Spatiotemporal changes and influencing factors of the intensity of agricultural water footprint in Xinjiang, China

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Abstract: Xinjiang Uygur Autonomous Region, the largest agricultural high-efficiency water-saving arid area in China, was adopted to explore the coupling relationship between agricultural water consumption and economic benefits, which is of great significance to guiding the efficient utilization and sustainable development of agricultural water resources. This study utilizes an indicator, termed the Agricultural Water Footprint Intensity (short as AWFI, which means the amount of water resource consumed per unit of agricultural GDP), to study the economic benefits of agricultural water in Xinjiang from 1991-2018. In addition, the Theil index, a measure of the imbalance between individuals or regions, was used to study the evolution in the spatial differences in water efficiency, and the Logarithmic Mean Divisia Index (LMDI) method was applied to quantify the factors driving the AWFI. The results showed that AWFI in Xinjiang has experienced three stages: obvious decline, stable and slow decline, which decreased from 16 114 $m^3/10^4$ CNY to 2100 $m^3/10^4$ CNY, decreasing by 86.97%. The Theil index indicated that the spatial evolution of 14 prefectures (cities) resembled an inverted N-shaped Kuznets curve over time. Among the influencing factors, the contributions of water-saving technology and planting structure to the change in the AWFI in Xinjiang, China from 1991 to 2018 were 154.03% and −37.98%, respectively. The total contribution to AWFI of the total population, urbanization rate, and production scale was −16.06%. This study concluded that further improvements in the economic benefits of agricultural water consumption can be obtained by continuing to promote more efficient or "water-conservation" irrigation technologies (engineering aspects), adjusting the planting structure (policy guidance aspects), and intensive management of cultivated land (management aspects).

Keywords: agricultural water footprint intensity, theil index, logarithmic mean divisia index, Xinjiang
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1 Introduction

Sustainable development is vital for the prosperity of all countries globally[1]. Agriculture is the sector of the economy using the most water and also has the largest potential for water-saving[2-5]. Agriculture accounts for approximately 70% of the consumption of freshwater resources globally, with this figure being as high as 90.0% in some rapidly developing countries. Although agriculture accounts for 62.0% of total freshwater use in China, it accounts for only 7.2% of the gross domestic product (GDP)[6,7]. Agricultural water use, therefore, places the greatest pressure on freshwater resources in China. The focus of the economy of China is currently changing from quantity of production to quality of production. Basic scientific research is urgently needed to guide this transition, particularly for the arid and semi-arid areas of Northwest China characterized by low development and a high proportion of agricultural water use. Optimizing agricultural water use is extremely important for overcoming water deficits in arid and semi-arid areas with an underdeveloped economy and a high proportion of agricultural water consumption[8-10]. The Xinjiang Uygur Autonomous Region (referred to as "Xinjiang") is a typical arid region in Northwest China. This region is characterized by a large area, rich land resources, and conditions suitable for agriculture. Xinjiang is also a base to produce high-quality cotton and animal husbandry. Although Xinjiang, accounts for 17.0% of China's land area and contains less than 3.0% of the total water resources of

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China, this region produces more than 60.0% of China's self-produced commercial cotton, 90.0% of tomatoes, and 50.0% of sugar beets[11]. However, Xinjiang suffers from scarce precipitation and strong evaporation, leading to frequent water shortages. The harsh natural conditions of Xinjiang limit the potential for farmers to overcome poverty. In addition, Xinjiang is located in the northwestern fringe region, far from the main domestic market, and there has been slow development of other aspects of the economy. The expansion of agriculture has become the main pathway for farmers in Xinjiang to increase their earnings. However, water shortages in Xinjiang restrict the indefinite expansion of agriculture[10]. Therefore, an understanding of the evolution of the economic outputs and spatial differences in agricultural water consumption and their driving factors are of great significance for agricultural development, the adjustment of industrial structure, and the optimal allocation of water resources.

It should be noted that due to the incomplete measurement facilities, the current agricultural water statistics could be quite different from the actual situation, while water management not only needs to regulate water use but also needs to examine and regulate the water consumption that is ultimately effectively utilized. Therefore, this study uses water footprint to characterize the real water consumption of agriculture. According to the composition type, water footprint can be divided into three parts: blue water footprint (groundwater or surface water consumed during crop growth), green water footprint (effective precipitation consumed during crop growth), and grey water footprint (the amount of freshwater resource required to dilute pollutants released during crop production to meet environmental standards)[11-14]. Precipitation in Xinjiang is concentrated in mountainous areas, but most of the cultivated land is in the plain area with scarce precipitation and relies on irrigation. Moreover, the degree of agricultural pollution in Xinjiang is very light, and there is almost no agricultural pollution control project. Therefore, the present study used the agricultural blue water footprint as an indicator of agricultural water consumption to study the economic benefits of agricultural water consumption[12,13].

