DOI 10.15302/J-SSCAE-2018.05.002

Agricultural Water Resources in China and Strategic Measures for Their Efficient Use

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Abstract: Over the 21st century, the cultivated areas, irrigated areas, and main grain-producing zones in China have been gradually concentrated in the north of the country. The north-to-south transportation of grain has further aggravated the dislocation of land and water resources, which has led to increased stress on agricultural water resources and the unsustainable exploitation of underground water in the main grain-producing zones to the north of the Yellow River. To ensure national food security and provide rational basic guarantees for agricultural water resources, this study employed the irrigation quote method to calculate the minimum thresholds of farmland irrigation water requirements in 2025 and 2030. This was done by adjusting for the irrigation method with a rational irrigation scale constrained by grain consumption demand and the projected limit of future total water use. Thresholds were calculated based on the analysis of the agricultural water resources situation, grain production and consumption, spatial distribution characteristics of food crop irrigation water requirements, and cropping areas that are adaptive to precipitation in China. The results showed that to meet the water demand for high-standard farmland of 66.67×10^6 hm^2 in the future, a minimum of 3.23×10^{11} m^3 of irrigation water should be guaranteed. Water-saving measures must be strengthened, and approximately 6.44×10^9 m^3 of unconventional water should be exploited to supplement the supply of fresh water. Strategic measures were proposed, including establishing water-saving and high-efficiency modern irrigation farming, as well as rainwater-collecting farming systems and high-efficiency dry farming systems. To this end, the following measures should be stressed: cropping that is adaptive to precipitation should be promoted to improve the efficiency of rainwater utilization, engineering and agronomic measures should be taken to increase the utilization efficiency of irrigation water, utilization of unconventional water resources should be increased, and water resource management should be enhanced.
Keywords: agricultural water resources; irrigation threshold; modern dry farming; modern irrigation farming; precipitation adaptation; strategic measures

The total amount of water resources per capita in China is low, and is unevenly spatio-temporally distributed. Resultantly, China has a strong dependence on irrigation for food security, with grain production increasing with an enlarged irrigation area. In 2015, the area of China's effective irrigated farmland reached 6.587×10^7 hm^2 [1], which accounted for 48.8% of the total cultivated area. The size of the area that employed water-saving irrigation methods was 3.107×10^7 hm^2, which accounted for 47.2% of the effective irrigation area. The efficiency coefficient of farmland irrigation water reached 0.536, which increased by 14.1% in the past 10 years. The average water consumption per hectare in the actual irrigation area decreased by 85 m^3 compared to that in 2001. This improvement in irrigation water efficiency has ensured a 12 year continuous increase in grain production.

Received date: September 10, 2018; **Revised date:** September 20, 2018
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Funding program: CAE Advisory Project "Research on Key Strategic Issues of Agricultural Resource and Environment in China" (2016-ZD-10)
Chinese version: Strategic Study of CAE 2018, 20 (5): 009–015
Cited item: Wang Hao et al. The Situation of the Agricultural Water Resources and the Strategy of Improvement Use Efficient in China. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2018.05.002

1 China's agricultural water situation

Since 2001, the amount of the agricultural water use in China has remained almost constant, with about 3.86×10^{11} m^3 used annually, while the total agricultural water use as a percentage of total water utilization decreased to 63.1% by 2015. However, the effective irrigation area has continued to move northward. Until 1996, the ratio of the amount of water used for agricultural purposes to the total amount of water used was greater in the south than in the north. Since 1996, this situation has reversed with the shift of water and land resources toward non-agricultural industries. The deficiency in irrigation water exceeds 3×10^{10} m^3 based on a multi-year average [2], which means that irrigation-based agriculture in China faces severe challenges.

1.1 The increasing degree of agricultural water stress in north China with an intensifying drought and water shortage

In China, the multi-annual average water resources were 2.8×10^{12} m^3 under the hydrological series of 1956–2000, of which 18.8% was in the north and 81.2% was in the south. Since 2000, the total water resources have decreased by 5.5%, but the north-south spatial distribution has changed little. However, the cultivated area has concentrated toward the north with an increasing trend from 55.5% in 2000 to 59.6% in 2015. This spatial disparity between water resource distribution and cultivated areas means that there is a greater amount of water resources per unit of cultivated land in the south than in the north. The amount of water resources per unit of cultivated land in the north was 1/6 of that in the south in 2015. In the next 50 years, the expected increase in temperature in China will further aggravate agricultural drought and water shortages.

In 2015, China's total grain production quantity was 6.21×10^8 t [3], which was distributed as 56.1% in the north and 43.9% in the south. From the view of the relationship between food production and consumption in the years 2007 and 2015, the number of major grain-producing regions decreased from 13 provinces [4] in 2007 to 7 provinces in 2015, and were continuously concentrated in the north. The six provinces that traditionally produce a grain surplus, namely Hubei, Jiangxi, Liaoning, Jiangsu, Hunan, and Sichuan, gradually reached balanced grain production and consumption. In 2007, the number of major grain-consuming regions increased from 7 to 13, including the 6 traditionally balanced provinces of Qinghai, Tibet, Guangxi, Guizhou, Chongqing, and Yunnan. This change in the distribution of grain-producing regions and grain-consuming regions aggravated the dislocation of cultivated areas and water resources and increased the stress on potential agricultural water resources.

