

Water Use Features of Typical Crops and Technical Modes of Modern Agriculture Irrigation in China

Zhang Baozhong^{1,2}, Peng Zhigong^{1,2}, Lei Bo^{1,2}, Du Lijuan^{1,2}, Wang Lei^{1,2}, Liu Yu^{1,2}

1. State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China

2. National Center of Efficient Irrigation Engineering and Technology Research–Beijing, Beijing 100048, China

Abstract: Surveys of the features of crop water use, and technical and modern systems of agricultural irrigation, are of instrumental and practical value to improve the efficiency of agricultural water use and achieve sustainable utilization of agricultural water resources. This study analyzes the irrigation schedules of typical crops, in particular those covering the Huang–Huai–Hai Plains wheat belt (the Yellow, Huai, and Hai Rivers), Northeast rice belt, rice belt in the middle and lower reaches of the Yangtze River, Sichuan Basin rice belt, eastern Inner Mongolia pasture, Guangxi sugar cane belt, and Xinjiang cotton belt; all classified according to the Chinese comprehensive agriculture zonation, and provides some optimal technology modes. Moreover, it summarizes the technical features of modern agricultural irrigation and proposes a corresponding policy assurance system. The main conclusions are as follows. First, the application of optimized irrigation schedules to major crops in each comprehensive agricultural zone not only ensures water supply during sensitive water shortage periods, but also saves irrigation water, stabilizes yields, and improves water productivity. Second, in view of the characteristics and restraints in each zone, recommending and promoting advanced modes of water-saving technology supports the precise implementation of optimized irrigation schedules and improves the comprehensive production capacity of regional agriculture. Third, the proposed IT-based modern irrigation scheme, coupled with its corresponding financing and water rights management mechanisms among other policy assurance practices, matches and supports the modern system of agricultural production and management.

Keywords: irrigation water requirement; water use efficiency; technical mode; modern agriculture

1 Introduction

In China, the misaligned distribution of cultivated land with water resources, coupled with the practice of moving grain yields from the north to the south has intensified the shortage of agricultural water supply, which in turn aggravated its conflict with the increasing demand for grain production [1]. The efficiency of irrigation water use is 0.54, a figure far lower than the international level. Therefore, a massive water-saving agricultural scheme that promotes higher water productivity and irrigation water use efficiency should be adopted [2,3].

Agricultural water is influenced by several factors; the climate, soil, crops, irrigation technology, farming methods, and management. The constraints vary from region to region along with the economic level; thus, an appropriate water-saving technology based on the characteristics of each region should be determined to increase the efficiency of regional agricultural water use.

This paper includes an analysis of the irrigation water requirement for main crops in China and focuses on the characteristics

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Corresponding author: Zhang Baozhong, China Institute of Water Resources and Hydropower research, professor. Main research field is water-saving irrigation theory and new techniques. E-mail: zhangbz@iwhr.com

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of crop water use under the optimized irrigation schedule in each typical region of comprehensive agricultural production. It further proposes an advanced scheme of water-saving optimization technology for the main crops in each typical region, and suggests the feasibility of constructing an irrigated agricultural system. This paper may serve as an important reference for promoting the efficient use of water for major crops, achieving rational allocation of agricultural water resources, and creating a virtuous cycle of ecological environment.

2 Distribution of irrigation water requirement of typical crops in China

This study covers 219 regions, selected from among the third-tier regions as defined by the water resource regionalization in China. Of these, a few regions with minor agricultural water applications or inadequate data are excluded, but a few large third-tier regions divided into sub regions are included. For each region, the irrigation water requirement of three major crops, namely, wheat, rice, and cotton, are analyzed using meteorological data taken from a conventional meteorological station in that region.

