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Current status and recent trend of irrigation water use in China*

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ABSTRACT

China's irrigation water use witnessed a continuously increasing trend from 1949 to 1990, while it has begun to show a decreasing one with fluctuations since then. During 2003–2013, the amount of agricultural water use, of which over 95% is for irrigation, increased to a peak value of 392×10^9 m^3. In 2017, it decreased to 377×10^9 m^3 and accounted for 62.3% of total water use for the whole of China. It can be concluded that irrigation water use has reached its limit in China. In the northern part of China, the water scarcity situation sets a cap on irrigation water use, which will have further competition from environmental water use. In the southern part of China, the limited amount of irrigable land sets a cap on irrigation water use, which will have further competition from urbanization. Water-saving policies and high-efficiency irrigation technologies have been adopted by the Chinese government as the national strategy for sustainable irrigation water use. The challenges of irrigation development faced by China are increasing water productivity to reduce water consumption in north-west China, reducing groundwater exploitation to restore aquifers in north China, increasing food production to ensure national food security in north-east China, and promoting water conservation to control pollution in the southern part of China.

KEYWORDS
irrigation, water resources, China, water-saving technology

Résumé

La consommation d'eau d'irrigation de la Chine a connu une tendance à la hausse continue entre 1949 et 1990, alors qu'elle commençait à montrer une tendance à la baisse avec des fluctuations depuis lors. En 2003–2013, la quantité d'eau utilisée par l'agriculture, dont plus de 95% est destinée à l'irrigation, a atteint une valeur maximale de 392×109 m^3. En 2017, elle a diminué à 377×109 m^3 et occupé 62,3% de l'utilisation totale d'eau pour l'ensemble de la Chine. On peut en conclure que l'utilisation de l'eau d'irrigation a atteint sa limite en Chine. Dans les régions septentrionales, la situation de pénurie d'eau fixe le plafond d'utilisation de l'eau d'irrigation, qui sera de surcroît

*Situation actuelle et tendance récente de l'utilisation de l'eau d'irrigation en Chine.

concurrencé par l'utilisation environnementale de l'eau. Dans les régions méridionales, le peu de terres irrigables limite l'utilisation de l'eau d'irrigation, qui sera concurrencée par l'urbanisation. Le gouvernement chinois a adopté des politiques d'économie d'eau et des technologies d'irrigation à haute efficacité énergétique en tant que stratégie nationale d'utilisation durable de l'eau d'irrigation. Les défis du développement de l'irrigation auxquels la Chine est confrontée sont l'augmentation de la productivité de l'eau pour réduire la consommation d'eau dans le nord-ouest de la Chine, réduire l'exploitation des eaux souterraines pour restaurer les aquifères dans le nord de la Chine, augmenter la production alimentaire pour assurer la sécurité alimentaire nationale dans le nord-est de la Chine et promouvoir la conservation de l'eau pour lutter contre la pollution dans le sud de la Chine.

MOTS CLÉS

irrigation, ressources en eau, Chine, technologie d'économie d'eau

1 | INTRODUCTION

Although ranking sixth in total annual water resources, China is one of the most water-deficient countries in the world (United Nations World Water Assessment Programme, 2012) with per capita water resources of less than 2000 m^3. China faces the challenge of feeding its nearly 1.4 billion people with approximately 25% of the world's average per capita water resources. Even worse, water resources are unevenly distributed, with a mismatch between arable land and population. In addition, the intra-annual distribution of precipitation is uneven, making water resources insufficient at particular times. The large inter-annual variation of precipitation has caused frequent droughts, which exacerbates water shortages in China.

Water is essential for agricultural production in China, and great importance has been attached to the construction of irrigation infrastructure since 1949. National irrigated farmland increased rapidly from approximately 15.9 million ha in 1949 to 67.8 million ha in 2017, and agricultural water use increased from 100×10^9 m^3 in 1949 to 377×10^9 m^3 in 2017 (Gao, 2019; Ministry of Water Resources, 2018a). Irrigation has played an important role in China's food security (Feng, 2005; Heilig, Fischer, & Van Velthuizen, 2000; Wang et al., 2017). According to 2010 data, irrigated land produces approximately 75% of the nation's food, more than 80% of its cotton and 90% of its vegetables and fruits (Rural Water Resources Department and National Irrigation and Drainage Development Center, 2010). In 2017, 50.3% of cultivated land was equipped with irrigation facilities. However, irrigation development in China has been limited by water. A total of 53% of the cultivated land in the northern part of China was still rain-fed in 2017, and much irrigated land was insufficiently irrigated because of water shortage (Kang et al., 2017).

As it has a vast territory and diverse geography, climate, water endowment, population, economic level and irrigation schemes, mainland China is divided into six regions in this paper. The objectives of this paper are as follows: (i) to carefully analyse the current status of water for irrigation in the six regions; (ii) to contrastively chart recent changes in regional irrigation water use; (iii) to analyse challenges of water resources for irrigation in the six regions.