1.2 The increasing dependence of agricultural development on irrigation due to the mismatched distribution of crop planting layout and precipitation

Nationally, five of the seven main grain-producing areas, including the Northeast Plain, Huang-Huai-Hai Plain, Fen-Wei Plain, Hetao Irrigation Area, and Gansu-Xinjiang, lie in perennial irrigation and supplementary irrigation regions. Approximately 60% of the more than 800 major grain-producing counties lie in perennial irrigation and supplementary irrigation areas. From 2001 to 2015, China's rice planting area increased by 140.3×10^4 hm^2, of which 181.7×10^4 hm^2 was in the north. Although the wheat planting area decreased by 52.3×10^4 hm^2 (comprising 253.1×10^4 hm^2 in 2015), the north still accounted for 67.6% of the total wheat planting area, of which 48.4% of the national total planting area was distributed in the Huang-Huai-Hai Plain. Approximately 88% of the 24.87×10^6 hm^2 of increased maize planting area lies in the north. With the transfer of the main grain-producing areas and the plantation areas of three major grain crops to the northern perennial irrigation area and supplementary irrigation area, the demand for irrigation water has shown an increasing trend.

1.3 The continuous decline in the shallow groundwater table in North China with the increasing amount of groundwater exploited for irrigation

According to the China Water Resources Bulletin [5], with the exception of the Songhua River area, the exploitation and utilization rate of water resources in the north of China exceed the internationally recognized warning level of 40%. Of these, the North China region is the highest, reaching 118.6%. The exploitation and utilization rate of groundwater resources, except for those in the Northwest River area, is increasing in all other areas, and in North China has reached 105.2%. Groundwater levels continue to decline in the Huang-Huai-Hai Plain, Songliao Plain, and piedmont plain of the northwest inland basin.

Owing to the planting of winter wheat and summer maize in the North China Plain, agricultural groundwater consumption has been increasing continuously, and has formed three deep groundwater funnel areas of

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Ji-Zao-Heng, Cangzhou, and Nangong. According to relevant statistics, about 6.8×10^9 m^3 of groundwater is overexploited in the Beijing-Tianjin-Hebei region each year. The total amount of overexploited groundwater is more than 1×10^{11} m^3. The overexploitation area accounts for over 70% of the total plain area [6].

1.4 Lower efficiency of agricultural water use because of the delayed implementation of high-efficiency water-saving projects and information technology

The decentralized water use model, which was formed as part of the long-term land decentralized operation mode, has led to the current simple methods of water-saving irrigation, a small-scale irrigation area, and a low proportion of high-efficiency water-saving irrigation areas, as well as difficultly implementing water-saving irrigation systems. Together, these cause low water resource utilization efficiency. In 2015, China's efficient water-saving irrigation area covered 17.93×10^6 hm^2 [1], which accounted for 27.2% of the effective irrigation area. The areas with sprinklers and micro-irrigation, which has a high water-saving rate, only accounted for 13.7% of the effective irrigation area, which was far less than that of developed countries in 2000. The effective utilization coefficient of the national agricultural irrigation water was 0.536 with 0.58 in the north and 0.51 in the south, which was only 75% of that in developed countries. At present, the irrigation area monitoring system has not been established with elaborated water meters, and the construction of information projection for farmland water conservancy is in the pilot and exploratory stages. The price of agricultural water is relatively low, and less than 70% of water charges are collected. The operating funds in more than 40% of the irrigation area management units are not guaranteed. The delayed informatization construction of irrigation projects and the absence of a management system restrict the wider promotion and effect of water-saving irrigation technology.

2 Analysis of the threshold value of agricultural water demand for grain production security in China

The degree of exploitation of the surface water resources in most areas of northern China has exceeded the upper limit of allowable exploitation. Groundwater has also been seriously overexploited. The utilization of groundwater in the main grain-producing areas to the north of the Yellow River is on the verge of crisis and difficult to sustain. Strengthening water-saving measures and establishing modern irrigation agriculture and a modern drought farming system are important tasks for improving the efficiency of agricultural water resources and ensuring the creation of 6.67×10^7 hm^2 of high-standard farmland. By 2030, by which time modernization of irrigation will have been largely realized, the minimum amount of utilized agricultural irrigation water will be 3.73×10^{11} m^3 in China, the effective farmland irrigation area will reach 6.9×10^7 hm^2, and the proportion of this area implementing water-saving irrigation measures will reach 74%, of which the efficient water-saving irrigation rate will be up to 44%. By this time, the effective utilization coefficient of farmland irrigation water will increase to more than 0.60, and the grain yield per cubic meter of irrigation water will have exceeded 1.60 kg.

