

II. Impact of socioeconomic scenario on future diffusion of seawater desalination

To clarify the effects of socioeconomic scenario on the future diffusion of SWRO among different countries, the proportion of potential SWRO countries during 2015 – 2050 in three climate policy under each SSPs are illustrated in Figure 3.24(a) – (c). Moreover, based on the condition of $F_i \geq 1$, Figure 3.24(d) – (f) shows the global desalination population during 2015 – 2050 in three socioeconomic under each climate policy. The results in Figure 3.24(a) – (c) indicated that ~23% of 140 countries were recognized as CDSD in 2015. For the cases examined, the CDSD expanded slightly from 2015 to 2050, 35% – 36%, 33% – 39% and 34% – 39% under RCP2.6, RCP4.5 and RCP6.0, respectively. Similarly, the global desalination population is also increasing during 2015 – 2050. The simulation results show that the total global desalination population is 430 million in 2015. In the case of the three scenarios, our data show that the total desalination population in all CDSDs increases slightly from 2015 to 2050, to 770 – 870, 670 – 880 and 700 – 880 million under RCP2.6, RCP4.5 and RCP6.0 scenario, respectively (Figure 3.24(a) – (c))

In RCP2.6, RCP4.5 and RCP6.0 scenario, the increased number was slight lower in SSP2 than in SSP1. Contrastively, the diffusion of CDSD in SSP3 were relatively limited compared to that in SSP1 and SSP2. These results suggest that, without considering the change in water prices and climate policies, the decline in capital costs contributes to a diminishing unit production cost caused by various socioeconomic scenarios, especially the more sustainable ones, may gradually become a drive to the further diffusion of SWRO within the studied period.

In addition, comparing the significant diffusion of CDSD and global desalination population in Figure 3.24 originated from the effect of socioeconomic scenario with the slight gap between different in Figure 3.23, which is due to the effects of climate polices, clearly suggested the socioeconomic scenario overwhelmed the climate policy to be the main barrier for successful diffusion of SWRO under the investigated period.

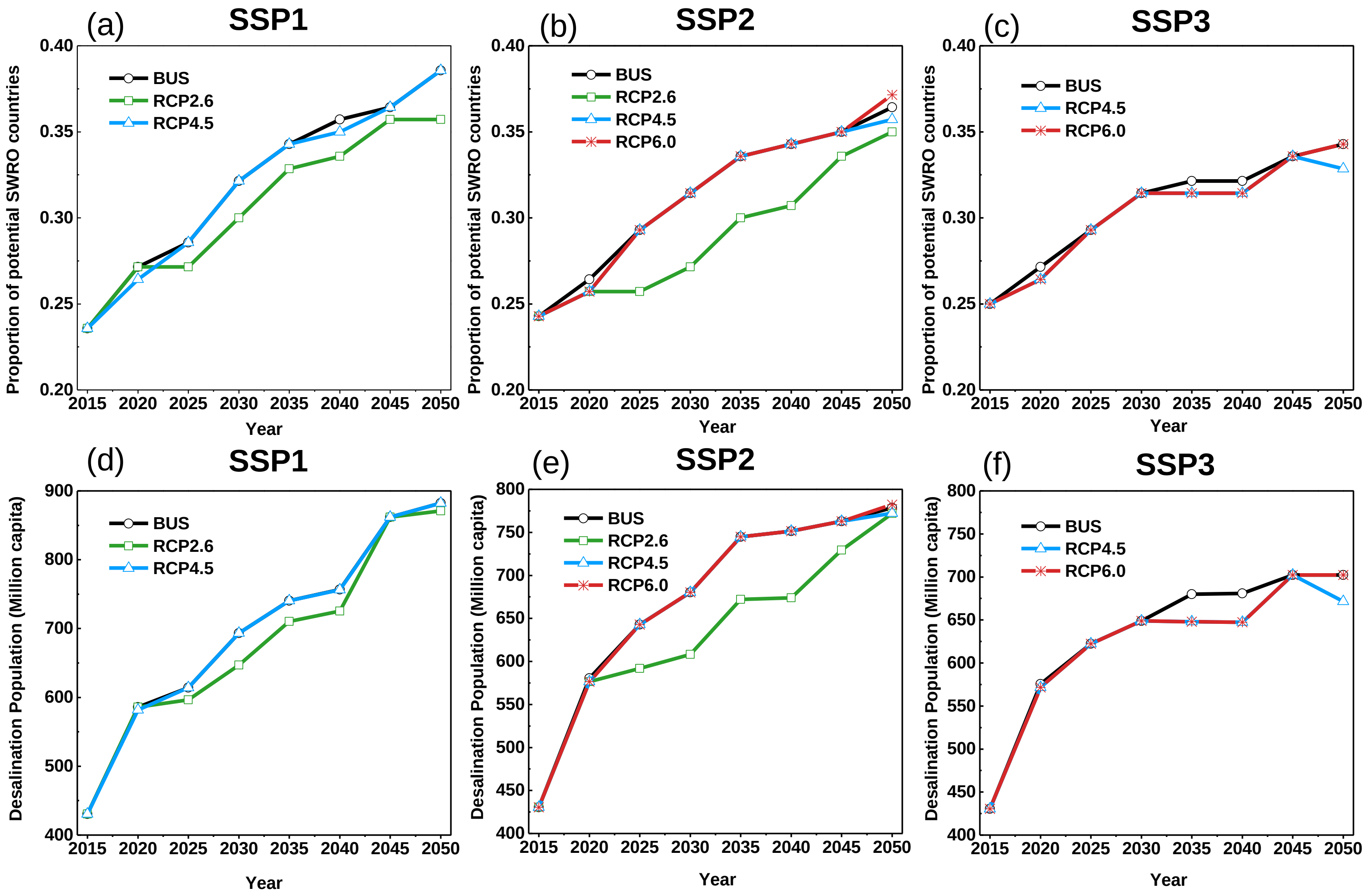

Figure 3.23 Proportion of countries which $F_i \geq 1$ during 2015 – 2050 in (a) SSP1 under business-as-usual (BUS), RCP2.6 and RCP4.5 scenario , (b) SSP2 under BUS, RCP2.6, RCP4.5 and RCP6.0 scenario, (c) SSP3 under BUS, RCP4.5 and RCP6.0 scenario ($F_i = W_{p\text{-}2015}/C_p$). Desalination population in (d) SSP1 under BUS, RCP2.6 and RCP4.5 scenario , (e) SSP2 under BUS, RCP2.6, RCP4.5 and RCP6.0 scenario, (f) SSP3 under BUS, RCP4.5 and RCP6.0 scenario.

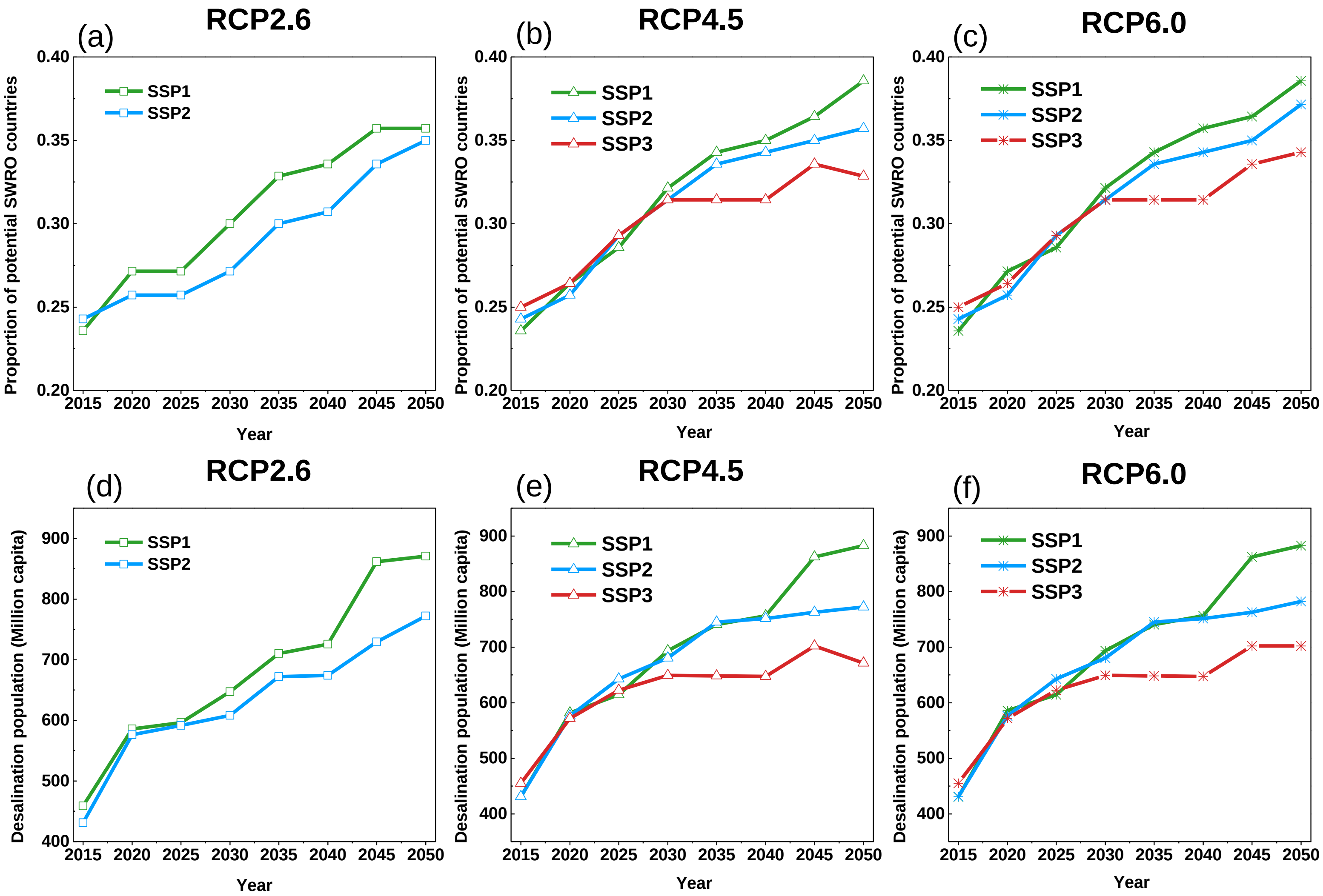

Figure 3.24 Proportion of countries which $F_i \geq 1$ during 2015 – 2050 in (a) RCP2.6 under SSP1 and SSP2 scenario, (b) RCP4.5 under SSP1, SSP2 and SSP3 scenario, (c) RCP6.0 under SSP1, SSP2 and SSP3 scenario ($F_i = W_{p\text{-}2015}/C_p$). Desalination population in (d) RCP2.6 under SSP1 and SSP2 scenario, (e) RCP4.5 under SSP1, SSP2 and SSP3 scenario, (f) RCP6.0 under SSP1, SSP2 and SSP3 scenario

3.3.5 Sensitive Analysis and Data Limitation

I. Sensitive Analysis

The previous sections use 1 as the threshold value of the F_i to identify potential desalination countries and estimate affected populations. However, in reality, different threshold values may significantly affect future simulation results; thus, we conduct a sensitive analysis based on different threshold values of F_i ranging from 0.2 to 1.4.

Figure 3.25 shows the results of the sensitive analysis. Under all conditions, a higher threshold value of F_i decreases the global total desalination population due to the reduction in the number of CDSDs. For 2015, the data show that the total global desalination population decreases significantly, from 2,327 million to 459 million, with a threshold of 0.2 to 1, indicating that desalinated water remains too expensive for most people, leading them to use cheaper water sources.

In SSP1, until the threshold of 0.6, the change of global desalination population was limited (from 3,170 – 2,746 million in line 1). The ratio of global desalination population to global seashore area population was change from 100% to 87% in line 7. These results suggesting that the F_i in almost studied countries would exceed 0.6 by 2050. In contrast, a large drop immediately appeared between the threshold of 0.2 and 0.6 in SSP2 (from 3,300 – 2,652 million in line 4) and SSP3 (3,563 – 2,111 million in line 5). Similarly, the ratio of global desalination population to global seashore area population was change from 97% to 78% in line 10 and 98% to 58% in line 11, respectively. It implying that the F_i in almost studied countries could only exceed 0.2 by 2050 in these scenarios. The discrepancies among SSPs were mainly ascribed to the difference in share of the high income counties, which was considered to be high in SSP1, medium in SS2, and low in SSP3. Moreover, it was worth noting that even under the threshold of 1.4, global desalination population showed significantly increase from 390 million in 2015 to 1,700, 1,300, and 1,100 million by 2050 in SSP1 – 3 scenarios, respectively, which clearly indicated the promising successful diffusion of SWRO in a large number of countries with relatively high economic feasibility. Furtherly, the sensitivity test of desalination plant lifetime showed a linear response (only the results of SSP1 are shown in Figure 3.25, line 1 and line 2) due to changes in lifetime. The results indicate the global desalination population expands by increase in lifetime.

Moreover, for 2050 in SSP1, the threshold value of F_i ranges from 0.2 to 1.4, the total global desalination population increases by 1.4 – 5.4-fold compared to the base year (from 2,327 – 459 million in line 6 to 3,170 – 1,936 million in line 1) under RCP2.6, and it increases by 1.4 – 5.7-fold (from 2,327 – 459 million in line 6 to 3,170 – 2,421 million in line 3) under RCP6.0. These discrepancies between different climates policies suggest the stringent ones may gradually become a barrier to the further diffusion of SWRO within the studied period.

II. Data Limitation and Uncertainties

Our evaluation of the global economic potential of seawater desalination in this study rests on several assumptions; thus, the limitations of this research should be noted and used as bases for future research.

First, the estimate of the unit production cost of SWRO rests on the following assumptions and is subject to the following limitations. In terms of the capital cost estimates, we assume that investors in each country tend to build SWRO plants with the largest capacity that is affordable. This is based on the reasonable assumption that the capital costs of SWRO plants generally show economies of scale. In reality, the capacities of SWRO plants reflect the total water demand and water use density in each region, which may also be influenced by the availability of cheap electricity; thus, it could be rather diverse, even within the same country. Because our models do not include many detailed design parameters, either unknown or not yet determined, this could render them ineffective. On the other hand, regarding the O&M cost estimate, the waste disposal cost is not included in this study despite the fact that it accounts for a remarkable proportion (3 – 19%) of the total O&M cost. This is based on the fact that, to some extent, the cost of brine disposal could be partially or fully offset by the profits from selling salt from the desalination by-products (Kesieme, et al., 2013; Ziolkowska, 2016). Moreover, considering the diversity of the environmental problems of different countries caused by brine discharge and its varied processes, it is nearly impossible to identify a standard quantitative cost of waste disposal.

Second, the assumptions underpinning municipal water price modeling are based on a historical time series analysis, but the limitations of this approach should be considered. We assume a uniform water price for each country, which might be unrealistic. For the same country, even within the same year, Ruester and Zschille (2010) report that the prices set by private utilities were higher than the prices set by public utilities when water services were subcontracted out. Although public and private companies may play important roles in pricing, differences within the same country are not considered in the formulation of the water price function due to the limitations of the data.

Finally, the limitations of the feasibility index are summarized. Because water resources are critical to life and economic production, some relatively low-income countries (e.g., Egypt and China) will adopt such technology because of large government subsidies, despite its ostensible lack of economic feasibility. Thus, the F_i threshold may differ among nations, and our model does not include such regional biases. Additionally, although the tradeoff between desalination and other adaptations related to the water supply, such as identifying alternative sources of water or increasing water use efficiencies, may play crucial roles in desalination projects, these mechanisms are not included in the present formulation of the F_i. Finally, in response to unexpected weather events and/or long-term drought in many countries in the world (the US, Australia, Europe), desalination has long been considered a solution to water scarcity. In a drought situation, economic necessity naturally creates demand for desalinated water, regardless of the water price. For example, Spain suffered a severe drought from 1991 to 1995, triggering the rapid construction of major desalination plants. However, when the drought ended and adequate water supplies were available, many users continued to use 'conventional' water sources that were then cheaper, and these plants were largely abandoned due to their lack of competitiveness (March, *et al.*, 2014). This kind of investment, which can be seen as temporary, is not included in this study.