2 | SIX IRRIGATION REGIONS IN CHINA AND THEIR WATER RESOURCES ENDOWMENT

China has a climate characterized by increasing aridity from the south-east to the north-west, and a topography characterized by higher elevations in the west and lower altitudes in the east. The cultivated lands in China are mainly distributed in the plains and hilly areas with better irrigation infrastructures in the east. By contrast, irrigation infrastructures are relatively weaker and vulnerable in the west. On the other hand, the southern part of China is characterized by rich water resources and a high level of industrialization and urbanization, whereas the northern part is characterized by more water scarcity and a relatively low level of industrialization and urbanization. The 31 provinces of mainland China are often divided into 6 or 7 geographic regions with

consideration of diverse climate, geography and socio-economy (China Irrigation and Drainage Development Center, 2017; Compiler Group of Physical Geography of China, 1993; Wu, Jin, & Zhao, 2010). In this paper, mainland China is divided into six irrigation regions: (I) north-west, (II) north, (III) north-east, (IV) south-west, (V) south central and (VI) south-east, with consideration of irrigation pattern and recent trends in irrigation water use. The first three regions are in the northern part of China, whereas the other regions are in the southern part. The characteristics of the six regions are listed in Table I, and their locations illustrated in Figure 1.

North-west China comprises Xinjiang, Qinghai and Gansu, which are mainly located in major inland river basins. It is the most underdeveloped region of China, with an agriculture-based economy, and has the lowest per capita gross domestic product (GDP). Its climate is the most arid, with a mean annual precipitation less than 200 mm in most areas. Wheat, maize and cotton are the region's staple crops.

North China comprises two metropolises (Beijing and Tianjin) and seven provinces, which are located in the middle and lower reaches of the Yellow River basin, the Haihe River basin and the northern part of the Huaihe River basin. Ningxia, Inner Mongolia and Shannxi, which

TABLE 1 Characteristics and annual mean renewable water resources during 2003–2017 of the six regions of China

Region[a]		Precipitation (mm)	Cultivated land (10^6 ha)	Population (10^9)	Per capita GDP (10^3 yuan)	Renewable water resources (10^9 m^3)		
						Total	Surface water	Groundwater
I	North-west	235	11.2	0.57	37.0	185	177	99.3
II	North	584	27.8	4.16	61.8	186	133	98.3
III	North-east	416	41.5	1.09	49.9	151	129	51.3
IV	South-west	811	20.3	2.01	43.6	1 020	1 020	259
V	South central	1 330	22.9	3.17	63.9	550	529	134
VI	South-east	1 680	11.2	2.90	78.5	637	634	151
Total		644	134.9	13.9	334.7	2730	2 630	792

[a]North-west China includes Xinjiang, Qinghai and Gansu. North China includes Ningxia, Inner Mongolia, Shannxi, Beijing, Tianjian, Hebei, Shanxi, Henan and Shandong. North-east China includes Heilongjiang, Jilin and Liaoning. South-west China includes Tibet, Guizhou, Yunan, Sichuan and Chongqing. South central China includes Hubei, Hunan, Jiangxi, Anhui and Jiangsu. South-east China includes Guangxi, Guangdong, Hainan, Fujian, Zhejiang and Shanghai.

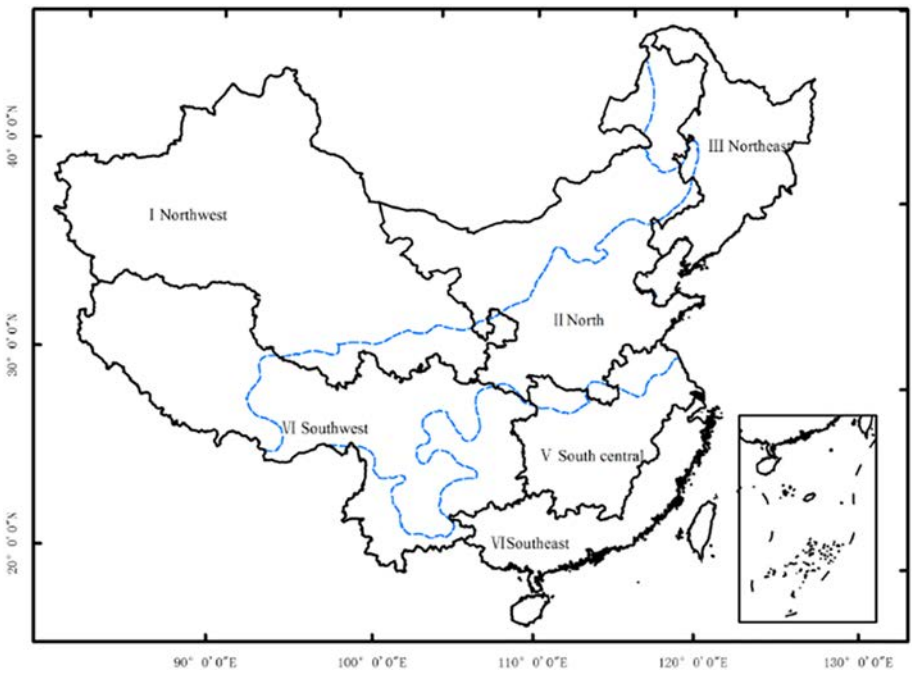

FIGURE 1 Six regions in this study and the precipitation isohyet (upper blue line is the 400 mm precipitation isohyet and lower blue line the 1000 mm isohyet). The mean annual precipitation data are from the National Meteorological Information Centre of the China Meteorological Administration [Colour figure can be viewed at wileyonlinelibrary.com]

are usually classified in north-west China on the basis of their geographic location (China Irrigation and Drainage Development Center, 2017; Wu et al., 2010), are regarded as parts of north China. The reason for this is that their irrigation schemes and trends in irrigation water use are similar to those in other provinces in north China. This region is the major agricultural area of China, with double cropping of winter wheat and summer maize as the main crops.

North-east China includes the Songhua and Liaohe River basins. This region is the old industrial base of China with shrinking industry and population but expanding agriculture in recent years. North-east China is also the most important agricultural area, with the largest cultivated land among the six regions. Maize, wheat and soybeans are its staple crops. Most areas of north and north-east China have a semi-arid climate, with mean annual precipitation between 400 and 800 mm.

