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Key Points:
- A new framework is proposed to evaluate water security for food production
- Respective contribution of rainfall and irrigation to water security is distinguished
- Spatial patterns of China's water security for food production are investigated

Supporting Information:
- Supporting Information S1

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Evaluating China's Water Security for Food Production: The Role of Rainfall and Irrigation

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Abstract China's water stress and its pressure on food security is a widely recognized crisis. A framework is proposed and applied at the provincial level to evaluate China's water security for food production. It is based on a water stress index that accounts for the deficit between water supply and aggregate demand of 23 major field crops over the study period (1961–2015). The water demand is estimated based on method recommended by the Food and Agriculture Organization of the United Nations. The water supply is composed of rainfall and irrigation. Consequently, the water security of both rainfed and irrigated agriculture is evaluated in our research, and the respective contribution of rainfall and irrigation is distinguished. Suggestions regarding adjustment in irrigation investment and planting area are proposed for practical application. The framework also holds great potential to investigate the impact of climate change and the virtual water flow of crops.

Plain Language Summary With 7% of the world's arable land and 6% of its water resources, China has to feed 20% of the world's population. Consequently, China's water stress and its pressure on food security is a widely recognized crisis. A framework is proposed in our research to evaluate China's water security for food production. It is mainly designed to answer the following three questions critical to China's food security but have not been systematically addressed in the literature. How much water is required under China's current agriculture planting structure? What is the respective role of rainfall and irrigation in meeting this requirement? What is the status of water security for China's rainfed and irrigated agriculture? The above three questions are answered based on a water stress index that accounts for the deficit between water supply and aggregate demand of 23 major field crops over the study period (1961–2015). We have also proposed suggestions regarding water security for food production from the framework. For future use, our proposed framework lays the groundwork to investigate the virtual water flow of crops. Climate change signals can also be incorporated into this framework to inform climate-driven water risk for agriculture.

1. Introduction

With 7% of the world's arable land and 6% of its water resources, China has to feed 20% of the world's population (Hofstedt, 2010; Wang et al., 2018). As a result, food security in China is of great concern both domestically and internationally (Dalin et al., 2015; Huang et al., 2017; Khan et al., 2009; Lu et al., 2015). To achieve self-sufficiency in food production, the Chinese government has invested huge amounts in irrigation infrastructure to increase agricultural production (Wang et al., 2017). Now irrigation consumes the largest proportion of the country's water use (i.e., 55.4% in 2015). However, due to the growing competition from urban and industrial sectors, looming water shortages in China have still imposed a serious constraint on its food production. On the one hand, more food is required to sustain the growing population with rapid urbanization. On the other hand, the agricultural water exploitation has already induced serious ecological problems, so any increase in irrigation water use is not easy in the future (Cao et al., 2015; Du et al., 2014; Yu & Wu, 2018). Against this background, water security in China is considered as the basis for its food security (Kang et al., 2017).

Different concepts of water security have been proposed in previous studies (Cook & Bakker, 2012; Jiang, 2015; Rodrigues et al., 2014). Considering its linkage with food security, water security was defined by the Food and Agriculture Organization (FAO) of the United Nations as the ability to provide adequate and reliable water supplies for populations living in the world's drier areas to meet agricultural production needs (Clarke, 1993). Consequently, crop yield was adopted as the indicator of food production in most previous studies (Davis et al., 2017; Liu et al., 2009; Rajagopalan et al., 2018). However, crop yield is the product of multiple factors such as water availability, pesticides, fertilizers, and tillage technique. As a result, it is usually difficult to distinguish the net effect of water availability on food production in the above concept. Besides, crop yield is only available on the annual scale. Detailed information on water availability for food production during the growing period is usually neglected in previous studies. Another critical question involved in the above concept is how much food we need. Its answer is widely open, especially for countries like China with a huge population and significant regional differences (Brown, 1995; Huang & Tian, 2019; Jalava et al., 2016; Lam et al., 2013). Motivated by the above three issues, this paper is intended to evaluate China's water security for food production from a new perspective. Water demand during the growing period is adopted as the indicator of food production. Accordingly, water security for food production is defined as the extent at which the water demand has been fulfilled. The objectives of this paper are to answer the following questions critical to China's food security but have not been systematically addressed in the literature:

1. How much water is required under China's current agriculture planting structure?
2. What is the respective role of rainfall and irrigation in meeting this requirement?
3. What is the status of water security for China's rainfed and irrigated agriculture?

To achieve this, first, we calculated daily and annual water demand of various crops through the method recommended by the FAO. Second, based on the water stress indices proposed by Devineni et al. (2015), daily and annual water deficit of rainfed agriculture was calculated. Third, annual water deficit of irrigated agriculture was estimated by using the current irrigation capacity (IC) as input. Finally, based on the water deficit produced above, China's water security for food production was evaluated, and the respective contribution of rainfall and irrigation were distinguished. Policy decisions on agriculture and water management are usually made at the provincial level. Accordingly, province was adopted in this study as the basic assessment unit.