Wheat is mainly distributed in Henan, Shandong, Hebei, Anhui, Jiangsu, Shaanxi, Gansu, Xinjiang, and Shanxi. The volume demand of supplementary irrigation water increases from south to north, with the high-value areas located in the western Qaramay City of Xinjiang and Ali area of Tibet, requiring between 500–600 mm. The low-value areas are located in the southern part of the Huaihe River Basin and middle and lower reaches of the Yangtze River, where the requirement is 100–200 mm. For the Huang–Huai–Hai area, the high-value areas are in Dezhou, Tianjin, Baoding, and Beijing, located at a strip extending from Weifang toward the northwest, where the requirement is 350–400 mm, which decreases from the center to both north and south.

Rice is mainly grown in the middle and lower reaches of the Yangtze River, Yunnan–Guizhou Plateau, Sichuan Basin, Sanjiang Plain, and Liaohe Plain in the Northeast. A small amount of rice fields are also found in Xinjiang and other zones. The need for supplementary irrigation water for mid-season rice increases from south to north, with the high-value areas in the Turpan Basin and Bayingol Mongolian Autonomous Prefecture of Xinjiang, where the requirement is 850–900 mm. The low-value areas are in the eastern part of Guangxi, western Guangdong, and Sichuan in southern China, where the supplementary irrigation water requirement varies within 100–150 mm.

Cotton is mainly planted in Xinjiang, Shandong, Henan, Hebei, Hunan, Jiangsu, and Anhui. For this crop, the areas with a high irrigation water requirement of 600–700 mm, are located in Qaramay of Xinjiang, while the low-value areas are in the eastern part of Guangxi and western Guangdong in South China, where the requirement is 30–100 mm. In the eastern region, the requirement is generally 150–250 mm. With the recent practice of mulched cultivation of cotton, the irrigation water requirements in a number of areas have dropped by 75–120 mm.

3 Water use efficiency characteristics and optimization technology modes of typical crops in main farm regions of China

3.1 Huang–Huai–Hai wheat production region

Winter wheat is one of the most widely grown crops in the Huang–Huai–Hai region; it accounts for more than 30% of the total sown area in this region and 68% of the sown area in China [4]. For this crop, the net irrigation volume is 119 mm where irrigation is sufficient with a water productivity of 1.46 kg/m³, or 71 mm where there is deficit with a water productivity of 1.38 kg/m³. Water productivity under the rainfed condition is 0.77 kg/m³. In the northern part of the Huang–Huai–Hai Plain where water is short, 87% of the winter wheat production is guaranteed if deficit irrigation is practiced, leading to a 40% drop in the irrigation water requirement.

For over-exploiting funnel areas, the planting area of high-water-consumption crops should be appropriately reduced, new irrigated areas should be prevented, efficient water-saving irrigation practices such as water and fertilizer integration should be promoted, irrigation quota management should be put in place, and agricultural water saving, deep plowing, and protection should be promoted [5]. The comprehensive water-saving technology approach combines winter wheat water saving and production-stabilizing (water saving and drought-resistant variety + deep scarification / straw returning / post-sowing pressing + jointing–booting irrigation); winter wheat conservation tillage and water saving (no-tillage / less tillage + straw returning + wheat no-tillage planter double operation); and water-and-fertilizer-integrated high-efficiency water saving (water and fertilizer integration + winter wheat / summer corn / vegetable + under-film drip irrigation / micro-spray / sprinkler irrigation) [6].

3.2 Rice production belt in the Northeast region

The Northeast region is a competitive rice-producing belt, characterized by a high grain commodity rate and an expanding cultivation area; nevertheless, the over-exploitation of groundwater resources has caused a series of ecological and environmental problems [7]. To overcome a severe water shortage in this region, the traditional over-abundant irrigation method has been

replaced with the exploration of a layered “shallow, dry, shallow” water management technique. Furthermore, a new controlled irrigation technology that does not allow a water layer in the normal growth process of rice, has been developed. The irrigation volumes of rice under “shallow, dry, shallow” and controlled irrigation are 450–545 mm and 275–345 mm, respectively, with corresponding water productivities of 1.14–1.34 kg/m³ and 1.53–2.25 kg/m³, respectively. Of the two, the controlled irrigation technology reduces the irrigation volume by 145–175 mm, reduces water consumption by 145–293 mm, increases the yield by 16–43 kg, and promotes water productivity by 35%–60%.