South-west China is composed of the Tibet Plateau, the Yunan-Guizhou Plateau and the Sichuan basin. This region has plenty of surface water resources. Most of its areas have a mean annual precipitation around 1000 mm, except for the Tibet Plateau (with mean annual precipitation of 582 mm), and the climate is warm and humid; it teems with paddy rice, wheat, rapeseed and vegetables.

South central China includes the middle and lower reaches of the Yangtze River basin, and the southern part of the Huaihe River basin. This region has a great potential for economic development, ranking second in per capita GDP among the six regions. The climate is warm and humid, with a mean annual precipitation more than 1000 mm.

South-east China includes the Pearl and the south-east river basins. The climate is the most warm and humid, with mean annual precipitation of more than 1500 mm. This region is the most developed area in China, with the highest per capita GDP among the six regions. South central and south-east China are main producers of paddy rice.

In most of north-west China and part of the northern region with mean annual precipitation less than 400 mm, there would be no stable agriculture without irrigation. In north-east China, most of the north region and part of south-west China where the mean annual precipitation greater than 400 mm but less than 1000 mm, irrigation plays a vital role in offsetting the water deficit and maintaining a high crop yield. In south central, south-east and part of south-west China where the mean annual precipitation is greater than 1000 mm, irrigation is needed for the paddy fields, and is a prerequisite to guarantee high production for other crops.

The provincial data for irrigation from 2003 to 2017 were collected from the *China Water Statistical Yearbook* issued by the Ministry of Water Resources, containing the areas equipped with irrigation facilities (termed as irrigated area hereafter), farmland (cultivated land for grain and vegetables) irrigated area (approximately 91.7% of the national irrigated area in 2017) and the irrigated area with highly efficient water-saving technologies such as sprinkling and drip irrigation, etc., which are often termed high-tech irrigation technologies (Khan & Abbas, 2010; Skaggs, 2001). Thus, we termed the irrigated area with highly efficient water-saving technologies as a high-tech irrigated area for convenience. The provincial census data of renewable water resources, water withdrawal and water use for the four main sectors from 2003 to 2017 were extracted from the provincial *Water Resources Bulletin.* The census data of agricultural water use are composed of irrigation water use for farmland and non-farmland (forest/fruit, pasture), and that for livestock and poultry. According to the water resources census in 2011 (Li, Han, et al., 2017), water use for livestock and poultry only accounts for 2.6% of national agricultural water use, ranging from 1.1% in north-west China to 7.0% in south-west China (Table II). As non-irrigation water use is a very small proportion of the total agricultural water use, agricultural water use is utilized instead where total irrigation water use data are not available. In irrigation water use, farmland used 91% of national agricultural water, and its percentage in agricultural water use ranges from 83.2% in north-west China to 95.2% in north-east China (Table II).

The mean annual renewable water resources of China from 2003 to 2017 were 2730 billion m^3, with 2630 billion m^3 surface water resources and 792 billion m^3 groundwater resources (the total water resources are less than the sum of surface and groundwater resources because of the amount of overlap between them). The

TABLE 2 Components of agricultural water use in 2011 (%). The data are from the first National Water Resources Census (Li, Zhang, *et al.,* 2017)

Item	I	II	III	IV	V	VI	China
Farmland	83.2	91.4	95.2	88.0	93.9	92.2	91.0
Non-farmland	15.6	5.0	1.8	5.0	4.1	6.1	6.4
Livestock and poultry	1.1	3.6	3.0	7.0	2.0	1.8	2.6

water resources are unevenly distributed among the six regions. The surface water resource of the three northern regions are only 439 × 10^9 m^3 (16.7% of the national total amount) and the groundwater resource is 249 × 10^9 m^3 (31.4% of the national total amount), respectively. North China is the most intensive water use region, with the highest ratio of water withdrawal to total renewable water resources (59.9%), followed by north-east China (40.4%). Among the six regions, north-east China has the lowest water resources (151 × 10^9 m^3), but the largest cultivated land area (41.5 × 10^6 ha), indicating a serious water scarcity situation. South-east China has the smallest cultivated land area (11.2 × 10^6 ha), but the most plentiful water resources (637 × 10^9 m^3). This mismatch is even worse when the population and GDP are considered. North China has only 6.8% of the water resources, but 30.7% of the cultivated land and 29.9% of the population, and produces 30.2% of GDP. By contrast, south-west China has 37.5% of the water resources, 15.0% of the cultivated land, 14.5% of the population and produces 10.3% of GDP.

3 | CURRENT STATUS AND RECENT CHANGES IN WATER RESOURCES FOR IRRIGATION IN THE SIX REGIONS

3.1 | Current status of irrigation water use in the six regions of China

The change in China's irrigation water use can be figured out from the changes of irrigated area and irrigation water use for farmland (Figure 2), which can be approximately divided into three periods. Both farmland irrigated area and water use increased rapidly during the first period (1949–1979). Then, the growth of irrigation water use slowed during the 1980s, and the farmland irrigated area slightly decreased. After 1990, irrigation water use decreased, but the farmland irrigated area increased again, which can be attributed to the extension of water-saving technologies. During the third period (2003–present), the growth of farmland irrigated area has been accelerating, along with the increasing investment to ensure food security. Farmland irrigation water use increased slightly from 2003 to its peak volume (344 × 10^9 m^3) in 2013, but has been slowing since then. More emphasis has been put on advocating highly efficient water-saving irrigation technologies since 2000s. The high-tech irrigated area increased rapidly from 5.9 × 10^6 ha in 2000 (9.8% of the total irrigated area) to 20.6 × 10^6 ha in 2017 (20.6% of the total irrigated area).