2.1 China's grain production and consumption

According to the National Statistical Yearbook [3], China's total grain production increased by 37.3% from 2001 to 2015. The proportion of this grain produced in the north increased from 43.9% to 56.1%. The plantation area of the three major grains, namely rice, wheat, and maize, was concentrated in the north. Among them, winter wheat was mainly grown in the Huang-Huai-Hai Plain, Shaanxi Guanzhong Plain, Hubei, Sichuan Basin, and Xinjiang. The dominant distribution zones were Shandong, Henan, Anhui, and Hebei provinces with a production of 8.413×10^7 t, and the corresponding grain production accounted for 70% of the total national production. Rice (medium-season rice) was mainly distributed in Heilongjiang, Jiangsu, Sichuan, Anhui, Hubei, Hunan, and Yunnan. Its production was 9.434×10^7 t, which accounted for 69.7% of the total national production. Maize was mainly distributed in the eight provinces (regions) of Northeast China, Inner Mongolia, Shanxi, Hebei, Shandong, and Henan. The planting area was kept at 900 hm^2 to 1000 hm^2 in the four provinces of Liaoning, Jilin, Heilongjiang, and Inner Mongolia, which accounted for about 40% of the national maize production.

Based on changes in consumption, the relationship between grain production and consumption in China have the three following characteristics. (1) Grain production is greater than consumption, but regional development is uneven. In 2015, 6.06×10^8 t of four major grain crops, i.e., rice, wheat, maize, and potato, were produced in China, while the corresponding consumption reached 5.82×10^8 t and self-sufficiency remained at 104%. In spatial terms, the grain production in the north is greater than the corresponding consumption, with the south presenting the contrary. (2) Taking the balance rate of grain production and consumption (the ratio of the difference between production and consumption to consumption) as the index, China's current main grain-producing provinces have decreased and become concentrated in the north, and the main consumption provinces have increased in the south. We used a threshold of a 10% difference between the production and consumption as the measure of a non-balanced area; areas with a production contribution rate greater than 3% were taken as main producing areas, those with a production-consumption balance rate less than −10% were seen as main consumption areas, and those with a production-consumption balance rate between −10% and 10% were seen as the balance areas. Using these criteria and comparing 2015 with 2007, the main grain-producing areas were concentrated in seven provinces (cities and autonomous regions), namely Heilongjiang, Jilin, Inner Mongolia, Henan, Anhui, Hebei, and Shandong, in 2015. The main producing areas of Hubei, Jiangxi, Liaoning, Jiangsu, Hunan, and Sichuan provinces became balanced areas. The main food consumption areas reached 13 provinces (cities and autonomous regions), namely Beijing, Shanghai, Guangdong, Tianjin, Zhejiang, Fujian, Qinghai, Hainan, Tibet, Guangxi, Guizhou, Chongqing, and Yunnan, with 6 newly added provinces (cities and autonomous regions), namely Qinghai, Tibet, Guangxi, Guizhou, Chongqing, and Yunnan, compared with the situation in 2007. The food balance areas then included 11 additional provinces, namely Ningxia, Xinjiang, Gansu, Jiangsu, Jiangxi, Hubei, Liaoning, Shanxi, Hunan, Shaanxi, and Sichuan, of which Liaoning, Jiangxi, Hubei, Hunan, and Sichuan originally belonged to the main producing areas, while the provinces originally belonging to the balance areas, namely Guangxi, Chongqing, Guizhou, Yunnan, Tibet, and Qinghai, became the main consumption areas. (3) The food gap, which was mainly related to the lack of forage food and industrial food in the south, widened.

At present, China's grain production can be divided into three major producing areas, namely the Northeast Plain, North China Plain, and Central-lower Yangtze Plain. The eight provinces of Heilongjiang, Jilin, Inner Mongolia, Henan, Anhui, Hebei, Jiangsu, and Shandong are the main net output provinces, and have become an important support for China's southern grain demand. The southeast region is the key input area for north-south grain transportation.

2.2 Spatial distribution and regional transfer of irrigation water (blue water) demand

The local Moran's I index [7] was used to analyze the spatial distribution of the provincial total water demand of three major crops, namely rice, wheat, and maize, the irrigation demand for irrigated areas, and the irrigation water (blue water) demand to produce 1 kg of grain in the irrigation area. Meanwhile, the ratio of the provincial value of blue water demand for per unit of *i*-th crop production to the national average value was applied to identify the precipitation-adaption plantation area for the three main grain crops. The results were as follows.

Rice: The areas with the lowest blue water demand were located in the six provinces of Sichuan, Chongqing, Guizhou, Hubei, Jiangxi, and Zhejiang. Their blue water demand per unit of rice production was less than or equal to 60% of the national average blue water demand. These were followed by the three northeastern provinces of Heilongjiang, Jilin, and Liaoning and the southern provinces of Hunan, Fujian, Yunnan, Guangxi, Guangdong, and Hainan, the blue water demands of which were less than or equal to the national average level.