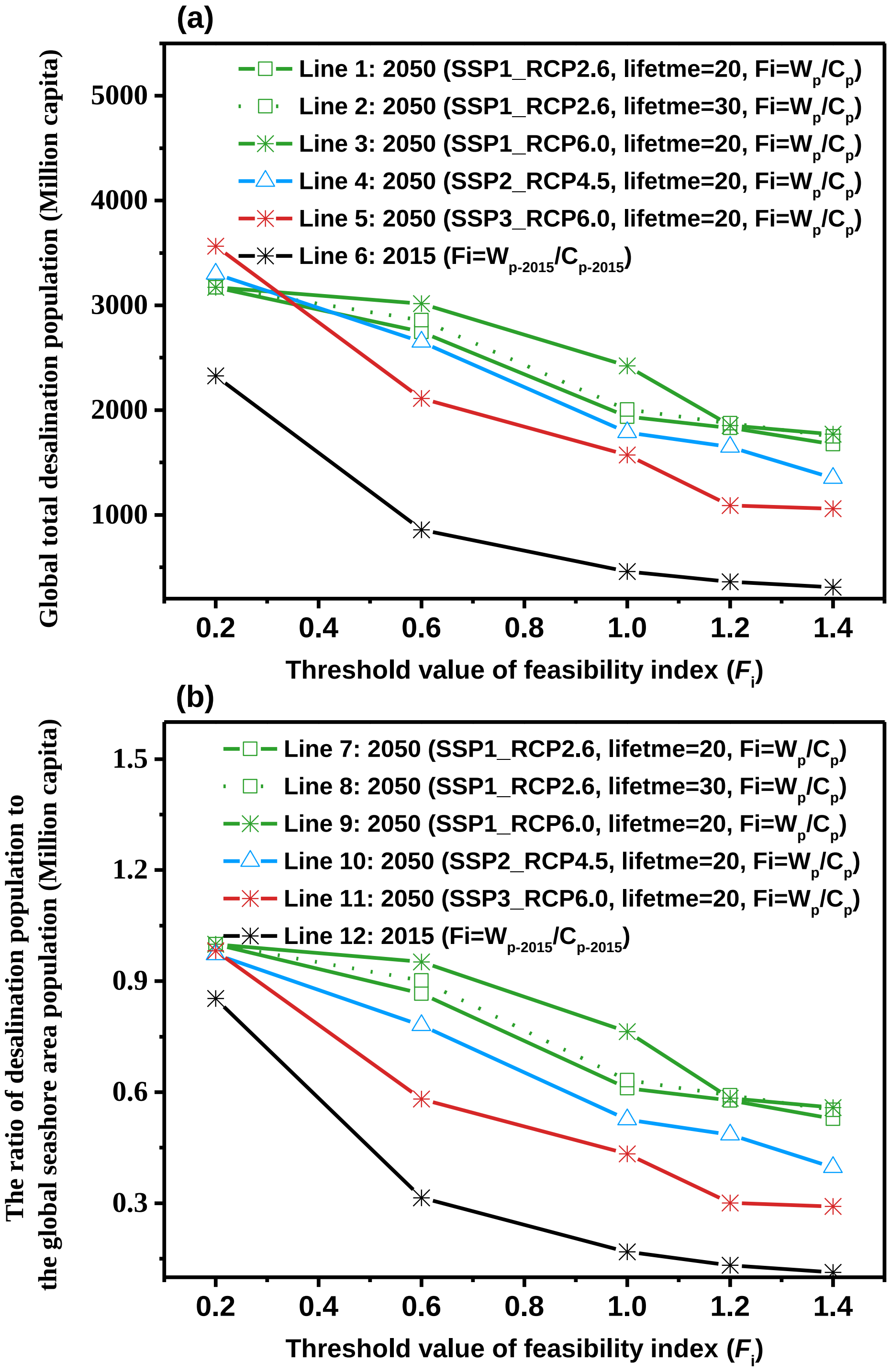

Figure 3.25 Sensitivity analysis of the feasibility index with respect to (a) the total global desalination population, (b) the ratio of total global desalination population to the global seashore area population which defined as the population living within approximately 165 km of the seashore. Green, blue, red, and black for SSP1 (2050), SSP2 (2050), SSP3 (2050), and SSP1 (baseline year of 2015), respectively. Solid and broken for lifetime of desalination plant = 20 and 30, respectively.

3.3.6 Combining the use of seawater desalination and increasing water efficiency to alleviate water scarcity: a case study in China

In chapter 2, we estimated the effect of increasing agricultural water use efficiency on alleviating water scarcity in China. As shown in Figure 3.26 (a), it reveals the balance between agriculture water withdrawal and water supply in different provinces of China to 2030 by only improving water use efficiency. The results shows that the majority of provinces will achieve a positive water surplus by adopting such countermeasure, indicating the improving agricultural water efficiency is an effective way to alleviate water scarcity. Nevertheless, the water scarcity will still appear in some provinces from their negative water balance, which can possibly be explained as the result of the relative increasing of demand of agricultural water in these regions. Therefore, the only implement of water management, i.e., improving water use efficiency here, may fail to deal with the water scarcity sufficiently in the whole countries, which calls for the combined usage of other approaches to increase the water supplies.

For the purpose of alleviating water scarcity, combined use of seawater desalination which serves as the water supply approach and increasing water efficiency which serves as the water management approach was evaluated. Figure 3.26 (b) presents the balance between agriculture water withdrawal and water supply in different provinces of China to 2030 when the countermeasures of seawater desalination and increasing water efficiency are both applied. It should be noted that the increased amount of water supply by seawater desalination has been calculated basing on the specific threshold values of feasibility index which is proposed in chapter3. As shown in the Figure 3.26, comparing with the water-lacked provinces in Figure 3.26 (a) which only considers the single countermeasure of improving water use efficiency with the ones in Figure 3.26 (b) which gives the effect of both improving water use efficiency and implementing the seawater desalination, their number decreases significantly. As a result, nearly all the provinces will achieve a positive water surplus in 2030 by adopting these two countermeasures (i.e., seawater desalination and increasing water use efficiency), which clearly suggests that most of the provinces will maintain the enough water to meet the significant increase of demand of agriculture water in the future and seawater desalination can really serve as an effective way to alleviate water scarcity over investigated period.

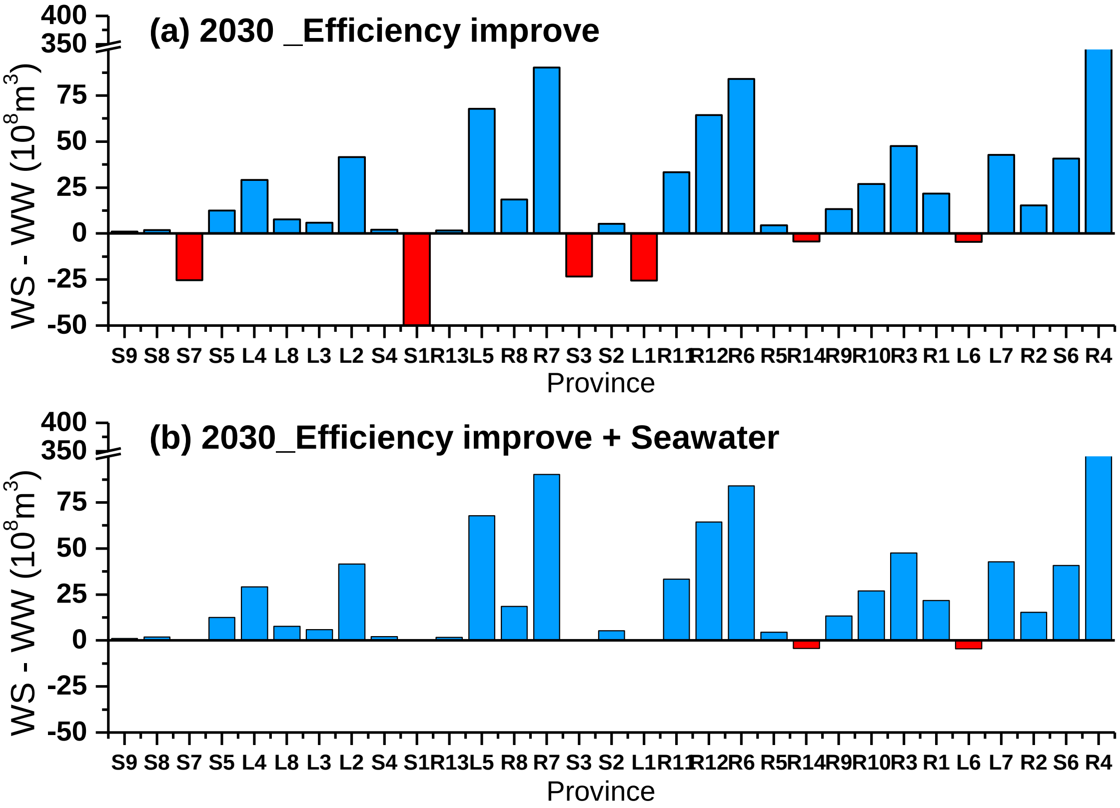

Figure 3.26 The different between agriculture water withdrawal and water supply in 2030 (a) just considering improving water use efficiency (b) both consider improving water use efficiency and using seawater desalination

3.4 Summary and Conclusions

In this study, the authors propose a method for evaluating the conditions under which it is economically feasible to develop SWRO in 140 countries up to 2050. We aim to identify the potential countries and estimate the populations that can economically benefit from SWRO and to clarify the economic determinants of future SWRO diffusion.

First, the authors identify two contributors to the SWRO unit production cost and the municipal water price, which are related reflections of feasibility. Based on the socioeconomic data and modeling techniques, this study specifies common key parameters, develops them into production cost and water price models, and demonstrates, via historical validation, that the models can simulate both factors. Second, the developed models are first applied to nine major desalination countries, and the variation in the calculated F_i for those countries is consistent with their actual historical development of SWRO on both the spatial and the temporal scales. Next, using the validated model functions and verified criteria, the unit production cost and water price in 140 countries are separately projected to calculate the F_i under SSP1 – 3 scenarios to 2050. Based on the future simulated F_i, the potential development of SWRO is assessed. The results suggest that SWRO would become a more promising approach for countries undergoing additional development by 2050, especially in developing countries. The corresponding total global desalination population will increase by 3.5 – 4.3-fold in 2050 compared to the present (from 446.8×10^6 in 2015 to 1561×10^6, $1{,}768\times10^6$ and $1{,}936\times10^6$ under the SSP1 – 3 scenarios, respectively). The spread of SWRO into more developing countries and larger populations is mainly attributable to two factors: diminishing unit production costs and increasing water prices. Given the effect of the former factor, the predicted diminishing unit production cost appears to provide a limited driving force for the future diffusion of SWRO because the increasing energy costs caused by stringent climate policies may gradually become a barrier. However, taking both factors into account, we suggest that increasing water prices constitutes the major determinant of the future diffusion of SWRO during the period under examination.

Currently, SWRO is becoming an important practical tool with which to deal with water scarcity in arid countries and satisfy the growing water demand worldwide. The present study is an attempt to evaluate its economic potential, estimate the countries and populations that can most benefit from SWRO from an economic perspective, and clarify the major barriers to its successful diffusion into other countries. The method developed is simple but designed to function with the currently available knowledge base and technology. Despite our assumptions and the limitations of our data, the results suggest general trends in the prospects of SWRO. Our results will be useful for comprehensive projections of the future development of seawater desalination as an integral part of water supply portfolios.

4. Summary and Conclusions

Nowadays water availability is subject to shortages, given effects of climate change, economic development, and population growth worldwide. Thus many countries are already engaged in water demand management and looking for alternative renewable countermeasures. In order to clarify applicability and potential of various countermeasures against water scarcity, systematic methods are respectively proposed in this study to assess their economic and environmental change based on specific socioeconomic data and modeling techniques.

First, the author focused on increasing water use as the representative potential approaches to deal with water scarcity. China is one of the countries which facing a growing water scarcity because of the rapidly growing population and economic growth. One way of alleviating water scarcity is to increase the efficiency of water use without developing additional water supplies. Therefore it is essential to develop a holistic policy tool which can help the policy-makers to decide the usage of water wisely. The fundamental work is to explicitly quantify the agricultural water use efficiency in target areas. In this study, the agriculture water use efficiency is measured by the Windows Data Envelopment Analysis method, and recommendations of sustainable water use are provided.

In the third, the author focused on seawater desalination as the representative potential approaches to deal with water scarcity, coupling with their potential evaluation. Seawater desalination is a promising adaptation measure to satisfy water demand in coastal countries suffering from water scarcity. Numerous studies have shown that production costs for desalination are decreasing and capacity is growing. Efforts have been made to incorporate desalinated water into various global hydrological models. To improve the incorporation of desalinated water into GHMs, we proposed the use of a feasibility index to analyze under which conditions developing desalination capacity is economically feasible for different countries. We considered both past and future periods and clarified in which countries seawater desalination might be economically feasible. The index was defined in detail by comparing the production cost of desalination and conventional water prices simulated by two established statistical models. For historical validation, Fi was first evaluated for nine major desalination countries. The model achieved good agreement with the actual historical development of desalination in these countries on both spatial and temporal scales. We then simulated the period of 2015 – 2050. Our projected results suggested that desalination would become more cost-effective for further developing countries by 2050. The large spread of seawater desalination into yet more countries was mainly attributed to diminishing production cost and increasing water price in these countries under specific socioeconomic/climate scenarios, while. We predicted that, in determining the impact of seawater desalination over the period studied, water price would be overwhelmed by production cost.

The results of this thesis would provide new insights to help the policy-makers to determine appropriate policies for sustainable utilizing of water resources.

Appendix

Appendix A

Table A1 Agricultural water use technical efficiency (TE) during 1999 – 2011

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Beijing	0.80	0.79	0.73	0.72	0.72	0.75	0.76	0.65	0.69	0.72	0.74	0.76	0.75
Tianjin	0.76	0.68	0.71	0.66	0.61	0.61	0.57	0.62	0.61	0.64	0.65	0.75	0.71
Hebei	0.47	0.45	0.46	0.46	0.52	0.59	0.63	0.66	0.73	0.75	0.80	0.93	1.00
Shanxi	0.34	0.39	0.31	0.35	0.39	0.45	0.38	0.36	0.37	0.39	0.50	0.59	0.60
Inner Mongolia	0.45	0.39	0.37	0.37	0.38	0.44	0.48	0.50	0.56	0.60	0.56	0.63	0.67
Liaoning	0.67	0.56	0.58	0.59	0.52	0.60	0.59	0.60	0.67	0.67	0.64	0.72	0.78
Jilin	0.72	0.52	0.65	0.63	0.66	0.71	0.71	0.75	0.79	0.84	0.81	0.78	0.79
Heilongjiang	0.47	0.39	0.42	0.44	0.44	0.49	0.54	0.57	0.64	0.67	0.63	0.65	0.77
Shanghai	0.55	0.57	0.61	0.64	0.59	0.65	0.66	0.78	0.75	0.78	0.79	0.95	0.97
Jiangsu	0.52	0.50	0.49	0.49	0.57	0.68	0.72	0.76	0.80	0.83	0.86	0.92	1.00
Zhejiang	0.52	0.52	0.52	0.53	0.53	0.58	0.63	0.64	0.66	0.70	0.72	0.80	0.83
Anhui	0.42	0.42	0.39	0.37	0.36	0.41	0.40	0.39	0.44	0.44	0.43	0.49	0.51
Fujian	0.50	0.48	0.47	0.45	0.48	0.50	0.53	0.55	0.58	0.60	0.61	0.65	0.69
Jiangxi	0.33	0.33	0.33	0.34	0.33	0.37	0.36	0.37	0.38	0.40	0.40	0.40	0.40
Shandong	0.53	0.55	0.54	0.51	0.59	0.68	0.71	0.73	0.81	0.85	0.89	0.96	0.98
Henan	0.50	0.51	0.48	0.49	0.43	0.56	0.62	0.60	0.67	0.68	0.70	0.85	0.81
Hubei	0.48	0.44	0.44	0.47	0.49	0.58	0.54	0.54	0.63	0.72	0.72	0.92	1.00
Hunan	0.34	0.31	0.33	0.33	0.31	0.39	0.41	0.42	0.47	0.52	0.54	0.62	0.69
Guangdong	0.48	0.42	0.40	0.40	0.42	0.45	0.50	0.52	0.53	0.54	0.53	0.56	0.60
Guangxi	0.30	0.25	0.25	0.25	0.27	0.31	0.33	0.36	0.39	0.42	0.40	0.43	0.48
Hainan	0.58	0.62	0.55	0.56	0.53	0.54	0.55	0.60	0.59	0.67	0.69	0.70	0.74
Chongqing	0.72	0.74	0.66	0.66	0.65	0.78	0.76	0.73	0.81	0.87	0.91	0.99	1.00
Sichuan	0.48	0.47	0.45	0.45	0.43	0.51	0.50	0.49	0.56	0.65	0.65	0.67	0.76
Guizhou	0.34	0.34	0.31	0.29	0.27	0.30	0.30	0.28	0.32	0.34	0.34	0.37	0.39
Yunnan	0.30	0.30	0.30	0.28	0.26	0.30	0.30	0.31	0.32	0.35	0.36	0.37	0.43
Tibet	0.23	0.22	0.21	0.21	0.26	0.14	0.13	0.17	0.20	0.20	0.18	0.17	0.18
Shaanxi	0.41	0.40	0.40	0.39	0.36	0.44	0.46	0.46	0.52	0.59	0.60	0.78	0.92
Gansu	0.29	0.26	0.27	0.25	0.26	0.29	0.29	0.30	0.33	0.36	0.38	0.44	0.46
Qinghai	0.17	0.12	0.15	0.15	0.15	0.17	0.17	0.17	0.21	0.22	0.22	0.28	0.29
Ningxia	0.25	0.19	0.19	0.20	0.20	0.24	0.24	0.26	0.30	0.34	0.35	0.43	0.46
Xinjiang	0.59	0.61	0.53	0.52	0.73	0.71	0.76	0.66	0.80	0.76	0.76	0.99	0.95