In 2017, China's agricultural water use was 377 × 10^9 m^3, which is 62.3% of the total water use. The percentage of agricultural water use to total water use decreased successively from 90.1% in north-west China to 51.4% in south-east China. The water-scarce northern regions used 181 × 10^9 m^3 agricultural water (48.1% of national agricultural water use), whereas the southern regions used 196 × 10^9 m^3 agricultural water. South central China used the largest volume of agricultural water (93.7 × 10^9 m^3), followed by north China (69.8 × 10^9 m^3) (Table III).

North China has the largest irrigated area (24.0 × 10^6 ha), followed by south central China (17.5 × 10^6 ha) (Table III). The water-scarce northern regions have 42.0 × 10^6 ha irrigated area (56.8% of the national irrigated area), whereas the southern regions have 31.9 × 10^6 ha irrigated area. North China has the largest high-tech irrigated area (10.6 × 10^6 ha, 44.4% of its total irrigated area), followed by north-west China (4.2 × 10^6 ha, 50.6% of its total irrigated area), and north-east China (3.1 × 10^6 ha, 32.1% of its total irrigated area). North China is characterized by the lowest irrigation water quota (281.4 mm for farmland), which is consistent with its high irrigation water use efficiency (China Irrigation and Drainage Development Center, 2017). All three southern regions have 2.6 × 10^6 ha high-tech irrigated area, which is only 12.6% of the national high-tech irrigated area. The irrigation water quota is the highest in south-east China (871.8 mm for farmland), where double or triple cropping paddy rice with high irrigation quota is the staple crop.

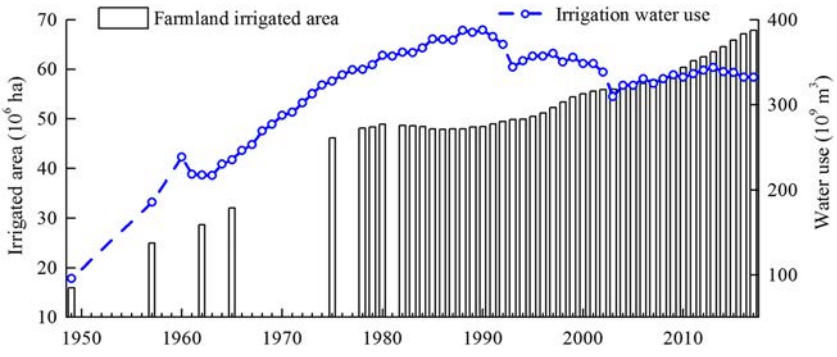

FIGURE 2 Changes in irrigated area and irrigation water use for farmland of China from 1949 to 2017. The data are from the *China Water Statistical Yearbook* (Ministry of Water Resources) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Water withdrawal, water use and status of irrigation in the six regions of China in 2017. The data are from the *China Water Statistical Yearbook* and provincial *Water Resources Bulletin* (Ministry of Water Resources, 2018b)

		I	II	III	IV	V	VI	China
Water withdrawal (10^9 m^3)	Total	69.4	111	61.1	63.7	175	124	604.2
	Surface water	54.9	58.2	34.3	60.9	166	120	494.3
	Groundwater	14.0	48.7	26.2	2.2	7.2	3.4	101.7
Water use (10^9 m^3)	Agriculture	62.6	69.8	48.8	38.0	93.7	63.8	376.7
	Industry	2.6	15.7	5.6	13.2	57.7	32.9	127.7
	Domestic	2.6	16.9	5.5	11.4	21.9	25.5	83.8
	Environment	1.6	9.0	1.2	1.1	1.5	1.9	16.2
Irrigation (10^6 ha)	Total irrigated area	8.3	24	9.7	7.3	17.5	7.2	73.9
	High-tech irrigated area	4.2	10.6	3.1	0.7	1.0	0.9	20.6
Irrigation for farmland	Area (10^6 ha)	6.5	21.8	9.5	6.8	16.7	6.4	67.8
	Water quota (mm)	757	281	487	486	513	872	490
	Proportion to arable land (%)	57.9	52.6	34.3	33.5	73.1	57.4	50.3

Surface water, which is diverted from reservoirs or ponds, diverted from rivers by gravity or pumped from rivers or lakes, is one of the main sources of irrigation in China. According to 2016 data (Gao, 2019), China has more than 97 000 reservoirs (storage capacity is more than 1×10^5 m^3) with a total capacity of 858×10^9 m^3 to supply irrigation water, and approximately 4.60×10^6 ponds and 6.90×10^6 pools. A total of 434 thousand fixed electromechanical pumping stations exist, with 27.2 million kW of capacity. According to 2003 data (Feng, 2005), the percentages of surface water diverted from reservoirs or ponds, diverted and pumped from rivers or lakes to total irrigation water are 31, 28 and 19%, respectively (Table IV). The southern regions mainly rely on surface water, and more than 40% of the irrigated area uses water storage in reservoirs and ponds, followed by diverting water from rivers and lakes. North-west China also mainly relies on surface water, mostly from rivers and lakes (Li, Zhang, *et al.,* 2017).