Many past studies have focused on the spatiotemporal characteristics of the water footprint (WF) and WF intensity (the amount of water footprint consumed per unit of GDP)[15-19]. Many studies have also focused on analyzing the relationship between water resources and economic growth. For example, Chen et al.[20] and Pan et al.[21] studied the relationship between water resource utilization and economic growth. Zhang et al.[22] used a geographical information system (GIS) and spatial correlation analysis methods to analyze the spatial correlation between gross domestic product (GDP) and water resources utilization in Xinjiang from a spatial scale. There have also been some recent studies that applied an agricultural water stress index[23], an agricultural water productivity index[24], or the agricultural value water footprint. However, these indices were applied only to characterize the efficiency of agricultural water use or the relationship between water and the economy for a single crop[25-28]. There has to date been no in-depth analysis of the spatiotemporal evolution of the economic benefits of agricultural water consumption and the influencing factors. The current study aimed to address this research gap. The present study utilizes the agricultural water footprint intensity (AWFI), based on the concept of the water footprint, as an indicator of the benefits of agricultural water consumption in Xinjiang. The present study also analyzed the spatiotemporal evolution of AWFI in Xinjiang from 1991 to 2018 and explored the evolution of spatial differences using the Theil index. The Logarithmic Mean Divisia Index (LMDI) method is proposed to quantitatively describe the impact of water-saving technology, planting structure, planting scale, and urbanization rate on AWFI.

2 Selection of study districts and materials

2.1 Selection of study districts

Xinjiang is located along the northwestern border of China (73°E-96°E, 34°N-48°N) in the hinterland of the Eurasian continent. The vast territory and abundant resources of Xinjiang make it the largest provincial-level administrative region in China, with a land area of 1.66 million km^2, accounting for approximately one-sixth of China's land area. Xinjiang is bordered by the Altai Mountains to the north and the Kunlun Mountains to the south. The Tianshan Mountains effectively divide Xinjiang into southern and northern regions, whereas the Turpan and Hami areas fall within Eastern Xinjiang. The towering and wide mountains of Xinjiang are arranged alongside vast and flat basins, effectively resulting in three mountain ranges surrounding two basins. According to the statistical data of Xinjiang Water Resources Bulletin and China Water Resources Bulletin, the average annual precipitation in Xinjiang of 154.8 mm is only 24% of the national average. The low precipitation can be attributed to the influence of geographical factors far removed from the sea and the mountains. Water resources in Xinjiang are extremely limited. Xinjiang generally has a lower level of economic and social development and has generally acted as a traditional agricultural and pastoral area. Therefore, Xinjiang occupies an important position in agricultural production in China. The importance of irrigated agriculture in Xinjiang has resulted in agriculture accounting for the largest proportion of total water use. According to the statistical data, the average annual total water consumption in Xinjiang over the last ten years was 55.92 billion m^3, of which total agricultural water consumption accounted for 93%, far exceeding the Chinese and global averages of 62% and 70%, respectively. An understanding of the economic benefits of agricultural water and its driving mechanism is the key to the efficient use of water resources in Xinjiang, China.

2.2 Dataset

The data sources analyzed in the present study mainly included: 1) Data for calculating the evapotranspiration of crops consisting of daily data for 74 national meteorological stations in Xinjiang from 1991 to 2018, including rainfall, sunshine hours, average wind speed, relative humidity, and maximum and minimum temperature; 2) Nearly 20 kinds of main crops were involved in the calculation, including wheat, corn, rice, potato, beans, cotton, oil, vegetables, fruit melon, apple, pear, grape, red date, alfalfa, hemp, and medicinal materials. The calculation also incorporated data for a variety of non-staple food products. These data were derived from the Xinjiang Statistical Yearbook and the Statistical Yearbook of Xinjiang Production and Construction Corps; 3) Economic data and water use data were derived from the Xinjiang Water Resources Bulletin and the Statistical Yearbook; 4) Population and agricultural production data originated from the Xinjiang Statistical Yearbook.