2. Materials and Methodology

2.1. Materials

Daily water demand of crops was calculated based on FAO-recommended crop coefficients and reference crop evapotranspiration (Allen et al., 1998; Wisser et al., 2008). Gridded daily observations including precipitation, air temperature, relative humidity, wind speed, surface pressure, and sunshine duration from 1961 to 2015 were produced using the inverse distance weighted interpolation technique based on 824 meteorological stations. The distribution of these meteorological stations is presented in Figure S1 in the supporting information. Gridded land use data of the year 2015 provided by the Institute of Geographical Sciences and Natural Resources Research of the Chinese Academy of Sciences was used to locate the spatial distribution of cropland. In total 23 different types of harvested crops (e.g., wheat, corn, rice, barley, sorghum, sugarcane, buckwheat, oats, peanut, soybean, red bean, mung bean, cotton, millet, sesame, tobacco, potato, sweet potato, flax, ramie, jute and kenaf, sunflower, and rapeseed) were selected. All kinds of crops except for vegetables and fruits have been included. Their respective planting area at provincial scale in 2015 was retrieved from China rural statistical yearbook. The planting season of different crops in each province was taken according to the FAO and discussions with local farmers. For irrigated agriculture, the annual irrigation withdrawal as well as the irrigation water use efficiency at provincial scale were retrieved from China water resources bulletin.

2.2. Water Security of Rainfed Agriculture

The water deficit of rainfed agriculture was evaluated using the water stress indices proposed by Devineni et al. (2015). The methodology is based on the sequent peak algorithm originally developed for reservoirs, which considers day-to-day rainfall variability as well as water demands (Chen et al., 2014; Etienne et al., 2016). Its specific procedure is described as below. For each crop during its growing season, the following quantities are defined:

$$DF_{j,t} = \max\left(DF_{j,t-1} + D_{j,t} - PS_{j,t}, 0\right) \quad (1)$$

$$DF_{j,t} = 0, t = 0 \quad (2)$$

$$PS_{j,t} = P_{j,t}\alpha_j = P_{j,t}\left(1-\beta_j\right) \quad (3)$$

where $DF_{j,t}$ refers to the accumulated daily water deficit, $D_{j,t}$ to daily water demand retrieved from the FAO recommendation, $PS_{j,t}$ to the daily water supply volume, for crop type j, and at day t. The renewable water supply was calculated as the product of rainfall ($P_{j,t}$) and a factor (α_j) that determines the usable fraction of rainfall for rainfed agriculture. In our analysis, α_j was retrieved from the long-term runoff ratio (β_j) of the cropland, which was estimated using a machine learning method (Yan et al., 2018). At annual scale, the total water deficit for the ith province (TWD_i) was calculated as follows:

$$TWD_i = \sum_{j=0}^{n} DF_{j,k} AC_{i,j} \quad (4)$$

where $AC_{i,j}$ is the planting area of crop j within the province. The subscript k represents the last day of the growing season, and thus, $DF_{j,k}$ represents the total water deficit of crop j over the whole growing season. Similarly, the total annual water demand of each province (TD_i) is estimated as follows:

$$TD_i = \sum_{j=0}^{n} \sum_{t=0}^{k} D_{j,t} AC_{i,j} \quad (5)$$

Following the concept of water security proposed in this research, the water security index of rainfed agriculture ($WSIR$) was defined as

$$WSIR_i = \frac{TPS_i}{TD_i} \times 100\% = \frac{TD_i - TWD_i}{TD_i} \times 100\% \quad (6)$$

where TPS_i is the total water volume supplied by rainfall, which was calculated as the difference between TD_i and TWD_i. The definitions and units of all the above variables are summarized in Table S2.

2.3. Water Security of Irrigated Agriculture

Due to the lack of irrigation records for each crop, the IC was used in this paper to evaluate the water security of irrigated agriculture. The IC of each province was defined as the maximum annual irrigation withdrawal from 2011 to 2015. It must be noted that this data covers the irrigation withdrawal of all kinds of crops including fruits and vegetables. As a result, the IC represents the maximum amount of water that can be used for irrigation use. The water security index of irrigated agriculture ($WSII$) was calculated as follows:

$$WSII_i = \begin{cases} \dfrac{TPS_i + IC_i WUE_i}{TD_i} \times 100\% & for \quad TWD_i > IC_i WUE_i \\ 100\% & for \quad TWD_i \le IC_i WUE_i \end{cases} \quad (7)$$

where WUE_i refers to current irrigation water use efficiency of province i. In theory, WSII represents the extent to which the water demand has been fulfilled by irrigated agriculture. A WSII of 100% indicates that the water demand of all crops concerned in this research has been fulfilled. Accordingly, the respective contribution of rainfall (CR_i) and irrigation (CI_i) to water security was defined as follows:

$$CR_i = WSIR_i = \frac{TPS_i}{TD_i} \times 100\% \quad (8)$$

$$CI_i = \begin{cases} \dfrac{IC_i WUE_i}{D_i} \times 100\% & for \quad TWD_i > IC_i WUE_i \\ \dfrac{TWD_i}{D_i} \times 100\% & for \quad TWD_i \le IC_i WUE_i \end{cases} \quad (9)$$

Based on the above quantities, the optimal planting area of each province (OAC_i) was estimated as follows:

$$OAC_i = \frac{IC_i WUE_i}{TWD_i} AC_i$$

In theory, OAC_i is the maximum planting area without any water deficit under current irrigation infrastructure and planting structure.