Groundwater is another important water source for irrigation in China. A total of 4.9 million motor-pumped wells exist, with 49.5 million kW of capacity for irrigation. According to the 2011 survey (Li, Han, *et al.,* 2017), approximately 32% of the irrigated areas in China use groundwater. The annual irrigation water extracted from groundwater is approximately 66.6×10^9 m^3 (Gao, 2019), approximately 18~19% of total irrigation water use. Groundwater plays an important role in irrigation in the northern regions. A total of 68.2% of the irrigated area in north-east China is fed by groundwater, followed by north China (57.1%). By contrast, less than 7% of the irrigated area in southern regions is fed by groundwater.

3.2 | Recent trend of regional irrigation water use from 2003 to 2017

In this paper, the magnitude of the trend is given by

$$\beta = median\left[\frac{(X_j - X_i)}{(j-i)}\right], \forall i < j \quad (1)$$

TABLE 4 Percentages of irrigation water and irrigated areas from different sources

			Irrigated area[b]						
		National irrigation water use[a]	National	I	II	III	IV	V	VI
Reservoirs and ponds		31	25	16	12.3	10.3	46.1	41.2	40.3
Rivers and lakes	Diverting	28	24.1	55.1	17.2	11	32.4	17	29.6
	Pumping	19	15.8	3	11.6	9.6	8	33.1	19.7
Groundwater		18	32	24.9	57.1	68.2	1.6	6.7	2.9
Miscellaneous		4	3.1	1.1	1.8	0.9	11.9	2.1	7.4

[a]From (Feng, 2005).
[b]Calculated by using data from Li, Han, *et al.* (2017).

TABLE 5 Trends in water withdrawals, and water use during 2003–2017 in the six regions of China (10^9 m^3 $decade^{-1}$), calculated by using data from the provincial *Water Resources Bulletin*

		I	II	III	IV	V	VI	China
Precipitation (mm)		13.2	12.2*	42.5	5.2	133	278**	38.7**
Water withdrawal	Total	5.2**	5.3**	13.2**	6.4**	21.6**	−4.6**	54.6**
	Surface water	−0.2	8.6**	7.2**	6.9**	20.0**	−3.9**	41.9**
	Groundwater	5.4**	−5.7**	5.7**	−0.6**	0.9**	−1.4**	7.9**
Water use	Agriculture	5.9**	−3.2**	13.5**	3.4**	10.6**	−6.0**	26.5**
	Industry	−0.3**	1.6**	−2.7**	−0.1*	7.9**	−2.3**	3.7
	Domestic	0.1	2.1**	−0.1	2.1**	4.8**	4.2**	14.2**
	Environment	−1.4**	4.5**	0.8**	0.5**	−0.3	−0.6**	3.9**

*Significant at 90% confidence level.
**Significant at 99% confidence level.

where i and j refer to the year, X_i and X_j denote the data in years i and j, respectively and β is the change trend magnitude. The trend's significance was assessed by the non-parametric Mann–Kendall test with a trend-free, pre-whitening method (Yue et al., 2002). China's total water use showed an upward trend from 2003 to 2017 (54.6×10^9 m^3 $decade^{-1}$, $p < 0.01$), but reached a maximum value in 2013, and then decreased (Table V). Total water use decreased in south-east China (-4.6×10^9 m^3 $decade^{-1}$, $p < 0.01$), but increased in the other five regions. Groundwater withdrawal increased rapidly in north-east and north-west China, but significantly decreased in north China (-5.7×10^9 m^3 $decade^{-1}$, $p < 0.01$).

North-east China shows the most significant increasing trend in agricultural water use (13.2×10^9 m^3 $decade^{-1}$, $p < 0.01$), followed by south central China (10.6×10^9 m^3 $decade^{-1}$, $p < 0.01$) and north-west China (5.9×10^9 m^3 $decade^{-1}$, $p < 0.01$). However, agricultural water use in these three regions began to decrease around 2013 (Figure 3). By contrast, south-east China shows a significant decreasing trend in agricultural water use (-6.0×10^9 m^3 $decade^{-1}$, $p < 0.01$). Agricultural water use in north China increased from 2003 to 2006, but decreased thereafter, exhibiting a significant decreasing trend (-3.2×10^9 m^3 $decade^{-1}$, $p < 0.01$).

The trends in irrigated area are positively correlated with changes in agricultural water use (Table VI). Benefiting from significantly increasing agricultural water use, north-east and south central China show a rapid increase in irrigated area (4.86×10^6 and 3.36×10^6 ha $decade^{-1}$, respectively). By contrast, north and south-east China where agricultural water use is declining, indicate a relatively slow increase in irrigated area (1.78 and 0.41×10^6 ha, respectively). The adoption of highly efficient water-saving technologies contributes to the significant decrease in irrigation water quota, and restrains the increase in agricultural water use. The percentages of high-tech irrigated area in north-west, north and north-east China increased to 33.7, 29.6 and 21.4% in 2017, with trends of 3.04, 3.57 and 1.61×10^6 ha $decade^{-1}$, respectively. By contrast, the southern regions have a slow increase in high-tech irrigated area. The percentages of high-tech irrigated area were only 6.6, 3.7 and 8.2% in 2017, respectively.