3 Methods

3.1 Measurement of AWFI

The current study proposes AWFI as a novel indicator of the efficiency of agricultural water consumption. The AWFI can be equated to the ratio of the agricultural water footprint to the added value of the primary industry. The water footprint per unit of agricultural output value is inversely related to the efficiency of water consumption. The specific calculation equation is as follows:

$$\mathrm{AWFI} = \frac{\mathrm{AWF}}{\mathrm{AOV}} \tag{1}$$

where, the AWFI is the intensity of the agricultural water footprint, $\mathrm{m^3/10^4}$ CNY; AWF is the agricultural water footprint, $\mathrm{m^3}$; AOV is the total value of agricultural output, 10^4 CNY. It should be noted that the agriculture examined in the current study is limited to crop, vegetable, and fruit production, and excludes animal husbandry and aquaculture.

During agricultural production, virtual water content accounts for a large proportion of total water and many factors affect the water demand of crops, such as the type, growth cycle, and geographical conditions of crops. The present study calculated virtual water based on the CROPWAT 8.0 software recommended by the Food and Agriculture Organization of the United Nations (FAO). The present study used the crop production water footprint calculation method using evapotranspiration (ET_c) to measure the crop water footprint. This method is based on field crop evapotranspiration and crop unit area yield outlined in "The Water Footprint Assessment Manual: Setting the Global Standard". This study draws lessons from the specific steps of calculating water footprint described by Zhang[18].

3.2 Theil index

Theil index, also known as Theil entropy, is widely used to measure the relative disparity of economic development since the disparity can be decomposed into independent inter-group and intra-group differences. The present study applied the Theil index to quantify the spatial differences in the water footprint intensity according to two groups: 1) the inter-regional difference index TBR; 2) the intra-regional difference index TWR. The formula for the spatial difference index is as follows:

$$T = \mathrm{TBR} + \mathrm{TWR} = \sum\nolimits_{i=1}^{n} v_i \log\frac{v_i}{d_i} + \sum\nolimits_{i=1}^{n} v_i \left[\sum\nolimits_{j=1}^{m} v_{ij} \log\frac{v_{ij}}{d_{ij}}\right] \tag{2}$$

where, n and m are the number of regions and the number of sub-regions in each region, respectively; v_i and v_{ij} represent the share of the water footprint in the i region and the j subregion in this region, respectively, in the total water footprint of Xinjiang; d_i and d_{ij} are the proportions of total agricultural production value in sub-region i and sub-region j to total agricultural production in Xinjiang, respectively. The greater the T value, the greater the difference in AWFI among regions.

3.3 Improved Logarithmic Mean Divisia Index method

The Logarithmic Mean Divisia Index was proposed by Ang[29] and is mainly used to identify the drivers of changes in energy intensity. This index is widely used in the field of water resources and is commonly used for identifying influencing factors in models globally.

This model was in the current study to quantify the impact of five factors (population, water-saving technology, planting structure, per-capita production scale, and the proportion of the urban population) on AWFI:

$$\mathrm{AWFI} = \sum\nolimits_{i} \left[\frac{\mathrm{AWF}I_i}{Y_i} \times \frac{Y_i}{Y_a} \times \frac{Y_a}{P_a} \times \frac{P_a}{P} \times P\right] \tag{3}$$

$$\mathrm{AWFI} = \sum\nolimits_{i} [I_i \times S_i \times Y_i \times U \times P] \tag{4}$$

$$\Delta\mathrm{AWFI} = \Delta\mathrm{AWFI}_I + \Delta\mathrm{AWFI}_S + \Delta\mathrm{AWFI}_Y + \Delta\mathrm{AWFI}_U + \Delta\mathrm{AWFI}_P \tag{5}$$

where, Y_i indicates agricultural output, t; Y_a represents the planting area, $\mathrm{hm^2}$; P_a represents the rural population; P represents the total population; I represents water-saving technology; S represents the planting structure; Y represents the per-capita production scale, and U represents the proportion of the rural population.