Table A2 Agricultural water use pure technical efficiency (PTE) during 1999 – 2011

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Beijing	0.82	0.83	0.83	0.89	0.98	0.99	0.98	0.94	0.97	0.97	0.97	0.98	1.00
Tianjin	0.87	0.91	1.00	0.97	0.96	0.92	0.82	0.84	0.81	0.85	0.85	0.97	0.94
Hebei	0.48	0.46	0.46	0.47	0.52	0.60	0.64	0.67	0.74	0.76	0.80	0.93	1.00
Shanxi	0.38	0.44	0.37	0.41	0.45	0.51	0.46	0.44	0.43	0.45	0.53	0.62	0.62
Inner Mongolia	0.45	0.39	0.37	0.37	0.39	0.45	0.49	0.51	0.57	0.61	0.57	0.63	0.67
Liaoning	0.68	0.56	0.59	0.60	0.53	0.61	0.60	0.61	0.67	0.68	0.65	0.73	0.79
Jilin	0.73	0.53	0.66	0.64	0.67	0.72	0.72	0.76	0.80	0.85	0.82	0.80	0.81
Heilongjiang	0.48	0.40	0.43	0.45	0.45	0.50	0.55	0.57	0.64	0.67	0.63	0.65	0.77
Shanghai	0.69	0.77	0.83	0.90	0.80	0.81	0.85	0.94	0.93	0.93	0.93	0.99	1.00
Jiangsu	0.54	0.51	0.50	0.50	0.59	0.68	0.72	0.76	0.80	0.84	0.87	0.92	1.00
Zhejiang	0.52	0.52	0.52	0.54	0.53	0.59	0.64	0.64	0.67	0.71	0.73	0.81	0.85
Anhui	0.42	0.42	0.40	0.38	0.37	0.42	0.40	0.41	0.45	0.44	0.44	0.49	0.51
Fujian	0.51	0.48	0.47	0.46	0.48	0.51	0.54	0.56	0.59	0.61	0.62	0.67	0.70
Jiangxi	0.33	0.33	0.34	0.35	0.34	0.38	0.37	0.38	0.39	0.41	0.41	0.41	0.41
Shandong	0.53	0.55	0.55	0.52	0.59	0.69	0.72	0.73	0.81	0.85	0.90	0.97	1.00
Henan	0.53	0.58	0.52	0.54	0.50	0.66	0.76	0.69	0.82	0.81	0.81	0.99	1.00
Hubei	0.49	0.44	0.44	0.47	0.49	0.59	0.55	0.55	0.64	0.73	0.72	0.92	1.00
Hunan	0.34	0.32	0.34	0.33	0.31	0.39	0.41	0.42	0.47	0.52	0.55	0.62	0.69
Guangdong	0.50	0.43	0.41	0.41	0.42	0.46	0.51	0.53	0.53	0.55	0.54	0.56	0.60
Guangxi	0.30	0.25	0.25	0.25	0.27	0.31	0.33	0.36	0.40	0.42	0.41	0.43	0.48
Hainan	0.59	0.63	0.57	0.59	0.56	0.57	0.58	0.63	0.62	0.71	0.74	0.75	0.80
Chongqing	0.85	0.87	0.78	0.78	0.78	0.87	0.84	0.88	0.91	0.94	0.97	1.00	1.00
Sichuan	0.50	0.48	0.46	0.46	0.44	0.52	0.52	0.51	0.59	0.72	0.69	0.71	0.82
Guizhou	0.35	0.35	0.33	0.32	0.31	0.33	0.34	0.32	0.35	0.36	0.36	0.39	0.40
Yunnan	0.31	0.32	0.31	0.30	0.28	0.31	0.31	0.32	0.33	0.36	0.37	0.38	0.43
Tibet	0.63	0.62	0.62	0.60	0.65	0.61	0.55	0.52	0.50	0.49	0.52	0.46	0.49
Shaanxi	0.43	0.43	0.42	0.42	0.39	0.46	0.49	0.48	0.54	0.61	0.62	0.79	0.92
Gansu	0.29	0.27	0.28	0.26	0.27	0.30	0.30	0.31	0.34	0.37	0.39	0.46	0.48
Qinghai	0.51	0.51	0.52	0.53	0.52	0.51	0.52	0.51	0.54	0.50	0.50	0.47	0.47
Ningxia	0.38	0.34	0.33	0.33	0.33	0.32	0.31	0.31	0.32	0.35	0.37	0.43	0.47
Xinjiang	0.61	0.63	0.55	0.53	0.75	0.72	0.77	0.67	0.81	0.76	0.76	0.99	0.96

Table A3 Agricultural water use scale efficiency (SE) during 1999 – 2011

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Beijing	0.97	0.95	0.88	0.81	0.73	0.76	0.77	0.69	0.71	0.74	0.76	0.77	0.75
Tianjin	0.88	0.75	0.71	0.67	0.65	0.67	0.69	0.72	0.75	0.75	0.77	0.77	0.76
Hebei	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00
Shanxi	0.89	0.90	0.84	0.85	0.85	0.88	0.82	0.82	0.84	0.85	0.93	0.96	0.97
Inner Mongolia	0.99	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Liaoning	0.99	0.99	0.99	0.99	0.98	0.99	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Jilin	0.98	0.98	0.99	0.99	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Heilongjiang	0.98	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.99	1.00	1.00	0.99	1.00
Shanghai	0.79	0.73	0.73	0.71	0.74	0.80	0.77	0.82	0.80	0.83	0.85	0.95	0.97
Jiangsu	0.96	0.97	0.98	0.98	0.98	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00
Zhejiang	1.00	0.99	0.99	0.99	0.99	0.99	0.98	0.99	0.99	0.98	0.98	0.99	0.99
Anhui	0.99	0.99	0.98	0.97	0.98	0.97	0.98	0.97	0.98	0.99	0.99	0.99	0.99
Fujian	0.98	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Jiangxi	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.98	0.98	0.99	0.99	0.99
Shandong	0.99	1.00	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	0.99	0.98
Henan	0.94	0.88	0.92	0.90	0.84	0.85	0.81	0.87	0.82	0.85	0.87	0.86	0.81
Hubei	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00
Hunan	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00
Guangdong	0.95	0.98	0.98	0.99	0.98	0.98	0.98	0.98	0.99	0.99	1.00	1.00	1.00
Guangxi	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.99	0.99	0.99
Hainan	0.97	0.98	0.97	0.96	0.95	0.95	0.93	0.94	0.93	0.94	0.93	0.93	0.92
Chongqing	0.85	0.85	0.84	0.84	0.83	0.89	0.89	0.82	0.88	0.92	0.94	0.99	1.00
Sichuan	0.97	0.97	0.97	0.98	0.98	0.97	0.97	0.98	0.96	0.91	0.94	0.95	0.93
Guizhou	0.96	0.96	0.94	0.91	0.88	0.89	0.87	0.88	0.89	0.93	0.93	0.95	0.97
Yunnan	0.97	0.96	0.95	0.95	0.94	0.95	0.96	0.96	0.96	0.97	0.98	0.99	1.00
Tibet	0.36	0.35	0.35	0.35	0.39	0.23	0.22	0.32	0.39	0.40	0.35	0.37	0.36
Shaanxi	0.96	0.94	0.93	0.93	0.92	0.94	0.95	0.95	0.96	0.97	0.97	0.99	1.00
Gansu	1.00	0.98	0.97	0.96	0.96	0.96	0.96	0.95	0.96	0.96	0.96	0.96	0.96
Qinghai	0.34	0.24	0.28	0.27	0.29	0.33	0.33	0.33	0.40	0.45	0.43	0.60	0.63
Ningxia	0.65	0.57	0.58	0.61	0.60	0.74	0.75	0.84	0.94	0.97	0.97	0.98	0.98
Xinjiang	0.97	0.97	0.97	0.97	0.98	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00

Table A4 Input slack (agricultural water consumption: 100 million m^3) of window DEA analysis during 1999 – 2011

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Beijing	14.43	14.72	18.34	18.21	16.69	14.21	14.11	23.00	19.21	17.38	15.95	14.66	14.47
Tianjin	19.67	25.61	23.59	27.56	31.31	31.03	34.20	30.13	29.82	27.77	26.39	18.45	20.90
Hebei	862.98	911.54	901.28	886.09	803.87	648.56	570.88	508.36	393.47	364.54	296.14	102.88	0.00
Shanxi	431.51	400.59	452.14	426.46	396.24	351.62	396.41	405.57	401.80	391.72	317.59	259.20	255.73
Inner Mongolia	291.90	322.20	326.96	339.48	319.52	292.69	274.46	266.05	235.20	210.08	232.38	201.45	181.01
Liaoning	211.55	289.54	271.52	271.09	320.64	274.88	282.75	272.12	224.04	218.04	239.32	185.68	149.23
Jilin	148.24	248.26	178.52	188.07	170.82	142.84	146.10	124.47	103.32	77.94	96.75	109.68	108.98
Heilongjiang	395.56	450.56	429.65	418.79	412.26	356.75	318.27	297.15	241.95	223.93	253.44	237.36	155.51
Shanghai	41.01	36.71	32.75	28.95	29.22	23.00	20.25	10.03	12.99	10.26	9.50	1.85	1.00
Jiangsu	725.26	746.93	747.73	697.29	524.93	361.94	297.97	238.14	186.33	148.59	118.79	68.55	0.00
Zhejiang	514.57	489.54	477.34	433.64	412.70	344.54	294.55	266.62	231.73	200.13	182.40	125.49	103.47
Anhui	1159.49	1169.10	1205.89	1214.58	1193.42	1052.32	1068.87	1054.94	923.13	898.71	888.77	781.46	737.07
Fujian	392.17	402.40	406.69	413.72	386.12	359.63	326.38	298.62	269.22	254.01	245.12	215.98	193.47
Jiangxi	714.39	658.70	651.55	646.94	649.63	602.09	607.02	587.28	553.51	529.13	519.01	510.42	507.55
Shandong	1168.98	1117.13	1113.53	1155.92	932.84	693.66	589.78	536.07	372.57	298.10	212.82	85.32	40.00
Henan	1664.62	1736.90	1802.88	1740.99	1904.59	1438.14	1206.35	1212.62	952.69	896.90	818.01	410.49	501.15
Hubei	624.36	654.38	644.26	603.79	571.27	462.76	504.43	495.44	389.15	280.27	271.77	72.11	0.00
Hunan	1369.96	1419.96	1370.72	1353.41	1375.43	1209.22	1160.51	1118.02	1000.86	907.25	854.01	704.75	572.51
Guangdong	800.07	907.10	932.80	935.33	901.62	833.75	770.06	736.70	726.91	702.61	709.67	653.15	555.60
Guangxi	1128.20	1164.53	1164.08	1169.54	1131.22	1044.77	1010.15	969.93	913.83	897.18	922.90	888.02	806.25
Hainan	73.15	67.71	80.47	79.08	87.81	87.08	87.52	78.22	82.70	67.07	63.97	62.54	54.85
Chongqing	443.42	392.40	377.08	341.12	319.17	228.30	218.68	279.94	195.05	148.47	117.76	62.46	0.00
Sichuan	1427.68	1398.82	1420.37	1373.99	1372.11	1167.36	1152.68	1146.63	959.95	757.16	762.31	695.63	502.09
Guizhou	948.94	910.97	940.98	958.86	962.87	905.27	888.18	894.24	819.99	793.76	796.84	749.42	712.43
Yunnan	1159.98	1167.69	1191.08	1213.25	1247.85	1188.85	1180.98	1160.56	1135.50	1083.05	1057.36	1032.54	940.98
Tibet	71.07	70.67	69.79	70.31	62.82	73.01	74.76	72.09	70.22	71.02	74.42	75.92	75.74
Shaanxi	592.16	597.45	596.11	609.60	629.26	537.53	509.06	512.52	444.69	366.63	348.06	191.45	69.24
Gansu	490.49	512.83	510.22	555.10	565.36	545.43	538.45	524.66	495.59	465.97	457.43	406.78	385.69
Qinghai	119.01	124.91	120.73	116.55	114.83	109.75	106.44	102.67	94.22	93.57	93.86	86.55	83.67
Ningxia	115.33	123.75	122.57	120.43	116.51	109.36	106.81	100.90	96.18	88.42	82.43	71.94	66.49
Xinjiang	125.18	122.09	151.39	156.95	87.92	99.70	82.33	120.41	69.85	86.76	88.70	3.60	18.85

Table A5 Input slack (labor: 10,000 persons) of window DEA analysis during 1999 – 2011

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Beijing	3.75	3.48	4.70	4.39	3.62	3.18	3.05	4.22	3.66	3.19	2.98	2.64	2.54
Tianjin	3.13	3.88	2.90	3.68	4.32	4.62	5.84	5.17	5.36	4.73	4.48	2.74	3.30
Hebei	92.00	88.52	87.28	86.56	72.44	59.60	55.23	51.26	40.33	35.32	28.94	10.14	0.00
Shanxi	23.43	21.34	24.92	22.99	20.43	18.08	20.32	21.83	21.75	20.22	17.30	15.57	17.25
Inner Mongolia	83.44	95.33	98.86	100.66	90.75	83.50	74.62	70.86	61.91	53.48	61.01	50.13	45.37
Liaoning	30.45	38.64	35.16	34.20	40.12	34.35	35.91	36.58	30.69	29.92	32.97	25.13	20.18
Jilin	22.85	41.03	26.87	30.88	22.95	19.11	19.32	17.52	14.18	11.00	13.88	16.14	17.44
Heilongjiang	105.22	112.37	109.15	98.14	96.16	94.10	87.75	89.74	76.96	72.21	88.71	87.44	76.77
Shanghai	7.96	6.64	5.38	4.26	6.64	6.63	6.33	4.92	4.07	4.08	3.86	2.70	4.35
Jiangsu	119.59	131.91	144.55	148.91	95.19	92.02	74.28	65.69	53.79	47.63	40.68	24.25	0.00
Zhejiang	61.10	58.47	56.80	55.11	52.10	44.72	39.95	36.76	33.75	29.65	27.15	18.93	15.45
Anhui	81.70	70.85	75.68	80.42	60.17	71.38	68.69	82.68	67.87	85.71	94.90	85.60	83.13
Fujian	57.60	57.95	59.61	60.94	52.99	51.85	47.88	44.00	42.63	39.63	39.46	33.65	30.76
Jiangxi	103.00	102.35	100.28	89.96	69.63	80.54	85.91	83.24	93.34	88.81	94.18	90.54	102.61
Shandong	88.82	79.80	83.67	91.79	64.67	49.09	45.06	45.14	30.51	23.59	16.77	6.62	3.01
Henan	80.57	65.45	82.86	74.78	65.03	55.37	43.75	55.91	39.31	42.20	41.02	19.10	23.52
Hubei	84.40	93.09	98.84	72.65	70.05	55.12	65.07	65.23	49.27	40.19	42.05	11.08	0.00
Hunan	146.91	152.83	149.43	137.94	144.18	123.80	119.70	115.45	102.63	93.33	86.55	70.33	56.25
Guangdong	136.03	149.30	153.45	150.63	141.72	131.38	115.82	109.06	106.66	104.06	106.66	101.19	88.81
Guangxi	146.99	168.08	162.40	169.65	150.78	144.78	151.47	143.31	126.54	118.63	116.49	110.98	100.75
Hainan	15.65	13.54	15.62	15.56	16.74	17.28	15.90	14.62	14.83	11.89	10.49	10.32	8.89
Chongqing	5.52	4.83	6.97	7.13	7.26	4.49	5.15	4.97	3.64	2.49	1.65	0.12	0.00
Sichuan	68.59	70.34	67.95	67.10	69.17	59.76	60.59	61.40	51.79	39.45	43.88	41.54	30.91
Guizhou	32.13	33.32	35.75	36.35	38.02	36.48	35.34	38.96	33.19	34.06	33.54	31.57	30.38
Yunnan	79.41	77.97	77.81	79.20	80.92	76.96	75.75	73.05	72.29	68.58	65.99	59.67	54.92
Tibet	18.17	19.39	19.53	21.57	16.82	21.98	26.52	26.62	27.17	27.87	22.40	26.30	22.56
Shaanxi	33.49	33.27	33.12	33.47	32.26	27.93	28.00	30.69	26.67	23.45	22.82	12.48	4.73
Gansu	69.12	71.62	70.49	73.13	71.64	69.13	67.17	65.89	64.21	62.08	58.53	52.91	50.59
Qinghai	17.53	18.64	17.48	17.38	18.49	18.17	17.41	18.04	16.10	17.36	16.89	16.59	16.63
Ningxia	68.11	66.96	64.27	62.79	47.44	54.10	57.64	56.95	48.30	51.10	46.98	41.07	44.61
Xinjiang	218.49	283.12	290.37	302.66	265.68	257.60	257.69	318.90	267.76	341.63	314.05	173.29	344.83

Appendix B

Table B1 Water Price in 2015, 2030 and 2050 under three SSPs.