Wheat: The area with the lowest blue water demand was located in the provinces in the middle of China's continental belt, including Jiangsu, Anhui, Henan, Hubei, Shaanxi, and Sichuan. The blue water demand per unit of wheat production in these provinces was less than half of the national average level. In the provinces of Shandong, Hebei, and Qinghai, the blue water demand was less than or equal to the national average level.

Maize: The blue water demand presented the characteristics of block spatial distribution. The blue water demand per unit of maize production was less than or equal to the national average level in the following three main areas: (1) the northeast regions of Heilongjiang, Jilin, and Liaoning; (2) the south regions of Yunnan-Guizhou-Sichuan, Guangxi, and Hunan provinces; and (3) the central regions of Shandong, Shanxi, and Anhui, among others. Especially in the first two areas, the blue water demand was less than half of the national average level.

In general, the total water demand of China's grain crop production as well as the dependence on blue water for irrigation were greater in the north than in the south. However, the blue water demand per unit of grain production was smaller in the north than in the south, and that in the main grain-producing areas was smaller than that in the balanced areas and the main consumption areas (Fig. 1). It was shown that the water utilization efficiency of grain production was higher in the north than in the south under the current grain production conditions. The maximum efficiency was reached in the main producing area, followed by the balance area, and was smallest in the main distribution area.

DOI 10.15302/J-SSCAE-2018.05.002

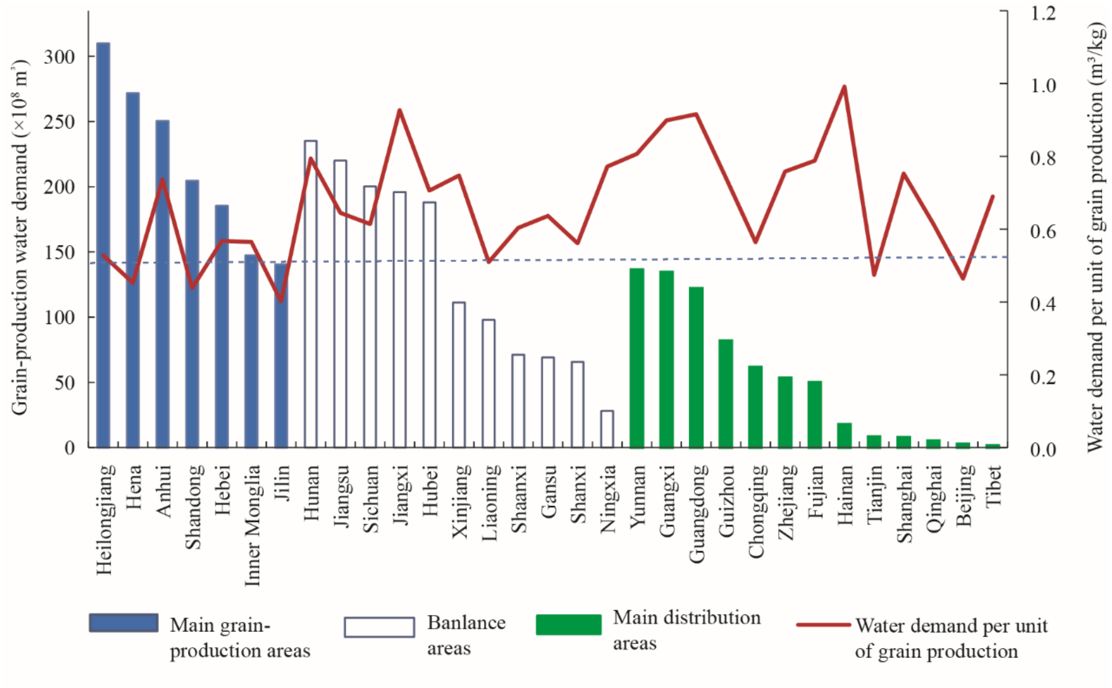

Fig. 1. The grain production water demand of the provincial administrative areas and the virtual water demand per unit of grain production in 2015.

According to the calculation of the difference between grain production and consumption multiplied by the irrigation water (blue water) demand per kilogram of grain production, 2.079×10^{10} m^3 of irrigation water (virtual water) was associated with surplus grain in major producing provinces in 2015, the amount of water associated with the shortage of grain was about 2.862×10^{10} m^3 in the main consumption provinces, and the slight surplus of grain in the balanced provinces included about 5.41×10^9 m^3 of irrigation water. In 2015, the total grain surplus in the 11 northern provinces, namely Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shandong, Henan, Ningxia, Gansu, and Xinjiang, was 1.23×10^8 t, which accounted for 91.2% of the national grain surplus, of which the irrigation water associated with grain products reached 2.29×10^{10} m^3. Because of the grain circulation from north to south, the northern water shortage and the imbalance of the north and south water resources were intensified. The amount of provincial virtual water transformation is shown in Fig. 2.