$$\Delta\mathrm{AWFI}_I = \sum\nolimits_{i} \frac{\mathrm{AWFI}_i^t - \mathrm{AWFI}_i^0}{\ln\left(\mathrm{AWFI}_i^t\right) - \ln\left(\mathrm{AWFI}_i^0\right)} \times \ln\left(\frac{I_i^t}{I_i^0}\right) \tag{6}$$

$$\Delta\mathrm{AWFI}_S = \sum\nolimits_{i} \frac{\mathrm{AWFI}_i^t - \mathrm{AWFI}_i^0}{\ln\left(\mathrm{AWFI}_i^t\right) - \ln\left(\mathrm{AWFI}_i^0\right)} \times \ln\left(\frac{S_i^t}{S_i^0}\right) \tag{7}$$

$$\Delta\mathrm{AWFI}_Y = \sum\nolimits_{i} \frac{\mathrm{AWFI}_i^t - \mathrm{AWFI}_i^0}{\ln\left(\mathrm{AWFI}_i^t\right) - \ln\left(\mathrm{AWFI}_i^0\right)} \times \ln\left(\frac{Y_i^t}{Y_i^0}\right) \tag{8}$$

$$\Delta\mathrm{AWFI}_U = \sum\nolimits_{i} \frac{\mathrm{AWFI}_i^t - \mathrm{AWFI}_i^0}{\ln\left(\mathrm{AWFI}_i^t\right) - \ln\left(\mathrm{AWFI}_i^0\right)} \times \ln\left(\frac{U_i^t}{U_i^0}\right) \tag{9}$$

$$\Delta\mathrm{AWFI}_P = \sum\nolimits_{i} \frac{\mathrm{AWFI}_i^t - \mathrm{AWFI}_i^0}{\ln\left(\mathrm{AWFI}_i^t\right) - \ln\left(\mathrm{AWFI}_i^0\right)} \times \ln\left(\frac{P_i^t}{P_i^0}\right) \tag{10}$$

where, the superscripts t and 0 replace the changes occurring in the previous year and the following year, respectively. These formulae can be used to quantitatively calculate the influence of the five factors on the time series.

4 Results

4.1 Agricultural blue water footprint

As shown in Figure 1, the crop blue water footprints of 14 prefectures in Xinjiang from 1991 to 2018 were measured according to the agricultural blue water footprint estimation method.

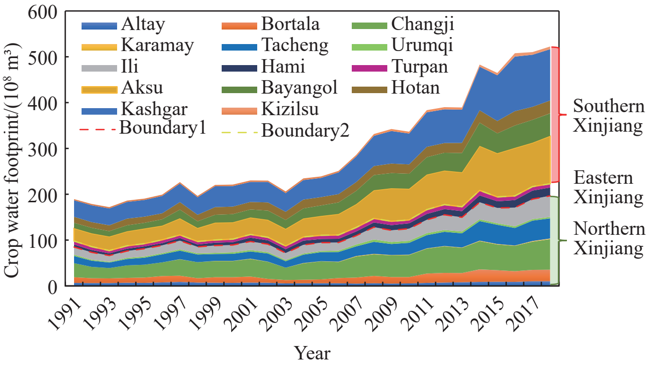


Figure 1 Inter-annual variations in the crop blue water footprint among the different prefectures in Xinjiang, China

As shown in Figure 1, the blue water footprint of crops in northern Xinjiang fell below boundary 1, that of eastern Xinjiang fell between boundary 1 and boundary 2, whereas that of southern Xinjiang was positioned above boundary 2. The results showed that the agricultural blue water footprint of Xinjiang has continued to rise since 1991, with the range of increase in southern Xinjiang exceeding that in northern and eastern Xinjiang. Within Xinjiang, the agricultural blue water footprints of the 14 prefectures have increased to varying degrees, with clear increasing trends in Aksu, Kashgar, Bayangol, Ili, and Changji.

4.2 Spatiotemporal evolution of AWFI

According to the calculation results of water footprint and agricultural economic indicators, AWFI is calculated. Figure 2 shows the AWFI of each region in Xinjiang from 1991 to 2018.

As shown in Figure 2, there were downward trends in AWFI in southern, eastern, and northern Xinjiang, indicating decreases in the water resources consumed by agriculture in the various regions of Xinjiang under increased efficiency of water use during the study

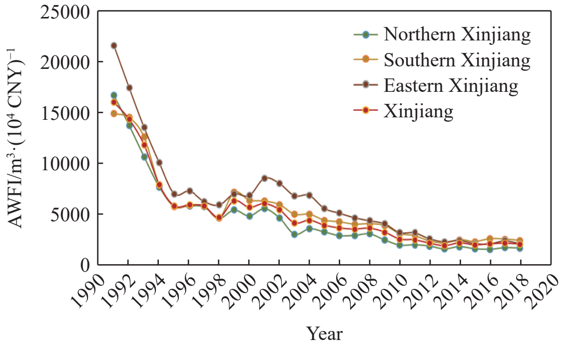


Figure 2 Inter-annual variation of the agricultural water footprint intensity (AWFI) in Xinjiang, China