Country		SSP1		SSP2		SSP3	
	2015	2030	2050	2030	2050	2030	2050
Albania	0.81	1.07	1.51	0.99	1.27	1.01	1.22
Algeria	0.40	0.58	0.86	0.48	0.60	0.54	0.61
Angola	0.43	0.80	1.23	0.59	0.72	0.55	0.63
Argentina	0.97	1.21	1.66	1.24	1.59	1.27	1.44
Aruba	0.05	0.20	0.52	0.06	0.17	0.10	0.22
Australia	1.86	2.12	2.51	2.15	2.44	2.23	2.47
Bahamas	1.08	1.28	1.64	1.28	1.49	1.31	1.43
Bahrain	1.45	1.68	2.02	1.73	2.06	1.75	1.90
Bangladesh	0.16	0.33	0.66	0.18	0.31	0.22	0.33
Barbados	3.59	3.72	4.02	3.76	4.00	1.82	1.91
Belgium	2.41	2.74	3.44	2.77	3.39	2.93	3.47
Belize	0.50	0.74	1.37	0.62	0.99	0.60	0.84
Benin	0.21	0.55	1.11	0.36	0.61	0.32	0.53
Bosnia and Herzegovina	0.81	1.24	1.85	1.14	1.62	1.16	1.55
Brazil	1.03	1.39	2.03	1.30	1.56	1.31	1.34
Brunei	2.66	3.50	4.77	3.28	4.26	3.12	3.57
Bulgaria	1.06	1.78	2.73	1.63	2.32	1.59	1.99
Cambodia	0.11	0.31	0.76	0.14	0.30	0.19	0.32
Cameroon	0.26	0.65	1.35	0.46	0.83	0.41	0.68
Canada	1.96	2.34	2.90	2.36	2.92	2.42	3.27
Cape Verde	0.10	0.26	0.63	0.15	0.31	0.21	0.35
Chile	0.71	1.01	1.53	0.98	1.34	1.00	1.21
China	0.47	1.01	1.78	0.83	1.26	0.85	1.11
Colombia	0.66	1.02	1.84	0.89	1.38	0.87	1.12
Comoros	0.06	0.19	0.49	0.10	0.18	0.09	0.18
Congo Dem. Rep.	0.16	0.48	0.99	0.30	0.54	0.27	0.48
Congo, Rep	0.39	0.91	1.83	0.69	1.19	0.62	0.95
Costa Rica	0.77	1.22	2.01	1.08	1.58	1.04	1.31
Cote D'Ivoire	0.24	0.72	1.75	0.51	1.11	0.44	0.78
Croatia	1.24	1.62	2.09	1.53	1.87	1.53	1.76
Cuba	0.76	0.82	1.07	0.87	1.04	0.91	1.04
Cyprus	0.69	0.83	1.10	0.72	0.88	0.78	0.90
Denmark	1.19	1.36	1.70	1.36	1.67	1.43	1.72
Djibouti	0.26	0.68	1.39	0.50	0.95	0.45	0.80
Dominican Republic	0.65	1.04	1.76	0.92	1.40	0.89	1.14

East Timor	0.47	0.45	0.77	0.59	0.75	0.65	0.77
Ecuador	0.54	0.62	0.99	0.68	0.90	0.72	0.86
Egypt	0.47	0.60	1.06	0.65	0.95	0.70	0.89
El Salvador	0.43	0.53	0.85	0.54	0.71	0.59	0.72
Equatorial Guinea	1.74	2.37	3.54	2.05	2.72	1.91	2.24
Eritrea	0.04	0.14	0.33	0.06	0.14	0.06	0.13
Estonia	1.69	2.26	3.11	2.26	3.06	2.41	3.16
Fiji	0.23	0.34	0.68	0.24	0.39	0.31	0.44
Finland	2.39	2.73	3.38	2.71	3.20	2.89	3.38
France	2.18	2.46	3.13	2.46	2.87	2.63	3.01
French Polynesia	0.48	0.65	1.05	0.46	0.62	0.48	0.59
Gabon	0.88	1.48	2.56	1.22	1.84	1.08	1.39
Gambia	0.24	0.62	1.27	0.43	0.77	0.39	0.64
Georgia	0.34	0.83	1.80	0.67	1.25	0.60	0.97
Germany	2.47	2.78	3.45	2.78	3.27	2.94	3.39
Ghana	0.11	0.28	0.65	0.11	0.25	0.16	0.27
Greece	0.87	1.13	1.58	1.10	1.46	1.15	1.42
Guatemala	0.38	0.62	1.29	0.50	0.86	0.48	0.69
Guinea	0.20	0.73	1.89	0.49	1.05	0.40	0.69
Guinea Bissau	0.14	0.27	0.56	0.16	0.28	0.17	0.28
Guyana	0.36	0.61	1.20	0.50	0.82	0.50	0.73
Haiti	0.12	0.26	0.58	0.15	0.28	0.16	0.27
Honduras	0.35	0.56	1.18	0.46	0.82	0.46	0.69
Iceland	2.15	2.76	3.59	2.66	3.52	2.66	3.32
India	0.26	0.45	0.90	0.34	0.56	0.40	0.53
Indonesia	0.60	1.03	2.04	0.86	1.40	0.89	1.32
Iran	0.62	0.70	0.99	0.77	1.00	0.83	1.04
Iraq	0.97	1.03	1.13	1.10	1.18	1.18	1.31
Ireland	2.53	2.87	3.34	2.90	3.32	3.06	3.44
Israel	1.16	1.40	1.83	1.45	1.84	1.52	1.85
Italy	1.33	1.44	1.72	1.50	1.76	1.57	1.79
Jamaica	0.58	0.60	0.81	0.66	0.80	0.72	0.84
Japan	1.34	1.52	1.88	1.56	1.81	1.62	1.82
Jordan	0.36	0.54	0.96	0.44	0.73	0.50	0.71
Kenya	0.22	0.58	1.16	0.40	0.68	0.35	0.57
Kuwait	2.15	2.58	3.21	2.58	3.09	2.73	3.44
Latvia	1.46	1.99	2.83	1.92	2.36	2.04	2.35
Lebanon	0.71	0.92	1.40	0.97	1.34	1.00	1.24
Liberia	0.17	0.50	1.05	0.32	0.57	0.28	0.49
Libya	0.94	1.19	1.53	1.23	1.52	1.29	1.49

Lithuania	1.59	2.06	2.74	2.02	2.47	2.12	2.41
Madagascar	0.10	0.22	0.45	0.13	0.21	0.12	0.22
Malaysia	1.13	1.72	2.70	1.53	2.25	1.52	2.06
Maldives	0.28	0.45	0.88	0.35	0.57	0.41	0.58
Malta	0.92	1.21	1.71	1.16	1.58	1.20	1.54
Mauritania	0.21	0.36	0.59	0.19	0.32	0.26	0.38
Mauritius	1.15	1.42	1.95	1.44	1.79	1.47	1.70
Mexico	0.71	0.84	1.27	0.89	1.16	0.93	1.09
Morocco	0.40	0.57	1.07	0.55	0.87	0.59	0.78
Mozambique	0.19	0.54	1.16	0.36	0.63	0.32	0.53
Myanmar	0.44	0.61	0.91	0.49	0.60	0.56	0.78
Namibia	0.31	0.49	0.87	0.39	0.60	0.44	0.61
Netherlands	2.60	2.96	3.66	2.98	3.57	3.13	3.59
New Caledonia	0.54	0.90	1.47	0.69	0.95	0.70	0.88
New Zealand	1.65	2.01	2.73	1.95	2.44	2.00	2.35
Nicaragua	0.30	0.51	1.16	0.42	0.83	0.42	0.69
Nigeria	0.20	0.37	0.67	0.20	0.34	0.26	0.37
Norway	2.92	3.38	3.81	3.24	3.57	3.34	3.56
Oman	0.99	1.39	2.01	1.20	1.52	1.23	1.32
Pakistan	0.27	0.37	0.60	0.28	0.40	0.34	0.45
Panama	1.02	1.83	3.07	1.66	2.56	1.59	2.10
Papua New Guinea	0.37	0.56	1.33	0.46	0.89	0.45	0.80
Peru	0.47	0.81	1.46	0.67	1.04	0.71	0.92
Philippines	0.37	0.46	0.74	0.41	0.56	0.47	0.59
Poland	1.65	2.13	2.77	2.12	2.59	2.27	2.73
Portugal	0.88	1.02	1.33	1.07	1.34	1.13	1.35
Puerto Rico	1.47	1.65	1.96	1.69	2.00	1.69	1.92
Qatar	3.24	3.77	3.85	4.01	4.05	4.19	4.24
Romania	1.00	1.52	2.37	1.39	1.88	1.38	1.64
Russia	0.88	1.67	2.71	1.48	2.15	1.41	1.90
Samoa	0.09	0.21	0.52	0.11	0.24	0.17	0.28
Sao Tome and Principe	0.08	0.41	1.13	0.21	0.52	0.26	0.49
Saudi Arabia	0.93	1.15	1.48	1.18	1.40	1.26	1.52
Senegal	0.09	0.24	0.59	0.10	0.21	0.13	0.23
Sierra Leone	0.19	0.52	1.04	0.34	0.59	0.31	0.52
Singapore	2.59	3.14	3.36	3.20	3.51	3.18	3.36
Slovenia	1.99	2.36	2.97	2.37	2.89	2.52	3.03
Solomon Island	0.05	0.17	0.51	0.07	0.21	0.13	0.25
South Africa	0.65	0.82	1.16	0.86	1.14	0.91	1.10
South Korea	1.42	1.91	2.50	1.96	2.58	2.00	2.52

Spain	1.21	1.28	1.47	1.35	1.53	1.41	1.56
Sri Lanka	0.32	0.57	1.12	0.46	0.75	0.51	0.68
St. Lucia	0.49	0.60	0.98	0.58	0.79	0.64	0.79
St. Vincent and the Grenadines	0.54	0.71	1.09	0.68	0.89	0.72	0.85
Sudan	0.24	0.63	1.28	0.44	0.75	0.39	0.62
Suriname	0.58	1.05	1.99	0.91	1.53	0.89	1.31
Sweden	2.52	2.93	3.60	2.94	3.44	3.12	3.60
Syria	0.40	0.56	1.02	0.59	0.87	0.62	0.82
Tanzania	0.21	0.58	1.20	0.39	0.69	0.35	0.58
Thailand	0.39	0.71	1.38	0.58	0.99	0.62	0.85
Togo	0.19	0.52	1.04	0.34	0.56	0.30	0.51
Tonga	0.09	0.21	0.53	0.11	0.24	0.17	0.29
Trinidad and Tobago	1.29	1.58	1.98	1.60	1.93	1.63	1.84
Tunisia	0.41	0.73	1.33	0.62	1.04	0.67	0.99
Turkey	0.70	0.91	1.36	0.94	1.25	0.97	1.13
Ukraine	0.54	0.70	1.16	0.74	1.03	0.79	1.00
United Arab Emirates	1.74	2.10	2.55	2.11	2.47	2.18	2.49
United Kingdom	2.36	2.80	3.54	2.77	3.22	2.93	3.33
United States of America	2.11	2.47	2.81	2.48	2.75	2.55	2.87
Uruguay	0.86	1.11	1.62	1.13	1.48	1.16	1.36
Vanuatu	0.09	0.22	0.67	0.12	0.31	0.18	0.32
Venezuela	1.08	1.17	1.39	1.22	1.45	1.29	1.61
Vietnam	0.13	0.32	0.72	0.21	0.42	0.28	0.45
West Bank	0.35	0.48	0.93	0.48	0.74	0.51	0.69
Yemen	0.08	0.17	0.37	0.08	0.17	0.15	0.26

Appendix C

Table C1 Feasibility index (F_i) in 2015, 2030 and 2050 under three SSPs. ($F_i = W_{p\text{-}2015}/C_p$). Red numbers indicate feasibility index in major countries using SWRO.

Country		**SSP1**		**SSP2**		**SSP3**	
	2015	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Congo Dem. Rep.	NA	0.09	0.12	0.09	0.14	0.10	0.13
Eritrea	NA	0.02	0.03	NA	0.01	NA	NA
Liberia	NA	0.10	0.13	0.10	0.15	0.10	0.10
Qatar	3.19	3.45	4.19	3.58	4.13	3.55	3.65
Barbados	3.07	3.26	4.39	3.38	4.58	1.58	1.64
Norway	2.68	2.91	3.40	2.96	3.39	2.90	3.12
Brunei	2.66	2.89	2.91	3.01	3.16	2.99	2.98
Singapore	2.44	2.63	3.02	2.79	3.17	2.71	2.73
Netherlands	2.15	2.43	2.76	2.44	2.92	2.28	2.48
Canada	2.13	2.33	2.61	2.38	2.66	2.32	2.51
Kuwait	2.12	2.29	2.79	2.39	2.75	2.38	2.45
Ireland	2.09	2.36	2.69	2.38	2.85	2.22	2.42
Sweden	2.08	2.35	2.67	2.37	2.83	2.21	2.41
Germany	2.04	2.31	2.62	2.33	2.78	2.17	2.37
United States of America	2.01	2.22	2.56	2.31	2.65	2.23	2.30
Belgium	1.99	2.25	2.55	2.27	2.71	2.12	2.31
Iceland	1.98	2.15	2.51	2.19	2.50	2.14	2.31
Finland	1.97	2.23	2.53	2.25	2.68	2.10	2.29
United Kingdom	1.95	2.20	2.50	2.22	2.65	2.08	2.26
Equatorial Guinea	1.81	1.76	1.75	1.91	2.02	1.94	1.99
Australia	1.80	1.96	2.30	2.00	2.35	1.97	2.23
France	1.80	2.03	2.31	2.06	2.46	1.93	2.10
United Arab Emirates	1.71	1.85	2.25	1.94	2.23	1.93	1.99
New Zealand	1.60	1.74	2.04	1.79	2.11	1.73	1.97
Slovenia	1.41	1.86	2.11	1.88	2.25	1.77	1.92
South Korea	1.34	1.44	1.65	1.54	1.75	1.51	1.53
Puerto Rico	1.26	1.63	1.80	1.40	1.90	1.40	1.81
Bahrain	1.20	1.55	1.88	1.63	1.87	1.63	1.68
Estonia	1.20	1.57	1.79	1.60	1.92	1.51	1.64
Poland	1.17	1.54	1.75	1.57	1.87	1.48	1.61
Israel	1.14	1.24	1.50	1.31	1.51	1.32	1.35
Lithuania	1.13	1.48	1.69	1.52	1.81	1.22	1.56
Bahamas	1.11	1.20	1.32	1.28	1.40	1.29	1.36
Trinidad and Tobago	1.10	1.44	1.58	1.52	1.68	1.53	1.61
Italy	1.10	1.24	1.41	1.24	1.49	1.17	1.27

Latvia	1.03	1.36	1.54	1.18	1.67	1.12	1.43
Spain	1.00	1.13	1.28	1.14	1.36	1.07	1.17
Mauritius	0.99	0.96	1.16	1.06	1.37	1.10	1.39
Japan	0.98	1.09	1.07	1.14	1.27	1.06	1.13
Denmark	0.98	1.11	1.26	1.10	1.31	1.04	1.13
Oman	0.97	1.05	1.28	1.05	1.21	1.06	1.09
Croatia	0.97	1.03	1.45	1.05	1.45	1.04	1.10
Malaysia	0.89	0.95	1.31	0.99	1.37	0.98	1.19
Panama	0.87	1.14	1.25	1.18	1.30	1.18	1.24
Venezuela	0.87	0.97	1.31	1.03	1.11	1.05	1.09
Libya	0.85	1.13	1.21	1.21	1.25	1.25	1.13
Argentina	0.83	1.08	1.19	0.93	1.27	0.95	1.23
Russia	0.80	1.05	1.16	1.11	1.24	1.12	1.20
Bulgaria	0.78	0.88	1.24	0.89	1.23	0.89	1.15
Saudi Arabia	0.76	0.99	1.20	1.05	1.21	1.06	1.09
Gabon	0.76	0.74	0.89	0.79	1.03	0.80	0.82
Iraq	0.76	0.81	1.00	0.85	0.95	0.86	0.88
Brazil	0.74	0.84	1.20	0.85	0.98	0.85	0.94
Romania	0.74	0.83	1.17	0.85	1.17	0.84	0.89
Uruguay	0.73	0.78	1.05	0.83	1.13	0.85	1.10
Malta	0.66	0.86	0.98	0.83	1.00	0.79	0.86
Portugal	0.62	0.82	0.93	0.84	1.00	0.68	0.87
Costa Rica	0.62	0.70	0.94	0.72	0.98	0.72	0.75
Greece	0.61	0.81	0.92	0.80	0.95	0.76	0.83
Cuba	0.61	0.65	0.74	0.69	0.79	0.71	0.73
Chile	0.60	0.79	0.86	0.67	0.91	0.69	0.90
Mexico	0.60	0.64	0.86	0.69	0.93	0.71	0.74
Albania	0.60	0.64	0.76	0.65	0.76	0.65	0.73
Bosnia and Herzegovina	0.59	0.67	0.94	0.68	0.76	0.68	0.72
Lebanon	0.58	0.62	0.92	0.66	0.93	0.68	0.85
Turkey	0.54	0.59	0.85	0.63	0.87	0.64	0.67
Colombia	0.53	0.60	0.81	0.62	0.67	0.59	0.65
South Africa	0.53	0.55	0.66	0.62	0.80	0.65	0.66
Dominican Republic	0.53	0.59	0.80	0.62	0.66	0.62	0.64
Cyprus	0.49	0.54	0.73	0.51	0.59	0.49	0.53
Iran	0.48	0.54	0.63	0.58	0.65	0.60	0.61
Suriname	0.47	0.53	0.71	0.55	0.59	0.55	0.57
Jamaica	0.47	0.49	0.57	0.54	0.61	0.56	0.58
Ukraine	0.46	0.52	0.70	0.56	0.62	0.56	0.63
New Caledonia	0.45	0.58	0.59	0.55	0.58	0.46	0.56