In north-west China, compared with increasing agricultural water use, environmental and industrial water use decreased significantly (-1.4 and -0.3×10^9 m^3 $decade^{-1}$, $p < 0.01$). The percentage of agricultural water use increased from 88.0% in 2003 to a maximum value of 92.1% in 2012, and gradually decreased to

TABLE 6 Trends in irrigated area and water use during 2003–2017, calculated by using data from the provincial *Water Resources Bulletin* and the *China Water Statistical Yearbook*

	I	II	III	IV	V	VI	China
Total irrigated area (10^6 ha $decade^{-1}$)	2.37	1.78	4.86	1.82	3.36	0.41	14.7
High-tech irrigated area (10^6 ha $decade^{-1}$)	3.04	3.57	1.61	0.27	0.36	0.34	9.34
Farmland irrigated area (10^6 ha $decade^{-1}$)	1.45	1.08	3.31	0.98	2.01	0.12	9.38
Farmland irrigation water use (10^9 m^3 $decade^{-1}$)	4.25	−6.00	13.3	1.01	5.86	−6.48	15.5
Per area farmland irrigation water use (mm $decade^{-1}$)	−185	−36	−63	−63	−50	−120	−55

Note: The trends are all significant at 99% confidence level.

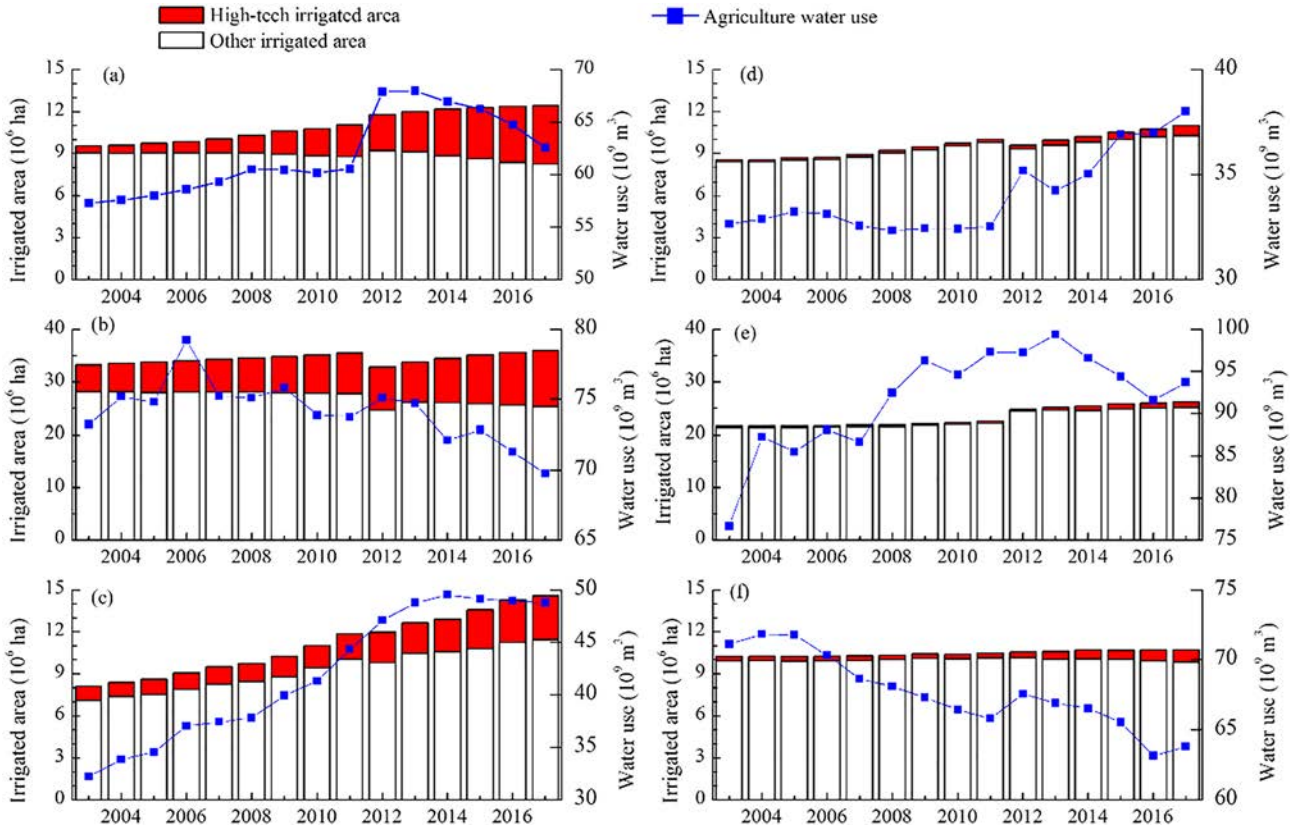

FIGURE 3 Irrigated area and agricultural water use in (a) north-west, (b) north, (c) north-east, (d) south-west, (e) south central, (f) south-east China during 2003–2017. The data are from the provincial *Water Resources Bulletin* and the *China Water Statistical Yearbook* [Colour figure can be viewed at wileyonlinelibrary.com]

90.1% in 2017 (Figure 4). In north China, the decrease in agricultural water use has been accompanied by increasing environmental (4.5×10^9 m^3 $decade^{-1}$), domestic (2.1×10^9 m^3 $decade^{-1}$) and industrial (1.6×10^9 m^3 $decade^{-1}$) water use. Agricultural water use percentage decreased from more than 70% in 2003 to approximately 62% in 2017. All the provinces in north China show decreased agricultural water use percentages, except for Shanxi. In north-east China, industrial water use decreased (-2.7×10^9 m^3 $decade^{-1}$) with increasing agricultural water use, and the agricultural water use percentage increased rapidly from 67.4% in 2003 to 78.9% in 2017.

In south-west China, domestic and environmental water withdrawal also increased as agricultural water use increases, resulting in the stable percentage of agricultural water use in recent years. In south central China, domestic and industrial water withdrawals increase more rapidly as agricultural water use increases, resulting in a decrease of agricultural water use percentage from 56.9 to 53.6%. In south-east China, domestic water withdrawal increases as agricultural water use decreases, and the agricultural water use percentage decreased from around 55 to 50%.