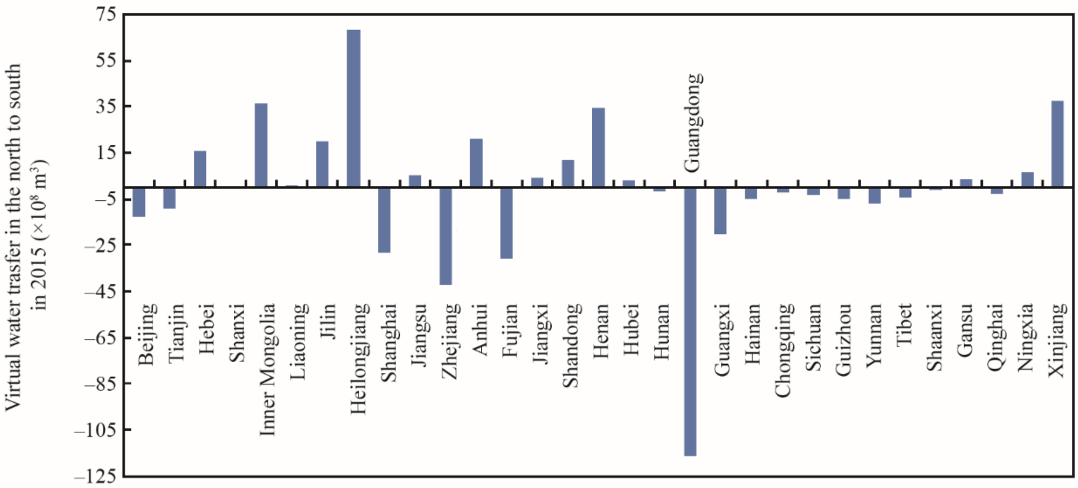

Fig. 2. The virtual water transfer in the north-south grain circulation in 2015.

2.3 Analysis of the lowest water demand threshold for ensuring China's future grain security

Under the present situation, with a daily mismatch between cultivated areas and water resources, the increasingly prominent contradiction between water supply and demand, and the transportation of grain from north to south, the pressure on water resources in the north has been further aggravated. To alleviate the shortage of water, the main way to guarantee grain security and improve water utilization efficiency is to fully exploit the utilization potential of natural precipitation (green water) and reduce the utilization rate of irrigation water (blue water). With the aim of ensuring the security of grain supply, this study predicted the irrigation area and the lowest threshold value of irrigation water demand for farmland based on the following three basic principles in agriculture water utilization: 1) ensuring the lowest possible level of basic agricultural water use and abiding to the irrigation amount determined by this allowable amount; 2) using the equal attention principle of increasing supply and reducing consumption with the priority of water conservation; and 3) optimizing the distribution of crop planting considering efficient water use and the benefit of its consumption.

2.3.1 Irrigation area

With the goal of meeting the future grain consumption demand and the constraint of controlling the level of total water consumption, the irrigation area was predicted using the quota method in combination with the National Modern Irrigation Development Plan (2012–2020) [8] and the precipitation-adaptive plantation zones of the major grain crops.

By 2025, the national irrigation area will reach 7.5×10^7 hm^2, of which 6.8×10^7 hm^2 of effectively irrigated cultivation areas will be ensured. The effectively irrigated cultivation area in the northern region will account for 56.1% of the total national area, and will be mainly concentrated in the six provinces (regions) of Heilongjiang, Shandong, Henan, Xinjiang, Hebei, and Inner Mongolia. The irrigation area in Heilongjiang will be the largest, and account for about 10% of the national area. According to statistics of the 10 major agricultural zones, the cultivated area will be distributed as follows: 15.5% in Northeast China, 22.3% in North China, 25.9% in the Yangtze River Basin, and less than 7% in other areas.

By 2030, China's irrigation area will reach 7.63×10^7 hm^2, of which 6.9×10^7 hm^2 will be effectively irrigated cultivated areas, and the increased areas will mainly be distributed in Heilongjiang, Jilin, Inner Mongolia, Sichuan, Shandong, and Hubei. The proportions of the effectively irrigated cultivation areas in China will be 16.6% in Northeast China, 22.1% in North China, 25.4% in the Yangtze River Basin, and less than 7% in other areas (Fig. 3).