Indonesia	0.45	0.48	0.70	0.50	0.59	0.50	0.54
Ecuador	0.44	0.46	0.66	0.50	0.58	0.52	0.58
St. Vincent and the Grenadines	0.43	0.49	0.66	0.52	0.56	0.55	0.57
China	0.42	0.58	0.65	0.46	0.64	0.50	0.64
Egypt	0.40	0.43	0.61	0.47	0.51	0.50	0.49
Belize	0.40	0.42	0.49	0.44	0.50	0.44	0.46
French Polynesia	0.40	0.43	0.52	0.39	0.41	0.40	0.40
St. Lucia	0.39	0.41	0.47	0.44	0.50	0.46	0.51
Peru	0.38	0.42	0.57	0.40	0.55	0.43	0.45
Angola	0.35	0.34	0.34	0.37	0.38	0.37	0.38
El Salvador	0.35	0.37	0.42	0.40	0.46	0.43	0.44
Tunisia	0.35	0.40	0.53	0.37	0.49	0.41	0.37
Algeria	0.34	0.37	0.41	0.35	0.38	0.37	0.35
Morocco	0.34	0.36	0.51	0.38	0.41	0.41	0.40
Congo, Rep	0.32	0.31	0.32	0.33	0.36	0.33	0.34
Syria	0.31	0.33	0.51	0.38	0.45	0.38	0.41
Guatemala	0.31	0.33	0.37	0.34	0.36	0.34	0.36
Thailand	0.29	0.33	0.46	0.31	0.43	0.33	0.33
Georgia	0.29	0.33	0.45	0.33	0.38	0.33	0.37
Papua New Guinea	0.29	0.31	0.33	0.32	0.33	0.32	0.32
Guyana	0.29	0.30	0.35	0.32	0.34	0.32	0.33
Honduras	0.28	0.30	0.34	0.31	0.33	0.31	0.33
Jordan	0.28	0.30	0.37	0.27	0.33	0.30	0.32
Philippines	0.28	0.29	0.35	0.28	0.31	0.30	0.30
East Timor	0.27	0.37	0.44	0.44	0.48	0.45	0.45
Myanmar	0.25	0.35	0.39	0.37	0.41	0.38	0.38
Namibia	0.25	0.25	0.26	0.24	0.26	0.27	0.29
Sri Lanka	0.25	0.28	0.35	0.25	0.27	0.27	0.29
Nicaragua	0.24	0.26	0.29	0.27	0.29	0.27	0.28
India	0.23	0.24	0.26	0.22	0.26	0.25	0.26
Maldives	0.22	0.23	0.25	0.21	0.23	0.24	0.25
Pakistan	0.20	0.23	0.23	0.21	0.21	0.23	0.23
Pakistan	0.20	0.23	0.23	0.21	0.21	0.23	0.23
Fiji	0.18	0.19	0.20	0.17	0.17	0.19	0.19
Djibouti	0.16	0.21	0.22	0.22	0.23	0.23	0.23
Nigeria	0.16	0.16	0.17	0.12	0.12	0.15	0.15
Cameroon	0.16	0.20	0.21	0.22	0.22	0.22	0.22
Gambia	0.15	0.19	0.19	0.21	0.21	0.21	0.21
Sudan	0.15	0.19	0.19	0.20	0.21	0.21	0.21

Cote D'Ivoire	0.15	0.19	0.20	0.20	0.22	0.20	0.21
Kenya	0.14	0.18	0.18	0.19	0.20	0.14	0.20
Benin	0.13	0.17	0.17	0.13	0.19	0.13	0.19
Tanzania	0.13	0.17	0.17	0.18	0.19	0.13	0.19
Mauritania	0.13	0.16	0.16	0.12	0.13	0.15	0.15
Guinea	0.12	0.16	0.17	0.17	0.19	0.17	0.18
Sierra Leone	0.12	0.11	0.15	0.11	0.17	0.12	0.11
Mozambique	0.12	0.11	0.15	0.11	0.17	0.12	0.17
Bangladesh	0.12	0.13	0.14	0.11	0.11	0.11	0.11
Togo	0.12	0.11	0.15	0.11	0.17	0.11	0.11
Vietnam	0.10	0.11	0.13	0.08	0.10	0.11	0.11
Guinea Bissau	0.08	0.08	0.11	0.06	0.09	0.06	0.09
Cape Verde	0.08	0.08	0.08	0.06	0.06	0.08	0.09
Haiti	0.07	0.10	0.11	0.05	0.08	0.05	0.08
Tonga	0.07	0.07	0.08	0.05	0.05	0.08	0.08
Vanuatu	0.07	0.07	0.08	0.05	0.05	0.08	0.08
Samoa	0.07	0.07	0.08	0.05	0.05	0.07	0.07
Ghana	0.07	0.08	0.09	0.05	0.05	0.06	0.07
Cambodia	0.06	0.08	0.10	0.05	0.05	0.06	0.06
Madagascar	0.06	0.06	0.08	0.04	0.06	0.04	0.04
Senegal	0.06	0.07	0.07	0.05	0.05	0.04	0.05
Yemen	0.05	0.07	0.08	0.04	0.05	0.05	0.07
Sao Tome and Principe	0.05	0.06	0.08	0.01	0.01	0.04	0.04
Comoros	0.04	0.04	0.05	0.02	0.03	0.02	0.02
Solomon Island	0.04	0.04	0.04	0.01	0.01	0.04	0.04
Aruba	0.03	0.04	0.05	0.02	0.02	0.02	0.02

Table C2 Desalination population (million capita) in 2015, 2030 and 2050 under three SSPs. ($F_i = W_{p\text{-}2015/}C_p$).

Country		SSP1		SSP2		SSP3	
	2015	2030	2050	2030	2050	2030	2050
Congo Dem. Rep.	3.66	0.00	0.00	0.00	0.00	0.00	0.00
Eritrea	5.81	0.00	0.00	8.27	0.00	8.26	11.63
Liberia	2.74	0.00	0.00	0.00	0.00	0.00	0.00
Qatar	1.73	2.39	2.87	2.45	3.05	2.24	2.68
Barbados	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Norway	3.70	4.35	5.20	4.31	5.07	3.95	4.04
Brunei	0.43	0.50	0.55	0.53	0.62	0.52	0.62
Singapore	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Netherlands	13.98	14.84	15.68	14.68	15.19	13.91	12.95
Canada	11.33	13.16	15.40	13.03	14.97	11.91	11.80
Kuwait	2.83	3.82	4.83	3.95	5.25	3.74	4.84
Ireland	4.34	5.05	5.92	5.01	5.76	4.68	4.82
Sweden	5.80	6.58	7.62	6.50	7.40	5.98	5.96
Germany	15.47	15.58	15.55	15.36	14.94	14.55	12.64
United States of America	117.57	132.13	149.17	131.26	146.23	122.88	122.17
Belgium	12.21	13.20	14.37	13.03	13.89	12.22	11.59
Iceland	0.20	0.24	0.30	0.24	0.29	0.22	0.24
Finland	4.10	4.41	4.76	4.35	4.60	4.09	3.85
United Kingdom	49.34	54.27	60.22	53.82	58.88	50.56	49.49
Equatorial Guinea	0.19	0.26	0.32	0.27	0.35	0.27	0.36
Australia	19.12	23.52	28.96	23.40	28.52	21.24	22.53
France	24.95	27.30	30.19	27.04	29.37	25.57	25.10
United Arab Emirates	3.01	4.23	5.15	4.33	5.49	3.96	4.74
New Zealand	4.17	4.80	5.47	4.78	5.37	4.48	4.54
Slovenia	2.20	2.30	2.40	2.27	2.33	2.14	1.95
South Korea	48.64	50.02	48.09	49.42	45.98	47.80	41.04
Puerto Rico	2.53	2.84	3.21	2.82	3.14	2.64	2.61
Bahrain	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Estonia	1.24	1.22	1.21	1.21	1.17	1.16	1.02
Poland	6.38	6.36	6.06	6.29	5.85	6.05	5.17
Israel	7.23	9.10	10.98	9.30	11.50	9.33	11.79
Lithuania	1.40	1.30	1.15	1.32	1.19	1.35	1.27
Bahamas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trinidad and Tobago	1.09	1.07	0.95	1.10	1.01	1.14	1.11
Italy	51.48	52.69	53.43	52.08	51.73	49.21	43.97
Latvia	1.63	1.50	1.34	1.51	1.37	1.52	1.40

Spain	28.55	30.49	32.68	30.19	31.77	28.38	26.69
Mauritius	0.00	0.00	0.91	0.94	0.96	0.95	1.01
Japan	0.00	101.78	94.58	100.15	90.34	96.05	79.43
Denmark	0.00	4.41	4.85	4.35	4.70	4.07	3.90
Oman	0.00	4.13	4.82	4.39	5.53	4.18	5.18
Croatia	0.00	2.06	1.98	2.06	1.99	2.01	1.87
Malaysia	0.00	0.00	31.07	0.00	33.74	0.00	37.03
Panama	0.00	2.54	2.74	2.64	3.01	2.74	3.34
Venezuela	0.00	0.00	28.64	28.00	31.56	29.39	35.62
Libya	0.00	6.53	7.22	6.79	7.94	7.05	8.77
Argentina	0.00	18.61	18.84	0.00	20.59	0.00	23.36
Russia	0.00	17.50	16.61	17.72	17.32	17.54	16.99
Bulgaria	0.00	0.00	2.36	0.00	2.42	0.00	2.45
Saudi Arabia	0.00	0.00	22.64	19.01	24.74	19.00	25.59
Gabon	0.00	0.00	0.00	0.00	0.27	0.00	0.00
Iraq	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Brazil	0.00	0.00	95.06	0.00	0.00	0.00	0.00
Romania	0.00	0.00	2.10	0.00	2.15	0.00	0.00
Uruguay	0.00	0.00	2.46	0.00	2.66	0.00	3.04
Malta	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Portugal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Costa Rica	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Greece	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cuba	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chile	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Albania	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bosnia and Herzegovina	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lebanon	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Turkey	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Colombia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
South Africa	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dominican Republic	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cyprus	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iran	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Suriname	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jamaica	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ukraine	0.00	0.00	0.00	0.00	0.00	0.00	0.00
New Caledonia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Indonesia	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Ecuador	0.00	0.00	0.00	0.00	0.00	0.00	0.00
St. Vincent and the Grenadines	0.00	0.00	0.00	0.00	0.00	0.00	0.00
China	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Egypt	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Belize	0.00	0.00	0.00	0.00	0.00	0.00	0.00
French Polynesia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
St. Lucia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peru	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Angola	0.00	0.00	0.00	0.00	0.00	0.00	0.00
El Salvador	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tunisia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Algeria	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Morocco	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Congo, Rep	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Syria	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Guatemala	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thailand	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Georgia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Papua New Guinea	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Guyana	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Honduras	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jordan	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Philippines	0.00	0.00	0.00	0.00	0.00	0.00	0.00
East Timor	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Myanmar	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Namibia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sri Lanka	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nicaragua	0.00	0.00	0.00	0.00	0.00	0.00	0.00
India	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maldives	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pakistan	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pakistan	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fiji	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Djibouti	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nigeria	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cameroon	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gambia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sudan	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cote D'Ivoire	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Kenya	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Benin	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tanzania	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mauritania	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Guinea	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sierra Leone	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mozambique	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bangladesh	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Togo	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vietnam	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Guinea Bissau	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cape Verde	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Haiti	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tonga	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vanuatu	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Samoa	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ghana	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cambodia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Madagascar	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Senegal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Yemen	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sao Tome and Principe	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Comoros	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solomon Island	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aruba	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table C3 Feasibility index (F_i) in 2015, 2030 and 2050 under three SSPs. ($F_\mathrm{i} = W_\mathrm{p}/C_\mathrm{p}$). Red numbers indicate feasibility index in major countries using SWRO.

Country		SSP1		SSP2		SSP3	
	2015	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Congo Dem. Rep.	NA	0.27	0.79	0.18	0.48	0.16	0.40
Eritrea	NA	0.08	0.26	NA	0.08	NA	NA
Liberia	NA	0.29	0.83	0.19	0.50	0.17	0.28
Qatar	3.19	4.02	4.98	4.39	5.11	4.50	4.68
Barbados	3.07	3.37	4.92	3.51	5.06	1.68	1.83
Norway	2.68	3.36	4.44	3.29	4.14	3.30	3.79
Brunei	2.66	3.81	5.22	3.71	5.06	3.50	3.99
Singapore	2.44	3.18	3.91	3.40	4.24	3.25	3.46
Netherlands	2.15	2.76	3.88	2.73	3.91	2.64	3.30
Canada	2.13	2.78	3.85	2.84	3.94	2.84	4.16
Kuwait	2.12	2.75	4.15	2.83	3.89	2.93	3.80
Ireland	2.09	2.68	3.54	2.65	3.63	2.58	3.15
Sweden	2.08	2.74	3.81	2.69	3.76	2.63	3.30
Germany	2.04	2.59	3.66	2.54	3.58	2.48	3.11
United States of America	2.01	2.59	3.40	2.67	3.39	2.61	3.03
Belgium	1.99	2.55	3.64	2.53	3.71	2.47	3.18
Iceland	1.98	2.75	4.18	2.70	4.09	2.63	3.53
Finland	1.97	2.54	3.58	2.48	3.50	2.44	3.10
United Kingdom	1.95	2.61	3.75	2.53	3.53	2.47	3.05
Equatorial Guinea	1.81	2.39	3.56	2.25	3.16	2.13	2.57
Australia	1.80	2.23	3.09	2.28	3.03	2.27	2.86
France	1.80	2.29	3.32	2.25	3.14	2.21	2.76
United Arab Emirates	1.71	2.23	3.31	2.30	3.11	2.35	2.75
New Zealand	1.60	2.11	3.36	2.06	3.04	2.04	2.73
Slovenia	1.41	2.20	3.14	2.17	3.16	2.13	2.77
South Korea	1.34	1.94	2.91	2.08	3.11	2.04	2.60
Puerto Rico	1.26	1.84	2.40	1.58	2.53	1.56	2.29
Bahrain	1.20	1.79	2.61	1.89	2.60	1.87	2.10
Estonia	1.20	2.11	3.29	2.07	3.35	2.03	2.90
Poland	1.17	1.99	2.93	1.94	2.84	1.91	2.51
Israel	1.14	1.50	2.37	1.59	2.32	1.63	2.05
Lithuania	1.13	1.92	2.90	1.85	2.70	1.53	2.21
Bahamas	1.11	1.42	2.01	1.47	1.88	1.49	1.70
Trinidad and Tobago	1.10	1.76	2.43	1.84	2.45	1.84	2.18
Italy	1.10	1.34	1.82	1.37	1.93	1.32	1.64
Latvia	1.03	1.85	3.00	1.48	2.58	1.47	2.15