period. The results showed that AWFI decreased rapidly from 1991 to 1995, after which the decline was more gradual. AWFI in Xinjiang decreased from 16 114 m^3/10^4 CNY in 1991 to 2100 m^3/10^4 CNY in 2018, decreasing by 86.97%. However, the current AFWI of Xinjiang remains much higher than the national average of 1315.79 m^3/10^4 CNY[30]. From a regional perspective, the AWFI in the southern, eastern, and northern regions of Xinjiang showed a downward trend. AWFI in southern Xinjiang decreased from 14 991 m^3/10^4 CNY in 1991 to 2454 m^3/10^4 CNY in 2018, decreasing by 83.63%. AWFI in eastern Xinjiang decreased from 21 709 m^3/10^4 CNY in 1991 to 2154 m^3/10^4 CNY in 2018, decreasing by a factor of 9.08. AWFI in northern Xinjiang decreased from 16 804 m^3/10^4 CNY in 1991 to 1717 m^3/10^4 CNY in 2018, decreasing by 89.78%. The rank of the different regions of Xinjiang according to the yield benefit of the AWFI in various regions changed from southern Xinjiang>northern Xinjiang>eastern Xinjiang in 1991 to northern Xinjiang>eastern Xinjiang>southern Xinjiang in 2018. By combining the results of the overall change in AWFI with the national five-year plan, the change in AWFI in Xinjiang can be grouped into five stages: 1) a rapid decline from 1991 to 1995; 2) stable fluctuation from 1996 to 2000; 3) a gradual decline from 2001 to 2005 but with large regional differences; 4) a continued decline from 2006 to 2010, with the rate of decline in eastern Xinjiang significantly higher than that in southern Xinjiang, and that of eastern Xinjiang similar to that of southern Xinjiang in 2010; 5) a gradual decline from 2011 to 2018. Records of the AWFI showed that the AWFI of southern Xinjiang surpassed that of eastern Xinjiang in 2014. Therefore, southern Xinjiang became the region with the lowest water use efficiency, although the regions tended to converge.

Figure 3 shows the AWFI of each state (city) from 1991 to 2018 every five years. The AWFI values of northern and eastern Xinjiang were significantly greater than that of southern Xinjiang in 1991. This indicates that southern Xinjiang showed the highest efficiency of water resource utilization during the early stage of the study period, with water consumption per unit of GDP in southern Xinjiang being far below that of northern and eastern Xinjiang. Boltala in northern Xinjiang showed the largest AWFI (lowest water use efficiency), followed by Hami and Turpan in eastern Xinjiang. Although the differences in AWFI between the states remained obvious in 1995, there were smaller differences between the large regions. The center of gravity of the high AWFI region gradually moved south from 2000 to 2015, with the AWFI of the other prefectures (cities) besides Kizilsu, Kashgar, and Hotan in southern Xinjiang falling below 4000 m^3/10^4 CNY. By 2018, the AFWI in southern Xinjiang was significantly higher than that in northern and eastern Xinjiang. Therefore, southern Xinjiang became the region with the lowest water use efficiency among the three regions. There were declining AWFI trends in all states besides Karamay, indicating a steady increase in the utilization efficiency of agricultural water resources.