3. Results

3.1. Water Security of Rainfed Agriculture

Controlled by climate variability, the water deficit of rainfed agriculture varies annually. Here we only focus the water security of rainfed agriculture on annual average scale. Figure 1 presents the total water demand, rainfall supply, and water deficit of each province as well as their values normalized by planting area. The water demand of the whole country is about 585×10^9 m^3/year. The water supplied by rainfall is 365×10^9 m^3, leaving 220×10^9-m^3 water deficit. As for the spatial patterns, the water demand of per unit area (*ND*) varies significantly across the country. The regions with high values are mainly distributed in the west, south, and north of China. Specifically, the highest *ND* is observed in the tropical Hainan province with a value of 587 mm, and the smallest is observed in Guizhou province with a value of 328 mm. However, when planting area is considered, the provinces with large planting area have higher total water demand (*TD*) values. Specifically, the water demand of Heilongjiang is highest with a value of 56×10^9 m^3, followed by Henan, Shandong, Anhui, and Inner Mongolia. In contrast, small *TD* values are observed in provinces with small planting area such as Beijing, Shanghai, Tibet, and Tianjin. Therefore, although *TD* is a product of *ND* and planting area, its spatial patterns are dominated by the planting area. Influenced by the East Asia Monsoon, the rainfall supply of per unit area (*NPS*) in the east is generally higher than that in the west. As a result, Xinjiang has the smallest *NPS*, which is only 79 mm. However, when the planting area is considered, the spatial patterns of the total water supply (*TPS*) are very similar to *TD*. Large values are observed in Heilongjiang, Henan, Anhui, and Shandong, while small values are observed in Beijing, Tibet, Shanghai, and Tianjin.

The spatial patterns of water deficit are controlled by both water demand and rainfall supply. In terms of water deficit of per unit area (*NWD*), it is still dominated by the monsoon climate. The values in the northwest are generally higher than those in the southeast. The highest and lowest values are observed in Xinjiang and Guizhou, respectively. However, in some cases the planting structure also plays an important role. For example, the farmers in South China usually plant rice twice or even three times during 1 year. The high water demand of rice makes the values of *NWD* in South China higher than those in the surrounding area. As for total water deficit (*TWD*), its spatial patterns are totally different. Although the highest value is still observed in Xinjiang, it is followed by provinces with large planting area such as Henan, Heilongjiang, and Shandong. The small values are observed in provinces with small planting area such as Beijing, Shanghai, Tianjin, Tibet, and Hainan. Therefore, planting area plays a dominant role in the spatial patterns of *TWD*.

The boxplot of water security index of rainfed agriculture (*WSIR*) from 1961 to 2015 is presented in Figure 2a. The spatial distribution of annual average *WSIR* is presented in Figure 2b. Across whole China, the annual average *WSIR* is 62%, which means that 62% of the water demand in rainfed agriculture can be fulfilled. However, Figure 2 indicates that the *WSIR* has significant annual and spatial variations. As for the annual average, the *WSIR* in the southeast is generally higher than that in the northwest. The five provinces in the northwest, including Xinjiang, Tibet, Ningxia, Qinghai, and Gansu, constitute the regions with the lowest *WSIR*. The *WSIR* in all other provinces is higher than 50% with the largest value of 76% observed in Yunnan. In the east, there are also two low value zones. The first one is located in the South China including Jiangxi, Hunan, and Fujian three provinces. As we explained above, the large planting area of rice is the leading cause. The second one is the Beijing-Tianjin-Hebei region in North China. In contrast, the water insecurity here is mainly caused by low rainfall. The regions with high *WSIR* are mainly distributed in the southwest (Yunnan, Guizhou, and Sichuan), south (Hainan, Guangxi, and Guangdong), northeast (Jilin, Liaoning, and Heilongjiang), and part of East China (Jiangsu, Anhui, Hubei, and Shanghai). These 13 provinces constitute the most suitable regions in China for rainfed agriculture under current planting structure.