The constraint factors in the Northeast region are summarized by “three lows” (low temperature, low water temperature, and low ground temperature) and “three problems” (soil gleization, swampization, and salinization) [8]. From this, the water-saving controlled irrigation technology for cold-region rice is recommended. In the various development stages, after transplanting the seedlings, the irrigation water layer is not maintained for a long time in the field; hence, the decision to start irrigation does not depend on the irrigation layer. In particular, the controlling factor is the lower limit of the moisture at the root layer at different development stages, from which the irrigation time, frequency of irrigation, and irrigation quota are determined. During rice development, moderate water stress, a technique that triggers some drought tolerance in the rice without reducing the yield, contributes to water saving, high quality, and high efficiency. This approach has been promoted and applied in the northeast of China [9].

3.3 Rice production belt in the middle and lower reaches of the Yangtze River

The middle and lower reaches of the Yangtze River account for more than 45% [10] of both the rice planting area and production in China, and are thus the most important rice production belt locally. The irrigation volumes of mid-season rice are 482 mm and 413 mm under the flooding irrigation and “shallow, thin, wet, and dry” irrigation regimes, respectively, for corresponding water productivities of 1.29–1.68 kg/m³ and 1.54–2.23 kg/m³, respectively, with the latter improving by 7%–34%.

The areas are low-lying, and with the abundance in water and heat resources, the constraint factors are grave pollution owing to agricultural non-point sources. To control this and achieve the sustainable development of agriculture, we recommend a comprehensive regulation that combines pollution control of agricultural non-point sources and efficient utilization of rice field water and fertilizers. With the combination of rice irrigation schedule, fertilizer operation, and pollution regularization, the approach has been demonstrated and extensively promoted in the Jiangxi province with notable effects that promote the income and production of farmers, while mitigating the negative effects of agricultural non-point source pollution [11].

3.4 Rice production belt of Sichuan Basin

Rice is the most important food crop in Sichuan Basin, where the hilly lands make up the major part of rice fields. The meteorological data of the past 50 years show that the frequency of spring drought, summer drought, and drought during the hottest summer days in its hilly zones is 63%, 71%, and 65%, respectively. Therefore, irrigation is an essential condition for a stable production of rice. Compared with flooding irrigation, the wet and “dry-wet alternating” irrigations save water by 27.31% and 34.77%, respectively. The latter, in particular, has a lower irrigation volume of only 522 mm for a water productivity of up to 1.69 kg/m³ [12].

The Sichuan Basin fields are low-lying and gentle, with fertile soil but occasional seasonal droughts [13]. Thus, for this region, the “dry-wet alternating” irrigation mode is the recommended high-efficiency water control technology for rice planting, as it adapts well to the drought resistance of rice and patterns of water demand for high-yield rice, aside from its effectiveness in saving water and improving irrigation efficiency. It consists of wetting irrigation prior to tillering to promote tillering; drying after tillering so as to boost roots and stalks; shallow irrigation during ear differentiation so as to boost ears; and irrigation during filling and fructification so as to boost roots, leaves, and filling. This mode is outstanding with significant water savings and increased yields [14].

3.5 Pastoral belt in eastern Inner Mongolia

There is less precipitation in the pastoral belt of eastern Inner Mongolia, creating a striking conflict between grass resources and livestock. The crude protein content of fresh samples of silage corn is as high as 3%. This silage is rich in sugar, requires little space in production, suitable for preservation over a long time, and conducive to the balanced supply throughout the year. It is therefore the most effective way to provide the silage required of livestock [15]. With sufficient irrigation, silage corn yield can be as high as 6 445 kg per mu (1 mu \approx 666.67 m²), but can also be as low as 4 548 kg per mu in the water deficit case in the shooting stage, where water productivity is the lowest (14.64 kg/m³). In contrast, this figure becomes 5 078 kg if a water deficit is experienced during the tasseling stage, where water productivity is the highest (17.14 kg/m³). The annual net irrigation quota for silage corn in a normal year is 200 mm, with the emphasis placed on providing water demand during the shooting stage.