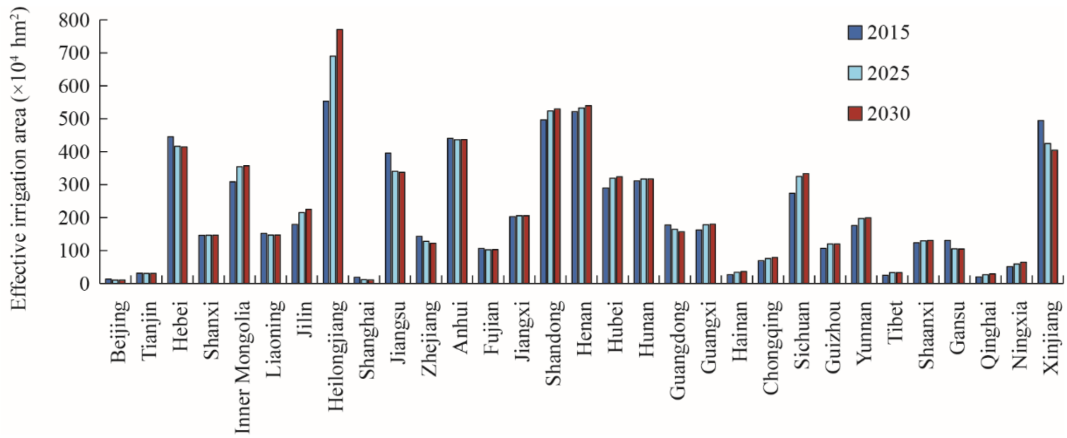

Fig. 3. The distribution of effective irrigation areas in provincial administrative regions in 2015, 2025, and 2030.

2.3.2 The lowest threshold of irrigation water demand for farmland

Associated with the demand for irrigation water and the available irrigation water for farmland, in order to safeguard the future demand of water for 6.67×10^7 hm^2 of high-standard farmland, comprehensive water-saving measures, such as strengthening water-saving projects, precipitation-adaptive planting, and optimized planting structures, should be furthered. By 2025 and 2030, the effective utilization coefficient of irrigation water should be improved by 0.575 and 0.600, respectively, from the present level of 0.536. Based on the effective irrigation area and the effective utilization coefficient, the farmland irrigation water demand will reach 3.705×10^{11} m^3 and 3.604×10^{11} m^3 in 2015 and 2030, respectively. Based on the calculated irrigation area (converted by multiplying the effective irrigation area by the ratio of the actual irrigation area to the effective irrigation area), the farmland irrigation water demand will reach 3.12×10^{11} m^3 and 3.031×10^{11} m^3 in 2025 and 2030, respectively. Under these

DOI 10.15302/J-SSCAE-2018.05.002

conditions, the total water shortage in the water-deficient provinces will be 1.096×10^{10} m^3 and 6.44×10^9 m^3, respectively.

In conclusion, to ensure that the water demand for 6.67×10^7 hm^2 of high-standard farmland is met in the future, it is necessary to guarantee the lowest water supply baseline of 3.23×10^{11} m^3 for farmland irrigation. At the same time, unconventional water sources of about 6.44×10^9 m^3 should be rationally developed.

3 Strategic measures for efficient utilization of agricultural water resources

At present, the major grain production problem in China has shifted from a quantity shortage to structural imbalance, where the mismatch between water resources and grain production in the north and south has been intensified with grain production transfer to the north. Under these new conditions, integrated water-saving measures should be taken to ensure grain security according to local conditions. In the northern region, a combination of intensive land utilization and production-efficient water-limiting irrigation (regulated deficit irrigation) systems should be implemented, and adjustment of the planting structure should take into account southward wheat migration and an agropastoral transitional zone. In the south, basic measures should be considered by stabilizing the basic farmland area and controlling drainage-suitable irrigation, collectively developing fruits and grasses, and developing green manure planting in winter.

3.1 Development of modern irrigation agriculture with high water efficiency

Under the condition of the current planting structure and irrigation water level, the major grain-producing areas should adopt the following comprehensive water-saving measures according to local conditions. This will ensure demand is met for a 6.67×10^7 hm^2 by achieving an average water savings of 900−1200 m^3/hm^2 in 2030.

3.1.1 Extension of high-efficiency irrigation technology and channel seepage prevention technology

High-efficiency, water-saving irrigation technologies dominated by sprinkler irrigation and micro-irrigation should be developed in order to improve irrigation efficiency. By 2025, the water-saving irrigation area will reach 5.167×10^7 hm^2, of which sprinkler irrigation, micro-irrigation, and pipeline irrigation will cover up to 2.8×10^7 hm^2. By 2030, the water-saving irrigation area will reach 5.667×10^7 hm^2, of which sprinkler irrigation, micro-irrigation, and pipeline irrigation will be up to 3.333×10^7 hm^2. In north China, with its severe shortage of water, pipeline irrigation, sprinkler irrigation, and micro-irrigation should be widely used.

3.1.2 Cropping that is adaptive to precipitation and wheat southward migration to alleviate the growth in irrigation water demand

It should be an aim to optimize the distribution of grain crops by cropping that is adaptive to precipitation based on the basic production holdings and according to regional characteristics of crop water demand and irrigation water quantity. Through the implementation of these measurements along with southward wheat migration, cropping that is adaptive to precipitation, and controlling the deficit irrigation system, the production of winter wheat in China’s advantageous areas will be stabilized. The wheat in North China, which lies in highly overexploited groundwater, should be reduced and replaced with drought-resistant winter rapeseed and silage maize, drought-resistant and saline-tolerant cotton, and oil anemone and potatoes to constrain the water demand of winter wheat. At the same time, to alleviate the water demand of the North China winter zone, the minimum irrigation water demand should be ensured for the production of rice and wheat in North China.