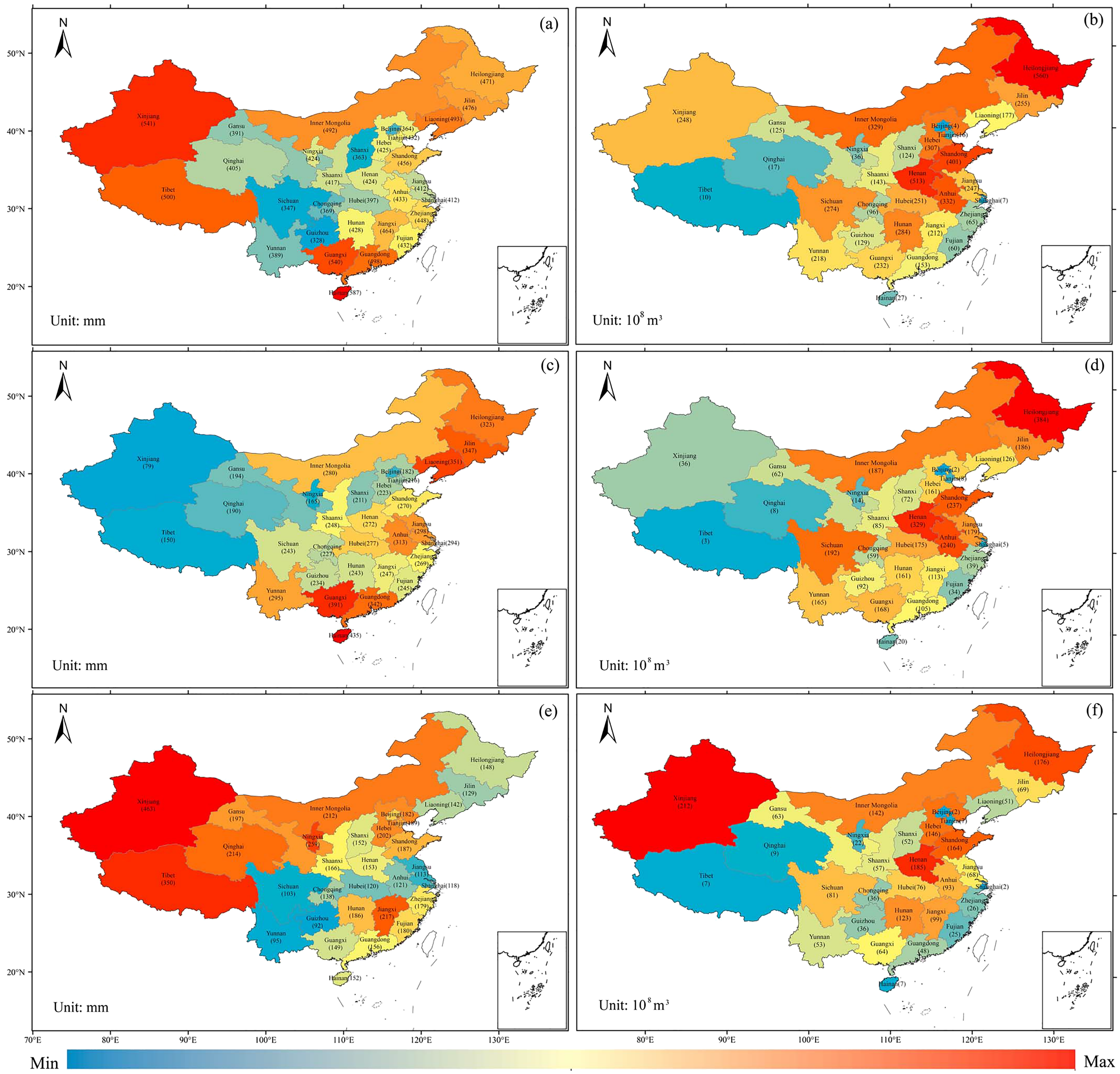

Figure 1. Spatial patterns of *ND* (a), *TD* (b), *NPS* (c), *TPS* (d), *NWD* (e), and *TWD* (f). The unit of *ND*, *NPS*, and *NWD* and the unit of *TD*, *TPS,* and *TWD* are millimeters and hundred million cubic meters, respectively.

3.2. Water Security of Irrigated Agriculture

Figure 3 shows the annual average water deficit of irrigated agriculture. Across China, the efficient water supplied by irrigation is 166×10^9 m^3. As a result, there is still 54×10^9 m^3 water deficit. As we interpreted in the methodology, the IC in our research covers the irrigation withdrawal of all kinds of crops. However, the planting area of vegetables and fruits is not considered in the estimation of water demand. Because of this mismatch there is a possibility that the product of IC and water use efficiency is larger than the water deficit of rainfed agriculture. Under such circumstances, the water deficit in Figure 3 is set as 0. It means that the water demand of all the 23 kinds of crops has been fulfilled. As Figure 3