Given the characteristics of this region and for silage corn, sprinkler and drip irrigation systems are worth promoting on a

large scale as modes of a high-efficient water-saving technology. Thus, in this region and for silage corn, a central pivot-type sprinkler irrigation system is recommended. This technology factors in the pattern of silage corn water demand, water use efficiency, fertilizer utilization rate, yield, and benefits. The sprinkler is a system easy to operate, combines irrigation and fertilization into one, and promotes precision in these activities, which improves the utilization rate of water and fertilizer. This technology is widely applied in the Inner Mongolia pastoral areas due to these benefits [16].

3.6 Sugarcane production belt in Guangxi

Guangxi is the most important sugarcane and sugar production base in China; it has a mean annual precipitation of 1 391 mm during the sugarcane growth period, which satisfies the water requirement. However, due to the uneven distribution of precipitation in time and space, seasonal drought occasionally occurs. More than 90% of the sugarcane fields in Guangxi are dry slopes, where water conservancy irrigation infrastructures are backward and drought resistance is low. Spring and autumn droughts have serious impacts on sugarcane germination, emergence, tillering, shooting, and elongation [17]. Moreover, water productivities under rainfed and suitable irrigation conditions are 7.02 kg/m³ and 10.12 kg/m³, respectively, which drop by about 31% under the rainfed condition. For the suitable irrigation condition, the irrigation volume is less than 300 mm, suggesting dual effects of increasing the production and efficiency.

In the production belt, the timing of the higher temperatures, ampler sunshine, greater rainfall, and abundant heat coincide, which is quite suitable for sugarcane growth [18]. However, its soil is infertile and thin, and irrigation and drainage infrastructures are poor. Therefore, integrated mulched drip is recommended as the irrigation mode. This mode combines land transferring, fully mechanized farming, and integrated water-fertilizer-pesticide applications, which can save more than 70% of the water, fertilizer, and pesticide. It has been widely promoted in Chongzuo City, Guangxi [19].

3.7 Cotton production belt of Xinjiang

China's largest economic cotton zone is located in the main cotton production belt in Xinjiang, which is ranked the best in terms of planting area and lint production. Cotton production has become a pillar industry in Xinjiang; nevertheless, its cotton belt is dry and receives little rain, making it a typical irrigated agricultural area. The production belt is divided into three major sub-regions: the southern margin of the Junggar Basin, Tuha (Turpan–Harmi) Basin, and northern and western margins and plains of the Tarim Basin. For the first and third sub-regions, the recommended irrigation quota is 375 mm, which corresponds to the maximum irrigation water productivity (1.53 kg/m³) [20]. On the other hand, in the Tuha Basin, the recommended cotton drip irrigation depth is 21 mm; a total of 29 irrigation operations are performed throughout the growth period, for a total irrigation quota of 609 mm.

The Xinjiang cotton belt is rich in light and heat resources, which is ideal for planting cotton. The constraint factors of cotton production are severe water shortage and land desertification. Here, the direction of agricultural water-saving technology is to accelerate the processes of promoting new cultivars, water and fertilizer savings, and full mechanization. Thus, in this region, the comprehensive technology mode of mulched drip is recommended. This technology performs well for water saving, heat preservation, salt inhibiting, and yield increasing, and has been widely used in the cotton fields in Xinjiang Autonomous Region [21].

4 Construction of the modern agricultural irrigation system

4.1 Characteristics of the modern agricultural irrigation system

China's modern agricultural irrigation system is built on irrigation technology characterized by high-efficiency water saving, which incorporates water–fertilizer integration and regulated deficit irrigation. It promotes the construction of an agricultural irrigation system, complemented by modern technology, with an aim to adapt itself to and support modern agricultural production and management systems. The modern agricultural irrigation system contains the following major characteristics: (1) high-efficiency water-saving technology that is developing on a large scale and becoming regional; (2) agricultural irrigation technology that is developing from irrigation-only water supply to comprehensive water and fertilizer supply, where the technical means are developing from simple engineering and technical measures to the integration of engineering, agronomy, agricultural machinery, seeds, fertilizer, and information technology; (3) agricultural water management that is increasingly informatized and is intelligent; (4) growing awareness of ecological civilization by the irrigation community, described by the popularity of maintaining good water ecology and water environment; and (5) emergence of multi-party cooperation among the government (through public private partnership), scientific research institutions, social enterprises, and beneficiaries.