4 | CHALLENGE: LIMITED WATER RESOURCES FOR IRRIGATION DEVELOPMENT

China has a growing population and the latest census estimates that the population will reach a peak of 1.45 billion in 2030. If the grain food per capita increases from 445 kg in 2017 to 470 kg in 2030 (Du et al., 2014), then at least a 10% increase in grain production from 618×10^6 t in 2017 to 682×10^6 t in 2030 is needed. The increasing food demand requires that the irrigated area keeps expanding in the next decade. However, agricultural water use has been decreasing since 2013, indicating that the water resources for irrigation have reached their limit in many regions of China. Water scarcity can be aggravated in the northern part of China and in several basins in the southern part of China (Wang et al., 2017). In addition, the studies reveal that due to climate change, the water supply and demand gap in the northern part of China will increase under future climate scenarios (Wang et al., 2017). Therefore, irrigation water use will likely decrease in the future, especially considering the increasing competition from other sectors. However, it should be noted that precipitation increased significantly

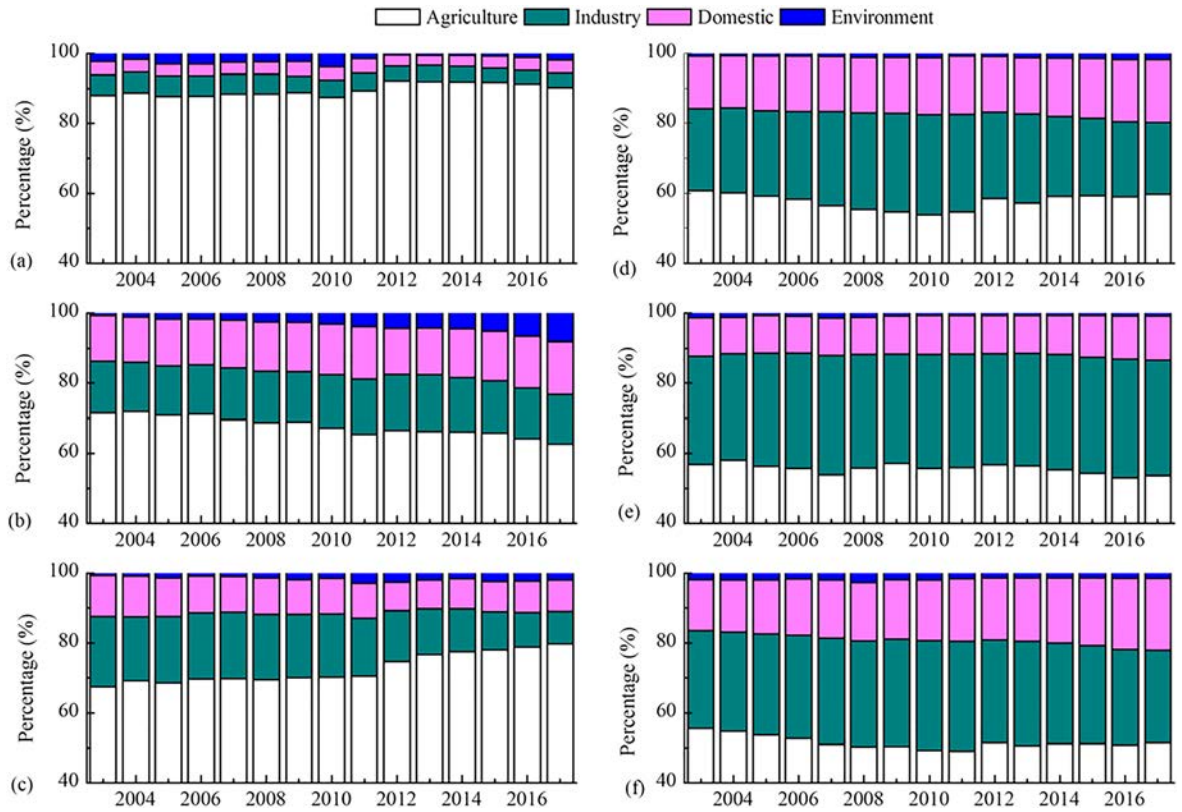

FIGURE 4 Percentages of water use by sector in (a) north-west, (b) north, (c) north-east, (d) south-west, (e) south central and (f) south-east China during 2003–2017. The data are from the provincial *Water Resources Bulletin*

from 2003 to 2017, which may also contribute to the recent decline in irrigation water use. Uncertainties of future changes of irrigation water use may be introduced by more frequent droughts (Han et al., 2017; Tian et al., 2019).

Thus, the major challenge for irrigation development in China are the limited water resources. China's government has adopted water-saving policies as the state strategy to increase irrigation efficiency and water productivity for the sustainable use of water resources. However, different regions face different problems. North-west China is the most vulnerable area to environmental degradation. The ecosystem and agriculture depend heavily on water, and the competition for limited water resources becomes a serious problem for irrigation development (Du et al., 2014; Liu et al., 2014; Zhou, Wang, & Shi, 2017). Along with the extension of highly efficient water-saving technologies, irrigation efficiency has been increasing significantly since the 2000s, and the irrigation water quota has significantly decreased (-185 mm decade $^{-1}$). However, the water saved through increasing irrigation efficiency is used for further farmland reclamation (Liu et al., 2014) The rapid increase in irrigated area has resulted in the significant increase in total irrigation water use since the 2000s, indicating an evident 'irrigation efficiency paradox' (Grafton et al., 2018). This increase has resulted in serious ecological problems, such as shrinking of oases and desertification of grasslands (Du et al., 2014; Liu et al., 2014). Thus, the increase in irrigation water use cannot be sustainable. Actually, irrigation water use has been decreasing since 2013. To make water resources sustainable, approximately an 8% reduction in irrigation water use in 2030 is planned in the National Modern Irrigation Development Planning approved by the State Council in 2014. The percentage of high-tech irrigated area was 50.6% in 2017, and per area irrigation for farmland is 757 mm, which is the second largest after water-rich south-east China. At present, flood irrigation is still an important irrigation scheme in north-west China. A large space exists to promote irrigation efficiency by adopting highly efficient water-saving technologies in north-west China. However, a direct cap on irrigated area should be conducted while promoting irrigation efficiency to reduce irrigation water use.