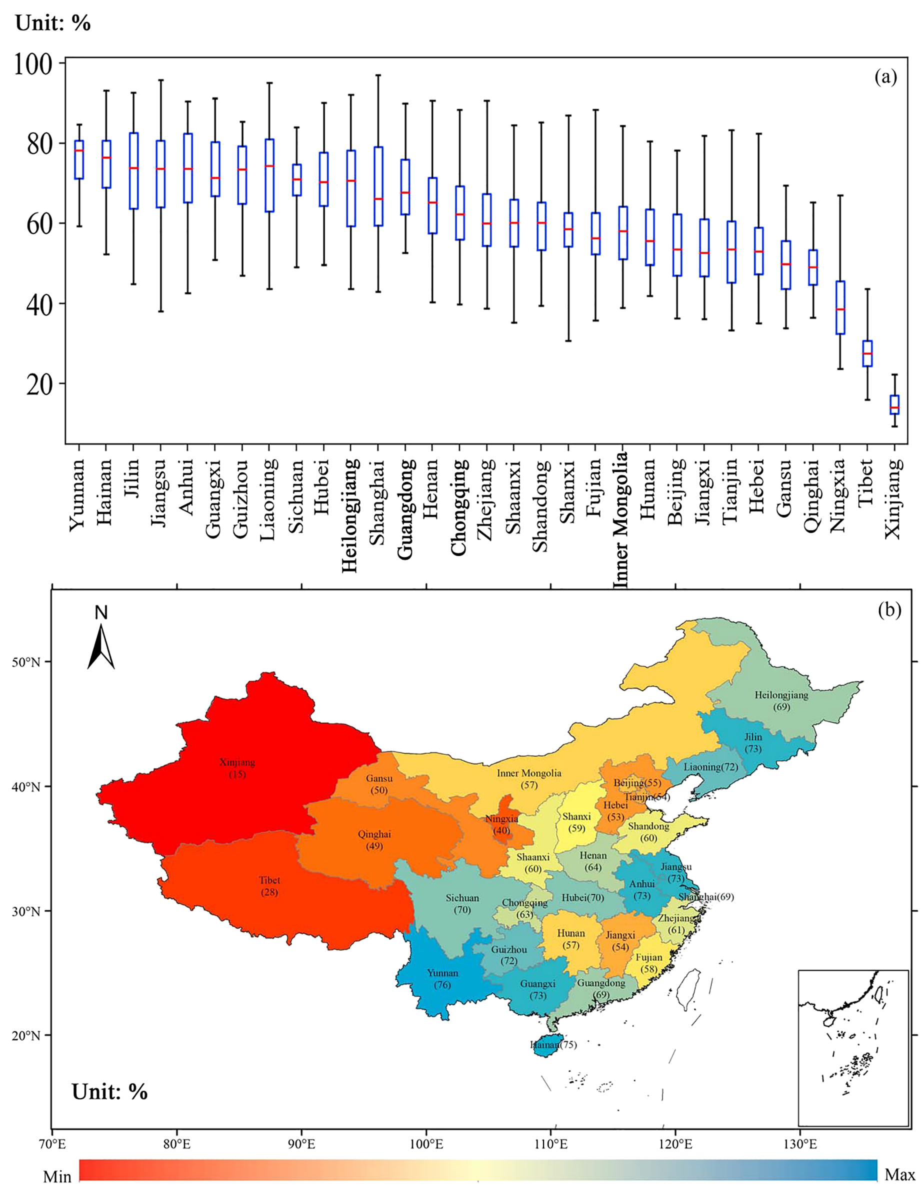

Figure 2. Boxplot of water security index of rainfed agriculture (*WSIR*) at the province level (a) and the spatial distribution of annual average *WSIR* (b). The boxplot was drawn from the annual *WSIR* of each province from 1961 to 2015 to show its variations. Specifically, the red lines represent the median values. The upper and lower boundary of the blue boxes represent the upper and lower quartiles, respectively. The upper and lower boundary of the black lines represent the maximum and minimum values, respectively.

indicates, in total there are 15 provinces with zero water deficit. They are mainly distributed in the west, south, and east of China. Obviously, the spatial patterns of water deficit in irrigated agriculture are completely different from those in rainfed agriculture. In terms of water deficit of per unit area (*NWD*), the value in the north is much larger than the value in the south with the largest observed in Inner Mongolia. In the south, Hunan and Jiangxi still constitute the high value zone. However, the high value center has shifted to Chongqing province. Its *NWD* is as high as 100 mm, which is the second largest value across all provinces. As for the total water deficit (*TWD*), the largest value is observed in Henan province, followed by Shandong, Inner Mongolia, and Hebei. Due to the small planting area, the *TWD* of Chongqing is only 2.6×10^9 m^3. The values in the north is still much larger than those in the south.