Spain	1.00	1.20	1.56	1.23	1.68	1.19	1.43
Mauritius	0.99	1.19	1.96	1.29	2.08	1.34	1.95
Japan	0.98	1.23	1.50	1.30	1.67	1.23	1.47
Denmark	0.98	1.27	1.81	1.24	1.83	1.20	1.58
Oman	0.97	1.48	2.60	1.31	1.91	1.32	1.45
Croatia	0.97	1.34	2.44	1.29	2.17	1.26	1.54
Malaysia	0.89	1.45	3.14	1.34	2.72	1.28	2.12
Panama	0.87	2.03	3.75	1.92	3.24	1.79	2.50
Venezuela	0.87	1.06	1.71	1.14	1.46	1.19	1.54
Libya	0.85	1.43	1.98	1.53	1.97	1.60	1.68
Argentina	0.83	1.34	2.03	1.16	2.01	1.16	1.71
Russia	0.80	1.99	3.54	1.83	3.00	1.76	2.54
Bulgaria	0.78	1.47	3.18	1.37	2.69	1.31	2.12
Saudi Arabia	0.76	1.23	1.91	1.29	1.76	1.35	1.68
Gabon	0.76	1.24	2.57	1.10	2.14	0.98	1.29
Iraq	0.76	0.85	1.16	0.93	1.11	0.98	1.12
Brazil	0.74	1.14	2.38	1.07	1.47	1.05	1.19
Romania	0.74	1.26	2.76	1.17	2.18	1.13	1.44
Uruguay	0.73	1.01	1.98	1.05	1.87	1.06	1.62
Malta	0.66	1.12	1.81	1.06	1.72	1.01	1.41
Portugal	0.62	0.95	1.41	0.98	1.46	0.82	1.24
Costa Rica	0.62	1.11	2.46	1.00	1.99	0.95	1.25
Greece	0.61	1.06	1.68	1.01	1.60	0.97	1.30
Cuba	0.61	0.71	1.05	0.76	1.05	0.79	0.94
Chile	0.60	1.12	1.87	0.91	1.70	0.92	1.43
Mexico	0.60	0.76	1.56	0.83	1.47	0.86	1.04
Albania	0.60	0.84	1.42	0.79	1.19	0.79	1.06
Bosnia and Herzegovina	0.59	1.03	2.15	0.96	1.52	0.95	1.35
Lebanon	0.58	0.81	1.81	0.87	1.69	0.89	1.36
Turkey	0.54	0.77	1.65	0.80	1.48	0.81	0.99
Colombia	0.53	0.93	2.25	0.83	1.39	0.75	1.07
South Africa	0.53	0.68	1.17	0.78	1.32	0.83	1.02
Dominican Republic	0.53	0.95	2.15	0.86	1.40	0.81	1.09
Cyprus	0.49	0.65	1.16	0.56	0.78	0.56	0.69
Iran	0.48	0.61	1.01	0.69	1.01	0.73	0.94
Suriname	0.47	0.95	2.43	0.85	1.54	0.81	1.25
Jamaica	0.47	0.52	0.79	0.58	0.80	0.63	0.75
Ukraine	0.46	0.67	1.51	0.73	1.12	0.73	1.05
New Caledonia	0.45	0.98	1.61	0.78	1.12	0.64	0.98
Indonesia	0.45	0.82	2.37	0.71	1.35	0.71	1.12

Ecuador	0.44	0.53	1.22	0.59	0.91	0.63	0.82
St. Vincent and the Grenadines	0.43	0.64	1.33	0.63	0.89	0.66	0.82
China	0.42	1.23	2.42	0.86	1.83	0.89	1.49
Egypt	0.40	0.54	1.37	0.61	0.97	0.65	0.82
Belize	0.40	0.64	1.34	0.54	0.99	0.52	0.76
French Polynesia	0.40	0.58	1.15	0.43	0.59	0.44	0.54
St. Lucia	0.39	0.51	0.95	0.51	0.79	0.55	0.76
Peru	0.38	0.73	1.78	0.63	1.32	0.65	0.88
Angola	0.35	0.64	0.98	0.50	0.64	0.47	0.55
El Salvador	0.35	0.46	0.83	0.47	0.72	0.51	0.65
Tunisia	0.35	0.71	1.71	0.61	1.34	0.66	0.91
Algeria	0.34	0.53	0.88	0.45	0.62	0.50	0.53
Morocco	0.34	0.52	1.38	0.51	0.89	0.55	0.72
Congo, Rep	0.32	0.72	1.53	0.58	1.12	0.53	0.83
Syria	0.31	0.47	1.32	0.50	0.87	0.52	0.74
Guatemala	0.31	0.53	1.27	0.44	0.82	0.41	0.63
Thailand	0.29	0.60	1.60	0.51	1.20	0.52	0.73
Georgia	0.29	0.80	2.36	0.62	1.35	0.56	1.02
Papua New Guinea	0.29	0.47	1.19	0.40	0.80	0.39	0.69
Guyana	0.29	0.52	1.17	0.44	0.77	0.43	0.66
Honduras	0.28	0.48	1.16	0.40	0.77	0.40	0.62
Jordan	0.28	0.45	0.98	0.37	0.73	0.41	0.64
Philippines	0.28	0.36	0.69	0.34	0.51	0.38	0.48
East Timor	0.27	0.36	0.73	0.49	0.68	0.52	0.62
Myanmar	0.25	0.49	0.81	0.41	0.55	0.44	0.63
Namibia	0.25	0.39	0.72	0.33	0.57	0.38	0.57
Sri Lanka	0.25	0.51	1.22	0.40	0.72	0.44	0.62
Nicaragua	0.24	0.44	1.14	0.37	0.78	0.37	0.62
India	0.23	0.41	0.91	0.33	0.62	0.39	0.52
Maldives	0.22	0.38	0.79	0.30	0.54	0.35	0.53
Pakistan	0.20	0.31	0.50	0.24	0.36	0.30	0.38
Pakistan	0.20	0.31	0.50	0.24	0.36	0.30	0.38
Fiji	0.18	0.29	0.61	0.21	0.35	0.27	0.38
Djibouti	0.16	0.54	1.16	0.42	0.84	0.39	0.70
Nigeria	0.16	0.30	0.56	0.17	0.30	0.22	0.33
Cameroon	0.16	0.51	1.13	0.39	0.74	0.35	0.59
Gambia	0.15	0.49	1.00	0.37	0.69	0.33	0.56
Sudan	0.15	0.50	1.02	0.37	0.66	0.33	0.54
Cote D'Ivoire	0.15	0.57	1.46	0.43	1.04	0.38	0.68
Kenya	0.14	0.46	0.92	0.34	0.60	0.21	0.50

Benin	0.13	0.44	0.88	0.22	0.54	0.20	0.47
Tanzania	0.13	0.46	0.95	0.33	0.62	0.21	0.51
Mauritania	0.13	0.29	0.47	0.16	0.28	0.22	0.33
Guinea	0.12	0.58	1.58	0.41	0.99	0.34	0.61
Sierra Leone	0.12	0.30	0.82	0.20	0.53	0.18	0.30
Mozambique	0.12	0.31	0.92	0.21	0.56	0.19	0.47
Bangladesh	0.12	0.28	0.59	0.16	0.28	0.19	0.29
Togo	0.12	0.30	0.82	0.20	0.50	0.18	0.29
Vietnam	0.10	0.25	0.68	0.18	0.41	0.22	0.36
Guinea Bissau	0.08	0.15	0.44	0.10	0.25	0.10	0.24
Cape Verde	0.08	0.20	0.52	0.13	0.27	0.18	0.30
Haiti	0.07	0.22	0.53	0.09	0.26	0.10	0.25
Tonga	0.07	0.17	0.48	0.09	0.21	0.14	0.25
Vanuatu	0.07	0.19	0.60	0.10	0.29	0.15	0.28
Samoa	0.07	0.18	0.46	0.09	0.21	0.15	0.24
Ghana	0.07	0.22	0.54	0.10	0.22	0.14	0.23
Cambodia	0.06	0.24	0.72	0.11	0.28	0.15	0.26
Madagascar	0.06	0.12	0.36	0.08	0.19	0.08	0.12
Senegal	0.06	0.19	0.47	0.08	0.18	0.08	0.20
Yemen	0.05	0.14	0.36	0.07	0.16	0.09	0.22
Sao Tome and Principe	0.05	0.33	1.13	0.18	0.49	0.22	0.45
Comoros	0.04	0.11	0.39	0.06	0.16	0.06	0.10
Solomon Island	0.04	0.14	0.45	0.06	0.18	0.11	0.22
Aruba	0.03	0.17	0.48	0.05	0.16	0.09	0.20

Table C4 Desalination population (million capita) in 2015, 2030 and 2050 under three SSPs. ($F_i = W_{p/}C_p$).

Country		SSP1		SSP2		SSP3	
	2015	2030	2050	2030	2050	2030	2050
Congo Dem. Rep.	3.66	0.00	0.00	0.00	0.00	0.00	0.00
Eritrea	5.81	0.00	0.00	8.27	0.00	8.26	11.63
Liberia	2.74	0.00	0.00	0.00	0.00	0.00	0.00
Qatar	1.73	2.39	2.87	2.45	3.05	2.24	2.68
Barbados	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Norway	3.70	4.35	5.20	4.31	5.07	3.95	4.04
Brunei	0.43	0.50	0.55	0.53	0.62	0.52	0.62
Singapore	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Netherlands	13.98	14.84	15.68	14.68	15.19	13.91	12.95
Canada	11.33	13.16	15.40	13.03	14.97	11.91	11.80
Kuwait	2.83	3.82	4.83	3.95	5.25	3.74	4.84
Ireland	4.34	5.05	5.92	5.01	5.76	4.68	4.82
Sweden	5.80	6.58	7.62	6.50	7.40	5.98	5.96
Germany	15.47	15.58	15.55	15.36	14.94	14.55	12.64
United States of America	117.57	132.13	149.17	131.26	146.23	122.88	122.17
Belgium	12.21	13.20	14.37	13.03	13.89	12.22	11.59
Iceland	0.20	0.24	0.30	0.24	0.29	0.22	0.24
Finland	4.10	4.41	4.76	4.35	4.60	4.09	3.85
United Kingdom	49.34	54.27	60.22	53.82	58.88	50.56	49.49
Equatorial Guinea	0.19	0.26	0.32	0.27	0.35	0.27	0.36
Australia	19.12	23.52	28.96	23.40	28.52	21.24	22.53
France	24.95	27.30	30.19	27.04	29.37	25.57	25.10
United Arab Emirates	3.01	4.23	5.15	4.33	5.49	3.96	4.74
New Zealand	4.17	4.80	5.47	4.78	5.37	4.48	4.54
Slovenia	2.20	2.30	2.40	2.27	2.33	2.14	1.95
South Korea	48.64	50.02	48.09	49.42	45.98	47.80	41.04
Puerto Rico	2.53	2.84	3.21	2.82	3.14	2.64	2.61
Bahrain	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Estonia	1.24	1.22	1.21	1.21	1.17	1.16	1.02
Poland	6.38	6.36	6.06	6.29	5.85	6.05	5.17
Israel	7.23	9.10	10.98	9.30	11.50	9.33	11.79
Lithuania	1.40	1.30	1.15	1.32	1.19	1.35	1.27
Bahamas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trinidad and Tobago	1.09	1.07	0.95	1.10	1.01	1.14	1.11
Italy	51.48	52.69	53.43	52.08	51.73	49.21	43.97
Latvia	1.63	1.50	1.34	1.51	1.37	1.52	1.40

Spain	28.55	30.49	32.68	30.19	31.77	28.38	26.69
Mauritius	0.00	0.91	0.91	0.94	0.96	0.95	1.01
Japan	0.00	101.78	94.58	100.15	90.34	96.05	79.43
Denmark	0.00	4.41	4.85	4.35	4.70	4.07	3.90
Oman	0.00	4.13	4.82	4.39	5.53	4.18	5.18
Croatia	0.00	2.06	1.98	2.06	1.99	2.01	1.87
Malaysia	0.00	28.11	31.07	29.09	33.74	30.13	37.03
Panama	0.00	2.54	2.74	2.64	3.01	2.74	3.34
Venezuela	0.00	26.88	28.64	28.00	31.56	29.39	35.62
Libya	0.00	6.53	7.22	6.79	7.94	7.05	8.77
Argentina	0.00	18.61	18.84	19.25	20.59	20.16	23.36
Russia	0.00	17.50	16.61	17.72	17.32	17.54	16.99
Bulgaria	0.00	2.58	2.36	2.60	2.42	2.61	2.45
Saudi Arabia	0.00	18.33	22.64	19.01	24.74	19.00	25.59
Gabon	0.00	0.22	0.25	0.23	0.27	0.00	0.29
Iraq	0.00	0.00	5.30	0.00	6.07	0.00	7.46
Brazil	0.00	95.48	95.06	98.57	102.57	101.95	112.21
Romania	0.00	2.37	2.10	2.40	2.15	2.45	2.27
Uruguay	0.00	2.66	2.46	2.74	2.66	2.88	3.04
Malta	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Portugal	0.00	0.00	10.15	0.00	9.88	0.00	8.29
Costa Rica	0.00	5.46	5.91	5.66	6.45	0.00	6.80
Greece	0.00	8.94	9.01	8.83	8.71	0.00	7.60
Cuba	0.00	0.00	6.12	0.00	6.26	0.00	0.00
Chile	0.00	17.71	17.82	0.00	18.97	0.00	20.30
Mexico	0.00	0.00	35.53	0.00	39.40	0.00	45.93
Albania	0.00	0.00	3.73	0.00	3.90	0.00	4.25
Bosnia and Herzegovina	0.00	2.41	2.18	0.00	2.22	0.00	2.24
Lebanon	0.00	0.00	4.63	0.00	4.90	0.00	5.15
Turkey	0.00	0.00	45.83	0.00	50.28	0.00	0.00
Colombia	0.00	0.00	19.64	0.00	21.60	0.00	24.39
South Africa	0.00	0.00	14.22	0.00	14.41	0.00	14.17
Dominican Republic	0.00	0.00	9.21	0.00	10.29	0.00	12.30
Cyprus	0.00	0.00	2.22	0.00	0.00	0.00	0.00
Iran	0.00	0.00	36.22	0.00	38.93	0.00	0.00
Suriname	0.00	0.00	0.76	0.00	0.82	0.00	0.90
Jamaica	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ukraine	0.00	0.00	12.88	0.00	13.36	0.00	13.29
New Caledonia	0.00	0.00	0.11	0.00	0.11	0.00	0.00
Indonesia	0.00	0.00	218.15	0.00	231.45	0.00	247.25

Ecuador	0.00	0.00	10.92	0.00	0.00	0.00	0.00
St. Vincent and the Grenadines	0.00	0.00	0.09	0.00	0.00	0.00	0.00
China	0.00	347.05	313.11	0.00	323.00	0.00	333.95
Egypt	0.00	0.00	50.29	0.00	0.00	0.00	0.00
Belize	0.00	0.00	0.41	0.00	0.00	0.00	0.00
French Polynesia	0.00	0.00	0.18	0.00	0.00	0.00	0.00
St. Lucia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peru	0.00	0.00	15.64	0.00	17.20	0.00	0.00
Angola	0.00	0.00	0.00	0.00	0.00	0.00	0.00
El Salvador	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tunisia	0.00	0.00	10.34	0.00	10.96	0.00	0.00
Algeria	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Morocco	0.00	0.00	23.52	0.00	0.00	0.00	0.00
Congo, Rep	0.00	0.00	3.65	0.00	4.02	0.00	0.00
Syria	0.00	0.00	36.27	0.00	0.00	0.00	0.00
Guatemala	0.00	0.00	21.65	0.00	0.00	0.00	0.00
Thailand	0.00	0.00	46.62	0.00	48.84	0.00	0.00
Georgia	0.00	0.00	1.13	0.00	1.17	0.00	1.41
Papua New Guinea	0.00	0.00	6.05	0.00	0.00	0.00	0.00
Guyana	0.00	0.00	0.66	0.00	0.00	0.00	0.00
Honduras	0.00	0.00	9.39	0.00	0.00	0.00	0.00
Jordan	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Philippines	0.00	0.00	0.00	0.00	0.00	0.00	0.00
East Timor	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Myanmar	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Namibia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sri Lanka	0.00	0.00	11.70	0.00	0.00	0.00	0.00
Nicaragua	0.00	0.00	6.05	0.00	0.00	0.00	0.00
India	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maldives	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pakistan	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pakistan	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fiji	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Djibouti	0.00	0.00	0.95	0.00	0.00	0.00	0.00
Nigeria	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cameroon	0.00	0.00	14.41	0.00	0.00	0.00	0.00
Gambia	0.00	0.00	0.94	0.00	0.00	0.00	0.00
Sudan	0.00	0.00	2.82	0.00	0.00	0.00	0.00
Cote D'Ivoire	0.00	0.00	16.30	0.00	18.53	0.00	0.00
Kenya	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Benin	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tanzania	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mauritania	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Guinea	0.00	0.00	1.98	0.00	0.00	0.00	0.00
Sierra Leone	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mozambique	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bangladesh	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Togo	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vietnam	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Guinea Bissau	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cape Verde	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Haiti	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tonga	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vanuatu	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Samoa	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ghana	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cambodia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Madagascar	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Senegal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Yemen	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sao Tome and Principe	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Comoros	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solomon Island	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aruba	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Reference

1. Ahmed, M. and Anwar, R. An assessment of the environmental impact of brine disposal in marine environment. *International Journal of Modern engineering Research* **2012**, *2*, 2756-2761.
2. Aidam, P. W. The impact of water-pricing policy on the demand for water resources by farmers in Ghana. *Agricultural Water Management* **2015**, *158*, 10-16.
3. Al-Karaghouli, A. and Kazmerski, L. L. Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. *Renewable and Sustainable Energy Reviews* **2013**, *24*, 343-356.
4. Al-Sahali, M. and Ettouney, H. Developments in thermal desalination processes: Design, energy, and costing aspects. *Desalination* **2007**, *214*, 227-240.
5. Al-Sahlawi and Abdulaziz, M. Seawater desalination in Saudi Arabia: economic review and demand projections. *Desalination* **1999**, *123*, 143-147.
6. Alcamo, J., FlÖRke, M. and MÄRker, M. Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrological Sciences Journal* **2007**, *52*, 247-275.
7. Alexander, Q., Christine, S., Kevin, F. and Vanessa, L. *National Economic & Labor Impacts of the Water Utility Sector: Technical Report*; San Francisco, 2014.
8. Ali, E. S., Alsaman, A. S., Harby, K., Askalany, A. A., Diab, M. R. and Ebrahim Yakoot, S. M. Recycling brine water of reverse osmosis desalination employing adsorption desalination: A theoretical simulation. *Desalination* **2017**, *408*, 13-24.
9. Ali, M. K. and Klein, K. K. Water Use Efficiency and Productivity of the Irrigation Districts in Southern Alberta. *Water Resources Management* **2014**, *28*, 2751-2766.
10. Amores, M. J., Meneses, M., Pasqualino, J., Antón, A. and Castells, F. Environmental assessment of urban water cycle on Mediterranean conditions by LCA approach. *Journal of Cleaner Production* **2013**, *43*, 84-92.
11. Angelakis, A. N. and Durham, B. Water recycling and reuse in EUREAU countries: Trends and challenges. *Desalination* **2008**, *218*, 3-12.
12. Apichitchat, S. and Jung, K. Hydrological simulation for impact assessment of Kaeng Sue Ten dam in Thailand. *KSCE Journal of Civil Engineering* **2015**, *19*, 2325-2332.
13. Arbués, F., Barberan, R. and Villanua, I. Price impact on urban residential water demand: A dynamic panel data approach. *Water Resources Research* **2004**, *40*.
14. Arnal, J. M., Sancho, M., Iborra, I., Gozálvez, J. M., Santafé, A. and Lora, J.