In the vast semi-arid and arid areas in the north, the plantation area of maize should be further compressed to restore the growth of drought-tolerant crops, such as millet, sorghum, naked oats, buckwheat, and herbage. Regions that are sliding into the main consumption zone from the main production zone, such as the Yun Gui Zone and Guangxi Province, should focus on adjusting the planting structure, with a particular focus on moving from forage grass planting to grain crop planting, which will be beneficial to reduce groundwater exploitation and fertilizer application and improve the utilization efficiency of natural precipitation through the relationship of cross-province sales of the maize resources in northern China. Meanwhile, the feed grain self-sufficiency in the north and south should be increased to reduce the pressure of north-south grain transportation.

3.1.3 Exploiting the potential efficiency of crop water use by promoting a deficit irrigation system

Regulated deficit irrigation should be promoted vigorously to limit the amount of water used in the sensitive crop water deficit period so as to reduce the influence of water stress on crop yield. Under multi-year average conditions in the North China Plain, the amount of irrigation water is 1500–3000 m^3 per hectare when wheat and maize are both ripening with the regulated deficit (or deficit) irrigation system for winter wheat and the rain-fed system of summer maize. Compared with the conventional irrigation mode, the amount of water saved is 750–1500 m^3 per hectare, and the reduction in wheat yield per hectare is less than 13% under the responding irrigation system. If the stable production were about 15 000 kg/hm^2, then the water utilization efficiency of crops could be improved by about 10% compared with that in the traditional irrigation system, which means that 6.93×10^6 hm^2 of wheat fields could be irrigated in North China under allowable water conditions. To gradually reduce the amount of groundwater that is overexploited and to achieve the rehabilitation of groundwater in an orderly manner, this development should abide by the following measures: agricultural irrigation areas should be developed according to the water resource conditions, grain and grass rotation should be promoted in non-irrigated areas, and agriculture modes with a combination of planting-breeding and other dry planting modes should be promoted.

Rice irrigation control measures should be adopted in Northeast China. The amount of irrigation water could be reduced from 5025 m^3/hm^2 to 3150 m^3/hm^2, and the yield per hectare should be increased by about 5% under the control irrigation mode. In the middle and lower reaches of the Yangtze River and Sichuan Basin, the amount of irrigation water could be reduced from 7800 m^3/hm^2 to 4650 m^3/hm^2 by adopting “shallow, thin, wet, and dry” irrigation measures, and the yield per hectare could be increased by approximately 13%.

3.1.4 Strengthen agricultural water-saving techniques to reduce inefficient water consumption in farmland

To improve the ability of soil to absorb and retain water and to reduce inefficient water consumption in farmland, the following agricultural water-saving measures should be implemented: a reasonable arrangement of farming and cultivation systems; selection of water-saving high-yield crop varieties; vigorous promotion of deep loosening for soil preparation; weeding; reducing intensive farming; retaining moisture; increasing organic fertilizer application; and reasonable use of biological drought-resistant agents, soil water retention agents, and other technologies.

In North China, these methods should be vigorously promoted by the combination of water-saving and stable production technologies for winter wheat (water-saving and drought-resistant varieties + deep loosening of soil/returning straw to field/post-sowing repression + jointing-booting water) and the water-saving technology model of winter wheat conservation tillage (no-tillage/low-tillage + returning straw to field + multiple operations of wheat no-tillage planting). Since corn planting and rainfall are during the same season, measures including the strengthening of tillage and returning wheat straw to the field should be implemented to promote precipitation conservation in the rainy season and increase production and income.

In Northeast China, these measures should be popularized by using straw mulching and plastic mulch technologies, deep loosening technology for farming, technology to return straw to the field, sitting water planting technology, and organic fertilizer technology.

In Northwest China, the integrated technology of drip irrigation and fertilizer under mulch should be actively developed with rational use of drought-resistant agents, water-retaining agents, and other measures so as to reduce the inefficient water consumption of farmland.

3.1.5 Strengthening management to protect groundwater resources

With the aim of total control of water utilization and enhanced management, a balance between mining and compensation should be achieved by the reasonable exploitation and utilization of shallow groundwater and limiting the exploitation of deep groundwater. In areas with rich shallow groundwater resources, the combination of wells and channels should be adopted to make efficient use of water resources. In areas with serious overexploitation of groundwater, the exploitation and use of groundwater should be strictly controlled to save local water. The amount of local water saved and the amount of externally diverted water under water-saving conditions should be rationally regulated when deep groundwater is taken as a strategic reserve resource. Modern water-saving agriculture should be developed, alternative sources of groundwater should be increased, and the exploitation of groundwater should be reduced through comprehensive treatment to restore groundwater ecology.