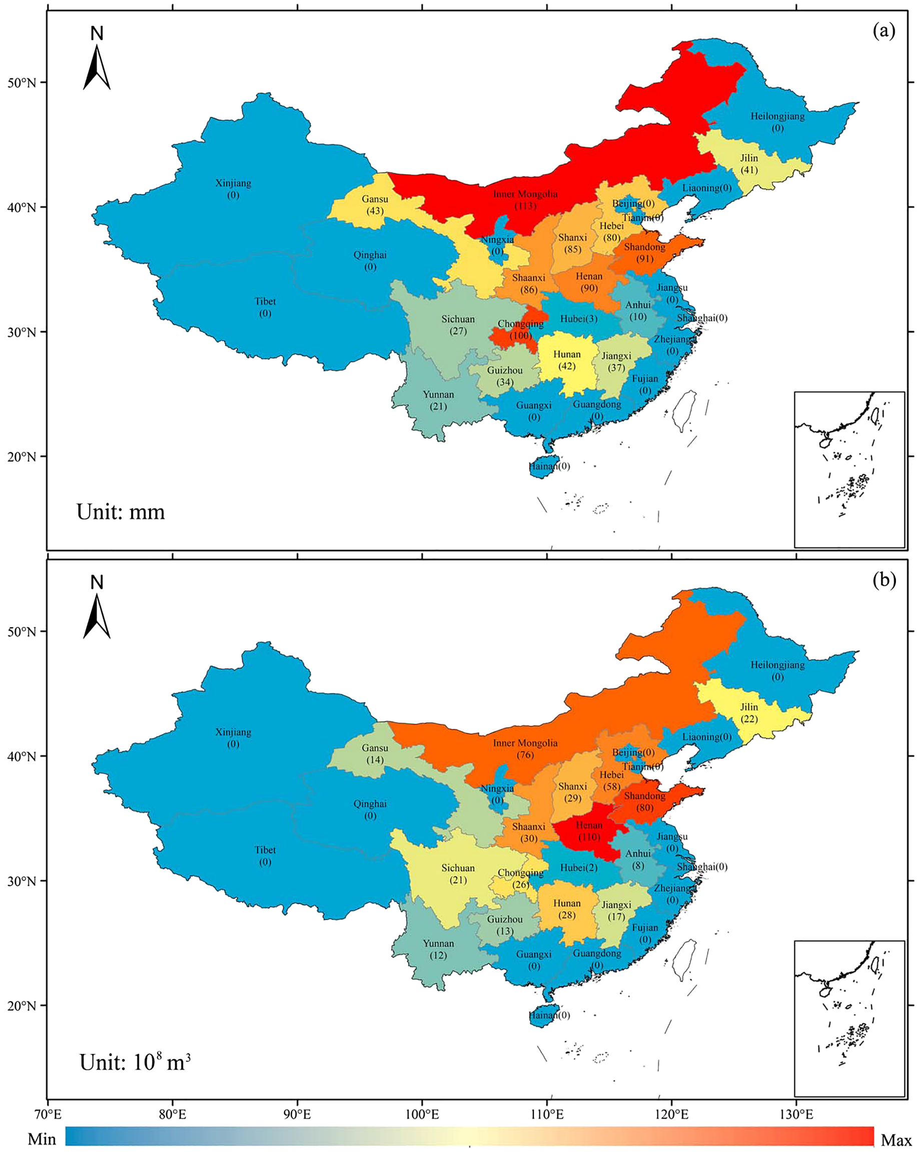

Figure 3. Spatial patterns of *NWD* (a) and *TWD* (b) in irrigated agriculture. The unit of *NWD* and *TWD* is millimeters and hundred million cubic meters, respectively.

The water security index of irrigated agriculture (*WSII*) is presented in Figure 4a. The comparison between Figures 4a and 2b shows that China's water security for food production has been improved significantly by agricultural irrigation, which is particularly obvious for the four provinces (Xinjiang, Tibet, Ningxia, and Qinghai) in the northwest of China. Besides these four provinces, there are another 11 provinces, the *WSII* of which has also reached 100%. In contrast, these 11 provinces are distributed in the south and east of China, and all of them are coastal provinces except Beijing. For irrigated agriculture, Chongqing becomes the province with the worst water security status. Its *WSII* is only 73%. Except Chongqing, the *WSII* of all other provinces in the south of China is larger than 90%. In contrast, the *WSII* of most provinces in the north is lower than 90%. Actually, most of them, including Inner Mongolia, Shanxi, Shaanxi, Henan, Shandong, and Hebei, have a *WSII* around 80%.

The relative contribution of rainfall and irrigation to water security is shown in Figure 4b. In order to investigate the spatial patterns, the values of irrigation contribution are presented in Figure 4c. Across China, the contribution of rainfall and irrigation is 62% and 28%, respectively. There is still 10% of water demand to be fulfilled. As for the spatial patterns, the role of rainfall is more important in all provinces except for the four