Concentration of brines from RO desalination plants by natural evaporation. *Desalination* **2005**, *182*, 435-439.

15. Arnell, N. W. Climate change and global water resources. *Global Environmental Change* **1999**, *9*, S31-S49.
16. Asmild, M., Paradi, J. C., Aggarwall, V. and Schaffnit, C. Combining DEA window analysis with the Malmquist index approach in a study of the Canadian banking industry. *Journal of Productivity Analysis* **2004**, *21*, 67-89.
17. Azad, M. A. S., Ancev, T. and Hernández-Sancho, F. Efficient Water Use for Sustainable Irrigation Industry. *Water Resources Management* **2015**, *29*, 1683-1696.
18. Balkhair, K. S., Ismail, S. M., El-Nakhlawy, F. S. and Al-Solaimani, S. G. Impact of wastewater irrigation on the yield and quality of white radish under arid environment. *Life Sci. J* **2014**, *11*, 246-254.
19. World Bank. Available online: http://databank.worldbank.org/data/home.aspx (29 June 2016).
20. Banker, R. D., Charnes, A. and Cooper, W. W. Some Models for Estimating Technical and Scale Inefficiencies in Data Envelopment Analysis. *Management Science* **1984**, *30*, 1078-1092.
21. Barnes, J. Mixing waters: The reuse of agricultural drainage water in Egypt. *Geoforum* **2014**, *57*, 181-191.
22. Berrittella, M., Rehdanz, K., Roson, R. and Tol, R. S. J. The Economic Impact of Water Taxes: A Computable General Equilibrium Analysis with an International Data Set *Water Policy* **2008**, *10*, 259-271.
23. Bhatia, R., Rogers, P. and Huber, A. *Water as a social and economic good : how to put the principle into practice*. Global Water Partnership (GWP): Stockholm, Sweden, 1998.
24. Blanke, A., Rozelle, S., Lohmar, B., Wang, J. and Huang, J. Water saving technology and saving water in China. *Agricultural Water Management* **2007**, *87*, 139-150.
25. Blazkova, S. and Beven, K. Flood frequency estimation by continuous simulation of subcatchment rainfalls and discharges with the aim of improving dam safety assessment in a large basin in the Czech Republic. *Journal of Hydrology* **2004**, *292*, 153-172.
26. Blum, A. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. *Field Crops Research* **2009**, *112*, 119-123.

27. Bouman, B. A. M. A conceptual framework for the improvement of crop water productivity at different spatial scales. *Agricultural Systems* **2007**, *93*, 43-60.
28. Bremere, I., Kennedy, M., Stikker, A. and Schippers, J. How water scarcity will effect the growth in the desalination market in the coming 25 years. *Desalination* **2001**, *138*, 7-15.
29. Budhu, M. and Adiyaman, I. The influence of clay zones on land subsidence from groundwater pumping. *Groundwater* **2013**, *51*, 51-57.
30. China Water Resources Bulletin. Available online: http://www.mwr.gov.cn/sj/tjgb/szygb/ (9 September 2014).
31. Caldera, U., Bogdanov, D. and Breyer, C. Local cost of seawater RO desalination based on solar PV and wind energy: A global estimate. *Desalination* **2016**, *385*, 207-216.
32. CDM. *Water supply cost estimation study*; South Florida Water Management District: 2007.
33. Charnes, A., Cooper, W. W. and Rhodes, E. Measuring the efficiency of decision making units. *European Journal of Operational Research* **1978**, *2*, 429-444.
34. Chen, S., Wang, Y. and Zhu, T. Exploring China's farmer-level water-saving mechanisms: analysis of an experiment conducted in Taocheng district, Hebei province. *Water* **2014**, *6*, 547-563.
35. Choi, Y., Cho, H., Shin, Y., Jang, Y. and Lee, S. Economic Evaluation of a Hybrid Desalination System Combining Forward and Reverse Osmosis. *Membranes* **2016**, *6*, 3.
36. Cooley, H., Ajami, N. and Heberger, M. Key issues in seawater desalination in California: marine impacts. *Pacific Institute Oakland, CA* **2013**, *32*.
37. Cooper, W. W., Seiford, L. M. and Tone, K. *Data Envelopment Analysis: A Comprehensive Text with Models, Applications, References and DEA-Solver Software*. Springer US: 2007.
38. Shared Socioeconomic Pathway (SSP) Database. Available online: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about (18 October 2016).
39. Deng, G., Li, L. and Song, Y. Provincial water use efficiency measurement and factor analysis in China: Based on SBM-DEA model. *Ecological Indicators* **2016**, *69*, 12-18.
40. Deng, X.-P., Shan, L., Zhang, H. and Turner, N. C. Improving agricultural water use efficiency in arid and semiarid areas of China. *Agricultural Water Management* **2006**, *80*, 23-40.

41. DeNicola, E., Aburizaiza, O. S., Siddique, A., Khwaja, H. and Carpenter, D. O. Climate Change and Water Scarcity: The Case of Saudi Arabia. *Annals of Global Health* **2015**, *81*, 342-353.

42. DesalData. Available online: http://www.desaldata.com/ (5 October 2015).

43. Döll, P. Impact of Climate Change and Variability on Irrigation Requirements: A Global Perspective. *Climatic Change* **2002**, *54*, 269-293.

44. Doppler, W., Salman, A. Z., Al-Karablieh, E. K. and Wolff, H.-P. The impact of water price strategies on the allocation of irrigation water: the case of the Jordan Valley. *Agricultural Water Management* **2002**, *55*, 171-182.

45. Dore, M. H. I. Forecasting the economic costs of desalination technology. *Desalination* **2005**, *172*, 207-214.

46. Elimelech, M. and Phillip, W. A. The future of seawater desalination: energy, technology, and the environment. *science* **2011**, *333*, 712-717.

47. Erie, L. J. Management: A Key to Irrigation Efficiency. *Irrigation and Drainage Division* **1968**, *94*, 285-294.

48. Falkenmark, M. The Massive Water Scarcity Now Threatening Africa: Why Isn't It Being Addressed? *Ambio* **1989**, *18*, 112-118.

49. Famiglietti, J., Lo, M., Ho, S., Bethune, J., Anderson, K., Syed, T., Swenson, S., De Linage, C. and Rodell, M. Satellites measure recent rates of groundwater depletion in California's Central Valley. *Geophysical Research Letters* **2011**, *38*.

50. Fang, X., Roe, T. L. and Smith, R. B. W. Water shortages, intersectoral water allocation and economic growth: the case of China. *China Agricultural Economic Review* **2015**, *7*, 2-26.

51. Farrell, M. J. The Measurement of Productive Efficiency. *Journal of the Royal Statistical Society. Series A (General)* **1957**, *120*, 253-290.

52. Fonseca, C. R., Esteller, M. V. and Díaz-Delgado, C. Territorial approach to increased energy consumption of water extraction from depletion of a highlands Mexican aquifer. *Journal of environmental management* **2013**, *128*, 920-930.

53. Fritzmann, C., Löwenberg, J., Wintgens, T. and Melin, T. State-of-the-art of reverse osmosis desalination. *Desalination* **2007**, *216*, 1-76.

54. Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D. S., Dai, H., Hijioka, Y. and Kainuma, M. SSP3: AIM implementation of Shared Socioeconomic Pathways. *Global Environmental Change* **2017**, *42*, 268-283.

55. Gadanakis, Y., Bennett, R., Park, J. and Areal, F. J. Improving productivity and water use efficiency: A case study of farms in England. *Agricultural Water Management* **2015**, *160*, 22-32.

56. Garrido, S. Governing scarcity. Water markets, equity and efficiency in pre-1950s eastern Spain. *International Journal of the Commons* **2011**, *5*.

57. Ghaffour, N., Missimer, T. M. and Amy, G. L. Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability. *Desalination* **2013**, *309*, 197-207.

58. Gleeson, T., Wada, Y., Bierkens, M. F. and van Beek, L. P. Water balance of global aquifers revealed by groundwater footprint. *Nature* **2012**, *488*, 197-200.

59. Gleick, P., H. and Michael, J. C. *The world's Water 2008-2009*. Island press: Washington, 2009.

60. Gleick, P. H. Roadmap for sustainable water resources in southwestern North America. *Proceedings of the National Academy of Sciences* **2010**, *107*, 21300-21305.

61. Glueckstern, P. Cost estimates of large RO systems. *Desalination* **1991**, *81*, 49-56.

62. Gorjian, S. and Ghobadian, B. Solar desalination: A sustainable solution to water crisis in Iran. *Renewable and Sustainable Energy Reviews* **2015**, *48*, 571-584.

63. Gosling, S. N. and Arnell, N. W. A global assessment of the impact of climate change on water scarcity. *Climatic Change* **2016**, *134*, 371-385.

64. Green, N. and MacQuarrie, K. An evaluation of the relative importance of the effects of climate change and groundwater extraction on seawater intrusion in coastal aquifers in Atlantic Canada. *Hydrogeology Journal* **2014**, *22*, 609-623.

65. Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B. and Moulin, P. Reverse osmosis desalination: water sources, technology, and today's challenges. *Water research* **2009**, *43*, 2317-2348.

66. Guan, D., Zhang, Y., Al-Kaisi, M. M., Wang, Q., Zhang, M. and Li, Z. Tillage practices effect on root distribution and water use efficiency of winter wheat under rain-fed condition in the North China Plain. *Soil and Tillage Research* **2015**, *146*, 286-295.

67. Gupta, N., Pilesjo, P. and Maathuis, B. Use of geoinformatics for inter-basin water transfer assessment. *Water Resources* **2010**, *37*, 623-637.

68. Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y. and Schewe, J. Global water resources affected by human interventions and climate change. *Proceedings of the National Academy of Sciences* **2014**, *111*, 3251-3256.

69. Hamdy, A., Ragab, R. and Scarascia-Mugnozza, E. Coping with water scarcity: water saving and increasing water productivity. *Irrigation and Drainage* **2003**, *52*,

3-20.

70. Hamoda, M. F. Water strategies and potential of water reuse in the south Mediterranean countries. *Desalination* **2004**, *165*, 31-41.

71. Hanasaki, N., Fujimori, S., Yamamoto, T., Yoshikawa, S., Masaki, Y., Hijioka, Y., Kainuma, M., Kanamori, Y., Masui, T., Takahashi, K., *et al.* A global water scarcity assessment under Shared Socio-economic Pathways -Part 2: Water availability and scarcity. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 2393-2413.

72. Hanasaki, N., Yoshikawa, S., Kakinuma, K. and Kanae, S. A seawater desalination scheme for global hydrological models. *Hydrol. Earth Syst. Sci.* **2016**, *20*, 4143-4157.

73. Ho, M., Lall, U., Allaire, M., Devineni, N., Kwon, H. H., Pal, I., Raff, D. and Wegner, D. The future role of dams in the United States of America. *Water Resources Research* **2017**, *53*, 982-998.

74. Huang, Q., Rozelle, S., Howitt, R., Wang, J. and Huang, J. Irrigation water demand and implications for water pricing policy in rural China. *Environment and Development Economics* **2010**, *15*, 293-319.

75. Hunter, P. R., MacDonald, A. M. and Carter, R. C. Water Supply and Health. *PLoS Medicine* **2010**, *7*, e1000361.

76. IBNET tariff database. Available online: https://tariffs.ib-net.org/ (27 May 2017).

77. IEA database. Available online: http://www.iea.org/statistics/ (9 May 2017).

78. Iglesias, R., Ortega, E., Batanero, G. and Quintas, L. Water reuse in Spain: Data overview and costs estimation of suitable treatment trains. *Desalination* **2010**, *263*, 1-10.

79. Ingman, M., Santelmann, M. V. and Tilt, B. Agricultural water conservation in China: plastic mulch and traditional irrigation. *Ecosystem Health and Sustainability* **2015**, *1*, 1-11.

80. Jiang, Y. China's water scarcity. *Journal of Environmental Management* **2009**, *90*, 3185-3196.

81. Jiang, Y. Adoption of Surface Pipe and Underground Pipe for Water Saving in North China - Impacts and Determinants. In *2013 Third International Conference on Intelligent System Design and Engineering Applications*, 2013; pp 216-221.

82. Karagiannis, I. C. and Soldatos, P. G. Water desalination cost literature: review and assessment. *Desalination* **2008**, *223*, 448-456.

83. Keller, A. A. and Keller, J. *Effective efficiency: A water use efficiency concept for allocating freshwater resources*. Center for Economic Policy Studies, Winrock International Arlington: 1995.

84. Kesieme, U. K., Milne, N., Aral, H., Cheng, C. Y. and Duke, M. Economic analysis of desalination technologies in the context of carbon pricing, and opportunities for membrane distillation. *Desalination* **2013**, *323*, 66-74.

85. Kim, S. H., Hejazi, M., Liu, L., Calvin, K., Clarke, L., Edmonds, J., Kyle, P., Patel, P., Wise, M. and Davies, E. Balancing global water availability and use at basin scale in an integrated assessment model. *Climatic Change* **2016**, *136*, 217-231.

86. Kirshen, P. *Adaptation Options and Cost in Water Supply*; Tufts University: USA, 2007.

87. Kriegler, E., O'Neill, B. C., Hallegatte, S., Kram, T., Lempert, R. J., Moss, R. H. and Wilbanks, T. The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways. *Global Environmental Change* **2012**, *22*, 807-822.

88. Kummu, M., Guillaume, J. H. A., de Moel, H., Eisner, S., Flörke, M., Porkka, M., Siebert, S., Veldkamp, T. I. E. and Ward, P. J. The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. *Scientific Reports* **2016**, *6*, 38495.

89. Kundzewicz Zbigniew, W. and Gerten, D. Grand Challenges Related to the Assessment of Climate Change Impacts on Freshwater Resources. *Journal of Hydrologic Engineering* **2015**, *20*, A4014011.

90. Kundzewicz, Z. W. and Dieter, G. Grand Challenges Related to the Assessment of Climate Change Impacts on Freshwater Resources. *Journal of Hydrologic Engineering* **2015**, *20*.

91. Lamei, A., Van der Zaag, P. and Von Münch, E. Basic cost equations to estimate unit production costs for RO desalination and long-distance piping to supply water to tourism-dominated arid coastal regions of Egypt. *Desalination* **2008**, *225*, 1-12.

92. Laspidou, C., Hadjibiros, K. and Gialis, S. Minimizing the environmental impact of sea brine disposal by coupling desalination plants with solar saltworks: a case study for Greece. *Water* **2010**, *2*, 75-84.

93. Li, L., Wu, X. and Tang, Y. Adoption of increasing block tariffs (IBTs) among urban water utilities in major cities in China. *Urban Water Journal* **2017**, *14*, 661-668.