For the seriously overexploited area of groundwater in the North China Plain, the agricultural land use mode should be adjusted according to local conditions, changed to forage grass to develop animal husbandry, or converted to leisure, sightseeing, or tourism to develop low-water-consumption agriculture so as to gradually restore the underground water level.

DOI 10.15302/J-SSCAE-2018.05.002

3.2 Development of modern drought farming by collecting rainwater and increasing rain efficiency

The multi-year average precipitation in China is about 6.19×10^{12} m^3, 56% of which is consumed by evaporation from the land surface and evapotranspiration of vegetation. In combination with the characteristics of the regional precipitation, various rainwater collection facilities should be built to improve the storage and utilization of precipitation. Based on the rainwater collection agriculture project including the four measures of engineering, agronomy, chemical control, and biology, modern supplementary irrigation technology should be applied to develop efficient and drought-adapted agriculture.

For the Loess Plateau dry area, owing to issues with low and unstable grain production and low production efficiency, a comprehensive development mode and technical system of drought agriculture with stable production and efficiency, such as the mode of "precipitation adapting cropping + rainwater collection irrigation water saving system + agronomic measures + ecological measures" should be established. The terraces and warping dams should mainly be constructed with the aim of promoting agricultural development.

For the northwest semi-arid and drought-prone areas, to solve the problems of climatic drought and high winds during the winter and spring seasons, the agricultural development model and technical system of water accumulation and soil conservation in dry farming should be established with the main aim of protecting the dry land environment and improving the production capacity of the planting industry.

For the semi-arid region of northwestern North China, owing to the serious shortage of water resources per capita, an unsustainable grain-cash crop-forage structure and low straw utilization rate, among others, the main direction of improvement in the output efficiency of water resources should be the establishment of a farming-grazing combination type of drought agricultural development mode and technical systems. An example includes the mode of "structural adjustment + coverage for moisture conservation and fertilization + rainwater supplementary irrigation + conservation tillage + chemical regulation."

For the semi-arid area in the western part of Northeast China, with the aim of tackling unstable grain yield with low economic benefits and other problems, the main direction of improving the drought agricultural production efficiency should be focused on changing from downslope to cross slope planting, establishing a comprehensive development mode and technical system associated with the integrated development of grass-grains and forest grains, and promoting the pattern of "increasing organic fertilizer + mechanical deep loosening + mechanical anti-drought sitting-water planting."

3.3 Strengthening the use of unconventional water resources

Technologies including unconventional agricultural water irrigation zoning, pollution identification, rational irrigation, monitoring and evaluation, and integrated application technology should be strengthened to ensure the safety of the unconventional water development and utilization process and their aftereffects. Reasonable safeguarding mechanisms and incentive policies should be formulated to promote unconventional water use patterns according to local conditions.

(1) For the utilization of renewable water, the amount of reclaimed water after sewage treatment in China is predicted to reach 1.365×10^{10} m^3 by 2030, with about 9.02×10^9 m^3 available after allowing for the current utilization amount (about 4.63×10^9 m^3 in 2014). Under the strict control and processing conditions for adequate water quality standards, different use patterns should be conducted according to the different local conditions.

(2) For the utilization of brackish water, the irrigation amount of underground brackish water with a salinity of 2–5 g/L in China is about 2.26×10^5 m^3, which is mainly distributed in the Haihe River Basin, western Jilin Province, central Inner Mongolia, and Xinjiang. Based on the full understanding of the soil buffer capacity and plant salt resistance, irrigation methods should be selected according to the various local conditions.

4 Conclusions

Profound changes are taking place in China's agricultural cultivation model, production mode, and operation. The development of agricultural irrigation is gradually moving into a new normalcy of moderate scale, full mechanization, high intensification, and strict constraints on resources and the environment. In the future, under conditions of a relatively stable agricultural water supply, the agricultural irrigation mode must shift from an inefficient extensive mode to a more suitable high-efficiency mode. To support the development of an efficient, precise, intelligent, and environmentally friendly modern agriculture irrigation system, traditional water-saving irrigation engineering measures should be combined with modern sciences and technologies, such as 3S technology, Internet of Things technology, artificial intelligence technology, and crop water use control technology. The scale and methods of irrigation should be adjusted in accordance with the carrying capacity of the available water resources. Modern drought agriculture should be practiced, with cropping that is adaptive to precipitation and the construction of water-harvesting facilities, and rain-collecting facilities such as rain-collecting cellars should be constructed in farmlands. Overall, it is necessary to develop modern drought farming and to develop modern irrigation agriculture and modern drought farming systems that are compatible with the new agricultural management system.

Acknowledgments

The authors express their sincere gratitude to all who provided help in this study. This study was supported by the Major Consulting Project of the Chinese Academy of Engineering (No. 2016-ZD-10-01).

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