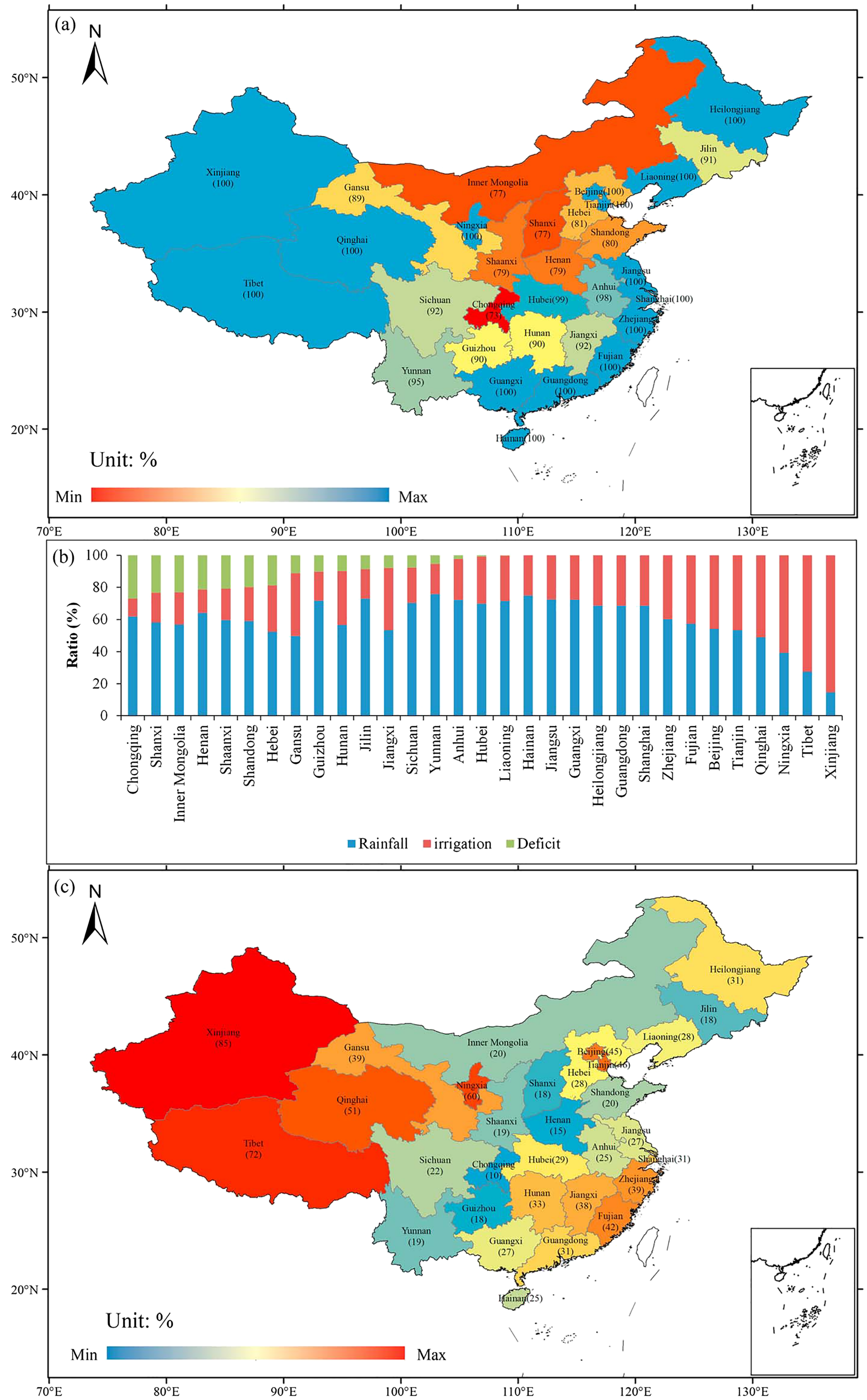

Figure 4. Annual average water security index of irrigated agriculture (*WSII*) at the province level (a), the respective contribution of rainfall and irrigation (b), and the spatial patterns of irrigation contribution (c).

provinces (Xinjiang, Tibet, Ningxia, and Qinghai) in the northwest. The contributions of irrigation in these four provinces are 85%, 72%, 61%, and 51%, respectively. For the rest of the 27 provinces, the contribution of rainfall has outweighed the contribution of irrigation. It is particularly obvious in Chongqing province where only 10% of water demand is supplied by irrigation. In addition to the five provinces in the northwest, there are another three regions where the role of irrigation is relatively important. The first one is Beijing and Tianjin located in North China. The second one is located in the southeast of China, including Fujian, Jiangxi, Hunan, Shanghai, and Guangdong provinces. The last one is Heilongjiang province in the northeast of China. The provinces that do not rely heavily on irrigation are mainly distributed in the middle of China and part of east regions.

Once the water demand and supply is known, it is possible for us to investigate the reasonability of current planting area from the perspective of water security. The current planting area and the optimal planting area retrieved from equation (11) without any water deficit as well as their differences are presented in Figure S3. The comparison shows that the planting area has been enlarged in provinces with *WSII* as 100% and reduced in provinces with *WSII* less than 100%. Across the whole country, the enlarged and reduced area is 178 and 338×10^9 m^2, respectively. As a result, the optimal planting area is 1184×10^9 m^2, which accounts for 88% of its original planting area. It means that more irrigation investment is required to secure food production under current planting structure. Specifically, more potential planting area can be reclaimed from the 15 provinces with *WSII* as 100% in Figure 4a. Among them, Jiangsu province accounts for 48% of the enlarged planting area, followed by Guangdong, Guangxi, Fujian, Zhejiang, Shanghai, and Hainan. Therefore, judging from water security, the seven coastal provinces in the southeast have the most potential for food production. Nearly 93% of the enlarged planting area is supplied by them. The big share of Jiangsu province can be explained from two aspects. On the one hand, its *NWD* of rainfed agriculture is only 113 mm (Figure 1e), which is lower than most other provinces. On the other hand, the IC of Jiangsu province is as high as 27×10^9 m^3, which is ranked third across the whole county and first in the south of China. As for the reduction in planting area, it is most obvious in the north of China. The biggest share is observed in Henan province with the reduction in area as high as 72×10^9 m^2. It is followed by Shandong, Inner Mongolia, Hebei, and Shanxi. In the south, the reduction is most significant in Sichuan and Chongqing. They are ranked fifth and seventh, respectively, across the whole country. The above seven provinces account for 70% of the total reduction in planting area, constituting the regions where irrigation investment is most needed under current planting structure. The comparison between Figures S3a and S3b shows that there is significant difference in the spatial patterns of planting area. Under optimal conditions, Jiangsu replaces Henan, becoming the province with the biggest planting area. It is followed by Heilongjiang, Anhui, Hubei, Guangxi, Sichuan, and Guangdong. In contrast, the top seven provinces of the original planting area are Henan, Heilongjiang, Shandong, Sichuan, Anhui, Hebei, and Inner Mongolia, respectively. Obviously, the center for food production has shifted from north to south.