North China has the largest groundwater-irrigated area, 61.9% of the total in China. Groundwater plays a crucial role in the rapid irrigation development in north China, especially in the North China Plain. Taking Hebei Province as an example, groundwater

withdrawal in 2017 accounted for 77.2% of the total water used in the province, and fed 73.7% of the irrigated area. Groundwater exploitation for irrigation has led to the severe depletion of the aquifer in the North China Plain (Han et al., 2017; Zheng et al., 2010). There has been general agreement in China about reducing groundwater exploitation, and reducing irrigation water use is inevitable. Along with the establishment of a strict water resource management strategy and the advocacy of highly efficient water-saving technologies, agricultural water use in north China reduced from a peak value of 79.2×10^9 m^3 in 2006 to 69.8×10^9 m^3 in 2017. Accordingly, the water table has risen and the environment of the aquifers has been restored. Groundwater exploitation is planned to be continuously reduced for additional restoration in the National Water Conservation Action Plan. The groundwater for irrigation is planned to be reduced by 10.4×10^9 m^3 by 2030 in the northern part of China (most of which in north China), which is the major challenge for irrigation development in north China. To achieve this target, the increase in irrigated area should be restrained by adjusting cropping structure, adopting crop rotation and a fallow system, and expanding rain-fed crops, in addition to advocating highly efficient water-saving irrigation technologies.

North-east China produces approximately 20% of the food production in China with 13% of the total agricultural water use over 14.1% of the irrigated farmland. As one of China's most important grain-producing areas and an important commodity grain base, north-east China is crucial for ensuring national food security. Irrigation extension has played an important role in increasing grain production in recent years. At present, 65.7% of farmland in north-east China is rain-fed. However, as a region with a serious water shortage, limited water resources are the main obstacle to the continuous increase in grain production. The recent increase in groundwater exploitation for irrigation in north-east China has resulted in the rapid decline of the water table of the shallow aquifers of the Songnen and Liaohe plains (Currell et al., 2012). Thus, the recent rapid increase in agricultural water use is unsustainable. The situation is similar to that in north China in the 1970s, when the groundwater system began to deteriorate because of exploitation for irrigation. To avoid that, north-east China has become 'the second North China Plain' with severe groundwater degradation, adopting precise and water-saving irrigation technologies can help increase grain production with limited water resources.

The southern part of China has abundant water resources, but the arable land is only 40.3% of the national total. The percentages of irrigated farmland to arable land are 73.1 and 57.4% in south central and south-east China respectively. Agricultural water use has begun to decrease in south-east China since 2005, and in south central China since 2013, indicating that limited irrigable land sets a cap on irrigation water use. In south-west China, renewable water resources are the most abundant, but only 33.5% of cultivated land are irrigated. Agricultural water use has increased in recent years in south-west China, but it makes up a small proportion of total agricultural water use in the southern part of China. Because most of the non-irrigated lands in the southern part of China are located in the mountainous area, extending the irrigated area on a large scale is difficult. Therefore, future increase in irrigation water use in south-west China cannot change the fact that the southern part of China has reached its limit in irrigation water use. Water for irrigation in the southern part of China is mainly a management issue (Heilig et al., 2000). A total of 78.9% of rice in China was grown in the three southern regions in 2017. A large amount of irrigation water is drained from paddy fields into water bodies, resulting in serious water pollution. The most urgent issue in the southern part of China is water pollution from paddy rice fields. Reducing drainage is an effective measure to control the water pollution induced by irrigation (Mao, 1996). Thus, promoting water conservation is the major challenge.

5 | CONCLUDING REMARKS

The concluding remarks are as follows:

- during the period 2003–2013, the amount of agricultural water use increased to a peak value of 392×10^9 m^3 in 2013, and a continuously decreasing trend has been witnessed since then. In 2017, China's agricultural water use was 377×10^9 m^3, which was 62.3% of the total water use for the whole of China;
- agricultural water use began to decrease in south-east and north China around 2006, and in north-east, south central and north-west China around 2013, whereas agricultural water use only keeps increasing in south-west China, with small-scale agricultural water use. The conclusion is that irrigation water use has reached its limit in China. In northern regions, the water scarcity situation sets a cap on irrigation water use, which can also be limited by the use of water by other sectors. In the southern regions, limited irrigable land sets a cap on irrigation water use, which can also be limited by urbanization;

- the major challenge for irrigation development in China are the limited water resources. China's government has adopted water-saving policies as the national strategy to increase irrigation efficiency and water productivity for the sustainable use of water resources. Specifically, the challenges are to increase irrigation efficiency by reducing water consumption in northwest China, to reduce groundwater exploitation to restore aquifers in north China, to increase food production to ensure national food security in north-east China, and to promote water conservation to control pollution in the southern regions.

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