94. Li, N., Wang, X., Shi, M. and Yang, H. Economic Impacts of Total Water Use Control in the Heihe River Basin in Northwestern China—An Integrated CGE-BEM Modeling Approach. *Sustainability* **2015**, *7*, 3460.

95. Linda, J., Reekie. *Electricity Use and Management in the Municipal Water Supply and Wastewater Industries*; California, 2013.

96. Liu, J., Zang, C., Tian, S., Liu, J., Yang, H., Jia, S., You, L., Liu, B. and Zhang, M. Water conservancy projects in China: Achievements, challenges and way forward. *Global Environmental Change* **2013**, *23*, 633-643.
97. Long, K. and Pijanowski, B. C. Is there a relationship between water scarcity and water use efficiency in China? A national decadal assessment across spatial scales. *Land Use Policy* **2017**, *69*, 502-511.
98. Loutatidou, S., Chalermthai, B., Marpu, P. R. and Arafat, H. A. Capital cost estimation of RO plants: GCC countries versus southern Europe. *Desalination* **2014**, *347*, 103-111.
99. Ma, J., Hoekstra, A. Y., Wang, H., Chapagain, A. K. and Wang, D. Virtual versus real water transfers within China. *Philosophical Transactions of the Royal Society B: Biological Sciences* **2006**, *361*, 835-842.
100. Macedonio, F., Curcio, E. and Drioli, E. Integrated membrane systems for seawater desalination: energetic and exergetic analysis, economic evaluation, experimental study. *Desalination* **2007**, *203*, 260-276.
101. Mamitimin, Y., Feike, T., Seifert, I. and Doluschitz, R. Irrigation in the Tarim Basin, China: farmers' response to changes in water pricing practices. *Environmental Earth Sciences* **2015**, *73*, 559-569.
102. March, H., Saurí, D. and Rico-Amorós, A. M. The end of scarcity? Water desalination as the new cornucopia for Mediterranean Spain. *Journal of Hydrology* **2014**, *519, Part C*, 2642-2651.
103. Mays, L. W. Groundwater Resources Sustainability: Past, Present, and Future. *Water Resources Management* **2013**, *27*, 4409-4424.
104. McKenzie, D. and Ray, I. Urban water supply in India: status, reform options and possible lessons. *Water Policy* **2009**, *11*, 442-460.
105. Mei, X., Van Gelder, P. H. A. J. M., Dai, Z. and Tang, Z. Impact of dams on flood occurrence of selected rivers in the United States. *Frontiers of Earth Science* **2017**, *11*, 268-282.
106. Miller, S., Shemer, H. and Semiat, R. Energy and environmental issues in desalination. *Desalination* **2015**, *366*, 2-8.
107. Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A. and Kijne, J. Improving agricultural water productivity: Between optimism and caution. *Agricultural Water Management* **2010**, *97*, 528-535.
108. Moore, B. C., Coleman, A. M., Wigmosta, M. S., Skaggs, R. L. and Venteris, E. R. A High Spatiotemporal Assessment of Consumptive Water Use and Water Scarcity in the Conterminous United States. *Water Resources Management* **2015**,

29, 5185-5200.

109. Morillo, J., Usero, J., Rosado, D., El Bakouri, H., Riaza, A. and Bernaola, F.-J. Comparative study of brine management technologies for desalination plants. *Desalination* **2014**, *336*, 32-49.

110. Mu, L., Fang, L., Wang, H., Chen, L., Yang, Y., Qu, X. J., Wang, C. Y., Yuan, Y., Wang, S. B. and Wang, Y. N. Exploring northwestern China's agricultural water saving strategy: analysis of water use efficiency based on SE-DEA model conducted in Xi'an, Shaanxi province. *Water Science and Technology* **2016**.

111. Murakami, D. and Yamagata, Y. Estimation of gridded population and GDP scenarios with spatially explicit statistical downscaling. *arXiv:1610.09041* **2016**.

112. Nancarrow, B. E., Leviston, Z. and Tucker, D. Measuring the predictors of communities' behavioural decisions for potable reuse of wastewater. *Water Science and Technology* **2009**, *60*, 3199-3209.

113. Nation Bureau of Statistics of the People's Republic of China (NBS). Available online: http://www.stats.gov.cn/tjsj/ndsj/

114. NWC. *Emerging trends in desalination : a review*

National Water Commission: Canberra, A.C.T, 2008.

115. Oki, T. and Kanae, S. Global Hydrological Cycles and World Water Resources. *Science* **2006**, *313*, 1068-1072.

116. Olmstead, S. M. and Stavins, R. N. Comparing price and nonprice approaches to urban water conservation. *Water Resources Research* **2009**, *45*, n/a-n/a.

117. Ophir, A. and Manor, S. The Curacao KAE-LT-MED and auxiliary steam turbine project: A model for dual purpose MSF plants replacement. *Desalination* **1987**, *66*, 33-42.

118. Owusu, K., Obour, P. B. and Nkansah, M. A. Downstream effects of dams on livelihoods of river-dependent communities: the case of Ghana’s Kpong Dam. *Geografisk Tidsskrift-Danish Journal of Geography* **2017**, *117*, 1-10.

119. Papapetrou, M., Cipollina, A., La Commare, U., Micale, G., Zaragoza, G. and Kosmadakis, G. Assessment of methodologies and data used to calculate desalination costs. *Desalination* **2017**, *419*, 8-19.

120. Peñate, B. and García-Rodríguez, L. Current trends and future prospects in the design of seawater reverse osmosis desalination technology. *Desalination* **2012**, *284*, 1-8.

121. Pimentel, D., Berger, B., Filiberto, D., Newton, M., Wolfe, B., Karabinakis, E., Clark, S., Poon, E., Abbett, E. and Nandagopal, S. Water Resources: Agricultural and Environmental Issues. *BioScience* **2004**, *54*, 909-918.

122. Piper, S. Impact of water quality on municipal water price and residential water demand and implications for water supply benefits. *Water Resources Research* **2003**, *39*.

123. Postel, S. L., Daily, G. C. and Ehrlich, P. R. Human Appropriation of Renewable Fresh Water. *Science* **1996**, *271*, 785-788.

124. Qadir, M., Sharma, B. R., Bruggeman, A., Choukr-Allah, R. and Karajeh, F. Non-conventional water resources and opportunities for water augmentation to achieve food security in water scarce countries. *Agricultural Water Management* **2007**, *87*, 2-22.

125. Qin, Y., Yang, Z. and Yang, W. Ecological risk assessment for water scarcity in China's Yellow River Delta Wetland. *Stochastic Environmental Research and Risk Assessment* **2011**, *25*, 697.

126. Quist-Jensen, C., Macedonio, F. and Drioli, E. Membrane technology for water production in agriculture: Desalination and wastewater reuse. *Desalination* **2015**, *364*, 17-32.

127. Reddy, K. and Ghaffour, N. Overview of the cost of desalinated water and costing methodologies. *Desalination* **2007**, *205*, 340-353.

128. Ren, C., Guo, P., Yang, G., Li, R. and Liu, L. Spatial and Temporal Analyses of Water Resources Use Efficiency Based on Data Envelope Analysis and Malmquist Index: Case Study in Gansu Province, China. *Journal of Water Resources Planning and Management* **2016**, *142*, 04016066.

129. Renwick, M. E. and Archibald, S. O. Demand Side Management Policies for Residential Water Use: Who Bears the Conservation Burden? *Land Economics* **1998**, *74*, 343-359.

130. Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* **2017**, *42*, 153-168.

131. Riediger, J., Breckling, B., Nuske, R. S. and Schröder, W. Will climate change increase irrigation requirements in agriculture of Central Europe? A simulation study for Northern Germany. *Environmental Sciences Europe* **2014**, *26*, 18.

132. Rijsberman, F. R. Water scarcity: Fact or fiction? *Agricultural Water Management* **2006**, *80*, 5-22.

133. Rodell, M., Chen, J., Kato, H., Famiglietti, J. S., Nigro, J. and Wilson, C. R. Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE. *Hydrogeology Journal* **2007**, *15*, 159-166.

134. Rodríguez Díaz, J. A., Weatherhead, E. K., Knox, J. W. and Camacho, E. Climate change impacts on irrigation water requirements in the Guadalquivir river basin in Spain. *Regional Environmental Change* **2007**, *7*, 149-159.

135. Romano, G. and Guerrini, A. Measuring and comparing the efficiency of water utility companies: a data envelopment analysis approach. *Utilities Policy* **2011**, *19*, 202-209.

136. Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J. and Schaphoff, S. Agricultural green and blue water consumption and its influence on the global water system. *Water Resources Research* **2008**, *44*.

137. Rozin, P., Haddad, B., Nemeroff, C. and Slovic, P. Psychological aspects of the rejection of recycled water: Contamination, purification and disgust. *Judgment and Decision Making* **2015**, *10*, 50.

138. Ruester, S. and Zschille, M. The impact of governance structure on firm performance: An application to the German water distribution sector. *Utilities Policy* **2010**, *18*, 154-162.

139. Samuelson, P. A. and Nordhaus, W. D. *Economics*. Beijing: China Machine Press, 1997.

140. Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., Alley, W. M., McGuire, V. L. and McMahon, P. B. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences* **2012**, *109*, 9320-9325.

141. Schallenberg-Rodríguez, J., Veza, J. M. and Blanco-Marigorta, A. Energy efficiency and desalination in the Canary Islands. *Renewable and Sustainable Energy Reviews* **2014**, *40*, 741-748.

142. Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., Dankers, R., Eisner, S., Fekete, B. M., Colón-González, F. J., *et al.* Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences* **2014**, *111*, 3245-3250.

143. Seckler, D., Molden, D. J. and Sakthivadivel, R. *The concept of efficiency in water resources management and policy*. Sri Lanka: International Water Management Institute (IWMI)Comprehensive Assessment of Water Management in Agriculture Series 1: Colombo, 2003.

144. Semiat, R. Energy Issues in Desalination Processes. *Environmental Science & Technology* **2008**, *42*, 8193-8201.

145. Shao, W., Cai, J., Liu, J., Luan, Q., Mao, X., Yang, G., Wang, J., Zhang, H. and Zhang, J. Impact of Water Scarcity on the Fenhe River Basin and Mitigation

Strategies. *Water* **2017**, *9*, 30.

146. Shen, Y., Oki, T., Utsumi, N., Kanae, S. and Hanasaki, N. Projection of future world water resources under SRES scenarios: water withdrawal/Projection des ressources en eau mondiales futures selon les scénarios du RSSE: prélèvement d'eau. *Hydrological Sciences Journal* **2008**, *53*, 11-33.
147. Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., Döll, P. and Portmann, F. T. Groundwater use for irrigation – a global inventory. *Hydrol. Earth Syst. Sci.* **2010**, *14*, 1863-1880.
148. Speelman, S., D'Haese, M., Buysse, J. and D'Haese, L. A measure for the efficiency of water use and its determinants, a case study of small-scale irrigation schemes in North-West Province, South Africa. *Agricultural systems* **2008**, *98*, 31-39.
149. Srinivasan, V., Seto, K. C., Emerson, R. and Gorelick, S. M. The impact of urbanization on water vulnerability: A coupled human–environment system approach for Chennai, India. *Global Environmental Change* **2013**, *23*, 229-239.
150. Steffen, W., Grinevald, J., Crutzen, P. and McNeill, J. The Anthropocene: conceptual and historical perspectives. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* **2011**, *369*, 842-867.
151. Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V. and de Haan, C. *Livestock's long shadow: environmental issues and options*. Food & Agriculture Org.: 2006.
152. van Vuuren, D. P., Stehfest, E., den Elzen, M. G. J., Kram, T., van Vliet, J., Deetman, S., Isaac, M., Klein Goldewijk, K., Hof, A., Mendoza Beltran, A., *et al.* RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change* **2011**, *109*, 95.
153. Varghese, S. K., Veettil, P. C., Speelman, S., Buysse, J. and Van Huylenbroeck, G. Estimating the causal effect of water scarcity on the groundwater use efficiency of rice farming in South India. *Ecological Economics* **2013**, *86*, 55-64.
154. Vassolo, S. and Döll, P. Global‐scale gridded estimates of thermoelectric power and manufacturing water use. *Water Resources Research* **2005**, *41*.
155. Voss, K. A., Famiglietti, J. S., Lo, M., Linage, C., Rodell, M. and Swenson, S. C. Groundwater depletion in the Middle East from GRACE with implications for transboundary water management in the Tigris‐Euphrates‐Western Iran region. *Water resources research* **2013**, *49*, 904-914.
156. Wada, Y. and Bierkens, M. F. P. Sustainability of global water use: past reconstruction and future projections. *Environmental Research Letters* **2014**, *9*,

104003.

157. Wada, Y., van Beek, L. P. H. and Bierkens, M. F. P. Modelling global water stress of the recent past: on the relative importance of trends in water demand and climate variability. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 3785-3808.

158. Wada, Y., van Beek, L. P. H., van Kempen, C. M., Reckman, J. W. T. M., Vasak, S. and Bierkens, M. F. P. Global depletion of groundwater resources. *Geophysical Research Letters* **2010**, *37*, n/a-n/a.

159. Wang, R. and Zimmerman, J. Hybrid analysis of blue water consumption and water scarcity implications at the global, national, and basin levels in an increasingly globalized world. *Environmental science & technology* **2016**, *50*, 5143-5153.

160. Wang, X.-y. Irrigation Water Use Efficiency of Farmers and Its Determinants: Evidence from a Survey in Northwestern China. *Agricultural Sciences in China* **2010**, *9*, 1326-1337.

161. Wang, Y., Shi, L., Zhang, H. and Sun, S. A data envelopment analysis of agricultural technical efficiency of Northwest Arid Areas in China. *Front. Agr. Sci. Eng.* **2017**, *4*, 195-207.

162. Wang, Y., Xie, Z., Malhi, S. S., Vera, C. L., Zhang, Y. and Wang, J. Effects of rainfall harvesting and mulching technologies on water use efficiency and crop yield in the semi-arid Loess Plateau, China. *Agricultural Water Management* **2009**, *96*, 374-382.

163. Ward, F. A. and Pulido-Velazquez, M. Water conservation in irrigation can increase water use. *Proceedings of the National Academy of Sciences of the United States of America* **2008**, *105*, 18215-18220.

164. Willardson, L. S., Boels, D. and Smedema, L. K. Reuse of drainage water from irrigated areas. *Irrigation and Drainage Systems* **1997**, *11*, 215-239.

165. Xiao, G., Zheng, F., Qiu, Z. and Yao, Y. Impact of climate change on water use efficiency by wheat, potato and corn in semiarid areas of China. *Agriculture, Ecosystems & Environment* **2013**, *181*, 108-114.

166. Yoshikawa, S., Cho, J., Yamada, H. G., Hanasaki, N. and Kanae, S. An assessment of global net irrigation water requirements from various water supply sources to sustain irrigation: rivers and reservoirs (1960-2050). *Hydrol. Earth Syst. Sci.* **2014**, *18*, 4289-4310.

167. Zachariadis, T. Residential Water Scarcity in Cyprus: Impact of Climate Change and Policy Options. *Water* **2010**, *2*, 788.

168. Zhai, H. and Rubina, E. S. Carbon capture effects on water use at pulverized coal

power plants. *Energy Procedia* **2011**, *4*, 2238-2244.

169. Zhang, J., Ren, W., An, P., Pan, Z., Wang, L., Dong, Z., He, D., Yang, J., Pan, S. and Tian, H. Responses of Crop Water Use Efficiency to Climate Change and Agronomic Measures in the Semiarid Area of Northern China. *PLOS ONE* **2015**, *10*, e0137409.

170. Zhang, L., Yan, F., Wang, Z. and Shen, J. Analyzing the Spatial Correlation Between Regional Economic Level and Water-Use Efficiency in Jiangsu Province. In *Geo-Informatics in Resource Management and Sustainable Ecosystem: Third International Conference, GRMSE 2015, Wuhan, China, October 16-18, 2015, Revised Selected Papers*, Bian, F. and Xie, Y., Eds. Springer Berlin Heidelberg: Berlin, Heidelberg, 2016; pp 525-533.

171. Zhou, Q., Wu, F. and Zhang, Q. Is irrigation water price an effective leverage for water management? An empirical study in the middle reaches of the Heihe River basin. *Physics and Chemistry of the Earth, Parts A/B/C* **2015**, *89-90*, 25-32.

172. Zhou, Y. and Tol, R. S. J. Evaluating the costs of desalination and water transport. *Water Resources Research* **2005**, *41*.

173. Ziolkowska, J. R. Is Desalination Affordable?—Regional Cost and Price Analysis. *Water Resources Management* **2015**, *29*, 1385-1397.

174. Ziolkowska, J. R. Desalination leaders in the global market – current trends and future perspectives. *Water Science and Technology: Water Supply* **2016**.

175. Zotalis, K., Dialynas, E., Mamassis, N. and Angelakis, A. Desalination Technologies: Hellenic Experience. *Water* **2014**, *6*, 1134-1150.