4.2 Modern irrigation technology based on information technology

4.2.1 Modern irrigation technology with efficiency and precision

This technology centers round crop water consumption by regulating and optimizing the water supply process through, for example, low-pressure pipes, sprinklers, and micro irrigations, to provide for the crop water demand in an efficient and precise manner.

4.2.2 Real-time regulation by water distribution system.

Water distribution is remotely monitored and automatically controlled based on the supply and demand information collected in real time with water level and flow monitoring devices, valve operation equipment, and data transmission devices installed at key nodes of the water supply and distribution system.

4.2.3 Remote-sensing-based water demand forecasting for irrigation district

The spatial information of the planting structure, soil distribution, and actual irrigated area in the irrigation district is extracted from near-Earth remote-sensing data of unmanned aerial vehicles and remote-sensing data of high-resolution satellites. Such spatial information is used as the input for water consumption analyses of regional crops, for the rapid prediction and forecasting of water consumption in the irrigation district.

4.2.4 Irrigation information service based on cloud platform

With the benefits of Internet of Things and cloud technologies, a National Irrigation Cloud Service Platform is established. Irrigation experimental data, regional planting structure, tempo-spatial pattern of water consumption, water availability, and engineering status in different regions are encoded on the cloud platform and included in the intelligent management. With its computing capacity, the cloud analyzes and processes the big data, achieving the dynamic collection, management, decision-making, and service of irrigation information.

4.3 Policy support system

Improvements shall be made to both the irrigation management system to make it more compatible with modern irrigation districts, and property rights system of farmland water conservancy projects. Construction of water rights in the agricultural market shall be accelerated, and comprehensive reform in agricultural water pricing shall be carried out. The dual control mechanism of water intake and water consumption shall also be promoted.

4.3.1 Innovation of a diversified investment and financing mechanism

The basic principle of public welfare shall be the responsibility of the government, and the industry issues shall go to the market, while the backbone infrastructures of water conservancy shall mostly be funded by fiscal resources. Water-saving irrigation facilities in fields or industrial parks should take full advantage of the investment inclination of enterprises and farmers, and the government should direct or encourage the efforts in the form, for example, of subsidy.

4.3.2 Promotion of reform in the operation and management system of small-scale farmland facilities of water conservancy

On the condition that project safety, public interest, and ecological protection are guaranteed, the titles on small farmland facilities of water conservancy should be permitted to be traded and transferred through contracting, leasing, auction, shareholding cooperation, and entrusted management, so as to promote operation rights; improve project management, protection capabilities, and levels; and maximize the irrigation benefits.

4.3.3 Promotion of comprehensive reform in agricultural water pricing

Total amount control and quota management of agricultural irrigation water shall be established progressively. Monitoring and measurement of agricultural irrigation water shall also be strengthened, with measurements at canal mouths promoted gradually in canal irrigation regions, as well as the gradual promotion of well-mouth measurements in well irrigation regions. Diversified water management modes, including autonomous water use among farmers and specialized services, are to be encouraged and promoted along with management by water authorities, with the participation of water users. Agricultural water pricing mechanisms of tiered, categorized, and split pricings should be appropriately and progressively placed, and a precise subsidy mechanism for agricultural water use, as well as water-saving incentives, shall also be established.

4.3.4 Establishment of a dual control mechanism for water intake and consumption

Based on the control of total water intake, one of the “three red lines,” for each administrative region, management mechanism of water rights based on water consumption control shall be explored, where the initial water intake and water consumption rights for cultivated lands shall be defined, and a mechanism shall be set up, thus encouraging farmers to

economically use water and to promote water rights trading.