4. Discussion

The results produced by our water security framework and its implications for policy making have been elaborated in the above section. However, owing to a combination of data inaccessibility and imperfection in the framework, it is necessary to understand the uncertainties involved in this research. The sources leading to these uncertainties and their influence on the results are discussed here. First, according to the review conducted by Cook and Bakker (2012), the divergence between different framings of water security has sparked debate over analytical approaches to, and definitions of, water security. As a result, assessing water security is largely an empirical matter with distinct conceptualizations, methods, and focuses (Jiang, 2015). In this paper, considering the linkage between water demand of crops and water supply of rainfall and irrigation, the ideal water security status for food production is defined with a water security index (*WSI*) of 100%. It means that all the water demand has been satisfied. This is a very rigid definition because it rarely happens in reality, even for irrigated agriculture. From an economics standpoint, a *WSI* less than 100% is more reasonable to improve the efficiency of water use due to the decreased marginal effect of water productivity (Grafton et al., 2017; Perry et al., 2009). In view of this, the water demand of the 23 considered crops listed in section 2.1 has been overestimated. Consequently, the water security has been underestimated. As we mentioned in the introduction, the water security defined by the FAO is related closely with food security. At the 1996 FAO Roma World Food Summit, food security was defined as a condition that exists when "all people, at all times have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO, 1996). As for China, the question "how much food does it need to feed itself" is still being widely debated although it has been first formulated by Brown (1995) more than 20 years ago. We have no intention to join this debate. However, judging from food self-sufficiency, which was defined by the FAO (1999) as the extent to which a country can satisfy its food needs from its own domestic production, the self-sufficiency of China's three major cereal crops including wheat, rice, and corn is about 95% (Cui & Shoemaker, 2018). It means that more water is required to achieve 100% food self-sufficiency. In this perspective, the water demand to achieve food security has been underestimated. Therefore, in terms of the water security proposed by the FAO, our framework has overestimated China's water security. Second, due to the overexploitation of water resources over the past few decades, there has been growing evidence of increasing water scarcity and environment problems over China (Famiglietti, 2014; Fang et al., 2010; Sun et al., 2019). Inspired by this, China's government has tried to change the water management strategies from supply side to demand side to promote sustainable socioeconomic development (Wang et al., 2017). The upper limit of water withdrawal, particularly of groundwater withdrawal, has been specified for each province by the Chinese government. Any increase in irrigation water use is not easy in the future. The water security of irrigated agriculture will rely more and more on the enhancement of irrigation efficiency rather than increase in irrigation withdrawal. In contrast, the IC in our research was estimated as the maximum annual irrigation withdrawal, and assumed to be invariant under different meteorological conditions. The overestimation of IC has led to the overestimation of water security. Third, because of data limitations, the water demand of fruits and vegetables is usually ignored or handled in a simple way (Davis et al., 2017). Similarly, although the water withdrawal of fruits and vegetables has been included in the IC, they are not included in our selected crops for the calculation of water demand. The mismatch between water demand and IC has resulted in an overestimation of water security for irrigated agriculture. Fourth, besides water availability, the availability of arable land also plays a dominant role for food production (Zhang et al., 2018). In this research current planting area of different crops was adopted as the substitute for arable land. This is reasonable for the water security assessment. However, when policy with regard to the adjustment in planting area is to be made based on our water security assessment, equal attention should be given to the availability of arable land. So the main contribution of our research is to identify the spatial imbalance between water demand and supply for food production. The suggestions proposed from our water security framework are theoretical guidances to maximize the satisfaction of water demand for food production, which can be achieved through water diversion project and agriculture distribution adjustment on the national scale. More factors such as the availability of arable land, economic benefits, and irrigation infrastructures should be incorporated into our framework when it is to be used in practice.

5. Summary and Conclusions

Based on the water stress indices proposed by Devineni et al. (2015), a framework was proposed in this paper to answer several questions critical to China's water security for food production. Specifically, the respective role of rainfall and irrigation in agriculture was investigated. The water security of both rainfed and irrigated agriculture was evaluated. We have also proposed suggestions regarding water security for food production from the framework. For example, both the regions that are most suitable for rainfed agriculture and the regions where more irrigation investment is required were distinguished, and an optimized adjustment scheme of planting area was presented. Considering the needs of national macrocontrol and the accessibility of data, the above framework was demonstrated at the provincial level. However, it can be applied to other geographical unit of interest such as town, county and basin. Besides, in this paper we only focused on the annual average water security for food production, but the framework was designed at annual scale. Consequently, it is possible for us to investigate the annual water security under different climate scenarios. Future climate change signals can also be incorporated into this framework to inform climate-driven water risk for agriculture. These provide the basis for water resources planning across sectors and locations.

Due to the uncertainties caused by data inaccessibility and imperfection in some assumptions, the suggestions proposed from our framework are theoretical guidances to maximize the satisfaction of water demand for food production on the national scale. More factors such as the availability of arable land, economic benefits, and irrigation infrastructures should be incorporated when it is to be used in practice. Despite these uncertainties, our research proposed a theoretical framework to monitor and evaluate water security for food production from a new perspective. It also lays the groundwork to investigate the virtual water flow of crops.

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