5 Conclusion

5.1 Improvement of crop water productivity through optimization of irrigation schedule

The irrigation schedule shall be optimized to ensure water supply during the water-sensitive period of crops to reduce the water consumption and stabilize production, while increasing water productivity. In the Huang–Huai–Hai region, the regulated deficit irrigation for winter wheat and rainfed irrigation for summer corn shall be practiced. Compared with conventional irrigation schedule, an economy of water of 50–100 m³ per mu will be achieved. Moreover, when the yield is stabilized (at approximately 1000 kg per mu), the water productivity of crops will grow by nearly 10% relative to the traditional irrigation schedule. In the Northeast region, when the rice control irrigation is practiced, a minimum of 95 m³ of water per mu will be saved, while water productivity will exceed 35% relative to the “shallow, dry, shallow” schedule. In the case of silage corn in the eastern pastoral belt of Inner Mongolia, a drought during the tasseling stage will result in a yield 12% greater than that in drought during the shooting stage, while the resulting water productivity will be 17% higher. In the middle and lower reaches of the Yangtze River and Sichuan Basin, the “dry-wet alternating” will cut the average irrigation volume from 520 m³ to 310 m³ and increase the yield by close to 13%. In the main sugarcane production belt in Guangxi, the appropriate irrigation schedule will increase the yield by 58% and the water productivity by 44%, compared with rainfed irrigation. Furthermore, in the main cotton production belt of Xinjiang, with an irrigation schedule set at a per-mu irrigation quota of 250 m³, the cotton water productivity will grow by a large margin.

5.2 Selection of advanced modes of water-saving technology and removal of regional constraints for agricultural water use

Advanced modes of water-saving technology shall be selected for the promotion and assurance of the accurate implementation of optimized irrigation schedule. Regional agricultural water constraints shall be removed so as to achieve regional capacity in agricultural comprehensive production. In Huang–Huai–Hai funnel areas for groundwater over-exploration, comprehensive modes of water saving, such as agronomic water conservation, conservation tillage, and water–fertilizer integration are recommended for winter wheat. In the Northeast region, the water-saving irrigation mode of cold-region rice is recommended for rice plantation so as to break the regional “three lows” and “three problems” constraints. In the eastern pastoral belt of Inner Mongolia, the central pivot-type sprinkler irrigation is recommended as an integrated mode to improve the region’s economies of scale for water saving. In the middle and lower reaches of the Yangtze River, pollution control of the agricultural non-point source is a recommendable technique for rice so as to control regional pollution from non-point sources. In the Sichuan Basin, the “dry-wet alternating” irrigation mode is recommended for rice planting to improve the water-saving effect. Moreover, in the Guangxi sugarcane production belt, integrated mulched drip is recommended as the irrigation mode for sugarcane to increase its water productivity and to save water, fertilizer, and pesticide. Furthermore, in the cotton production belt of Xinjiang, the comprehensive technology mode of mulched drip is recommended, so as to achieve a water saving, heat preservation, salt suppression, and a higher yield.

5.3 Construction of a modern agricultural irrigation system and transformation of agricultural water use from an inefficient and extensive mode to a moderate-yield and efficient mode

The agricultural cultivation mode, production methods, and operators in China are all undergoing profound changes with agricultural development gradually entering a new normal state characterized by moderate scale, full mechanization, high intensification, and rigid constraints of resources and the environment. In the future, when agricultural water consumption remains essentially stable and climate change needs to be overcome, agricultural irrigation must be transformed from its current inefficient and extensive state into a moderate-yield and efficient mode. Through high-efficiency water-saving irrigation technologies, the mechanism of efficient water use of crops should be fully exploited, and water–fertilizer integration, regulated deficit irrigation, and other new irrigation technologies should be incorporated in a dual control mechanism of water intake and water consumption. The construction of a modern system of agricultural irrigation should be promoted by up-to-date information technologies to achieve compatibility and enhance support for the latest agricultural production and management systems.

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