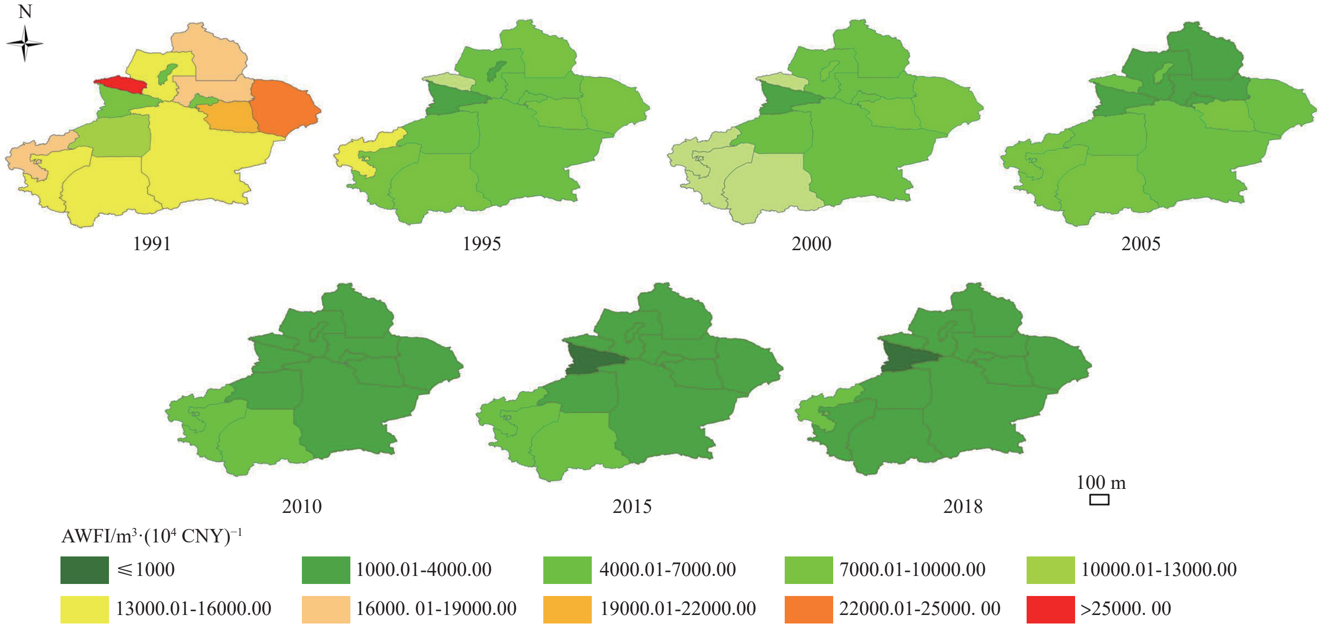
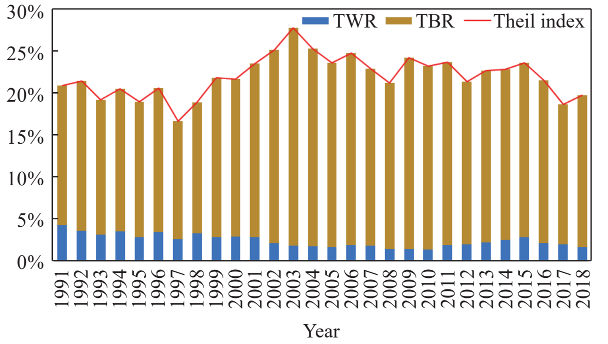


Figure 3 Agricultural water footprint intensity of various states (cities) in Xinjiang, China between 1991 and 2018 at a five-year timestep

4.3 Theil index calculation

Figure 4 shows the intra-group and inter-group differences in the Theil index whereas Figure 5 shows the inter-regional differences.

As shown in Figure 4, the AWFI Theil index experienced a small magnitude of change, remaining between 0.15-0.30. Overall, the Theil index first showed a declining trend, followed by a rise and a fall. Therefore, the trends in the Theil index could be divided into three stages: 1) A decrease in volatility from 1991 to 1997, with a minimum value of 0.17 reached in 1997; 2) a rapid increase from



Note: TWR represents the intra-regional difference indicator; TBR represents the difference indicator between regions.

Figure 4 Inter-annual variation of the Theil index in the Xinjiang Uygur Autonomous Prefecture

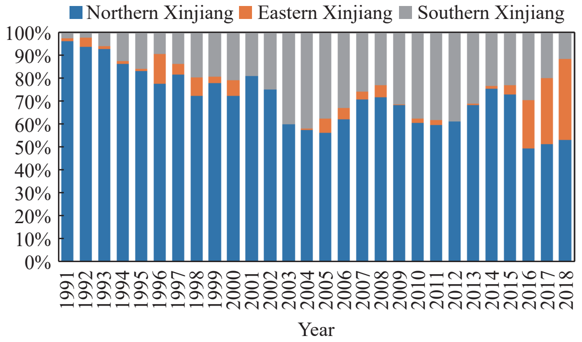


Figure 5 Difference in the ratio of agricultural water footprint intensity (AWFI) between regions in Xinjiang, China

1997 to 2003, reaching a maximum of 0.28 in 2003; 3) an overall decline from 2003 to 2018, with the rate of decline slightly slower than that during 1991-1997. There was a small intra-group difference, accounting for 1/10 of the total Theil index, whereas the inter-group difference was relatively large. Figure 5 shows the percentage of differences between the three regions. The inter-group differences in AWFI gradually decreased in northern Xinjiang, whereas inter-group differences in southern Xinjiang first increased and then decreased. There were relatively small inter-group differences in eastern Xinjiang, although they increased significantly after 2016.

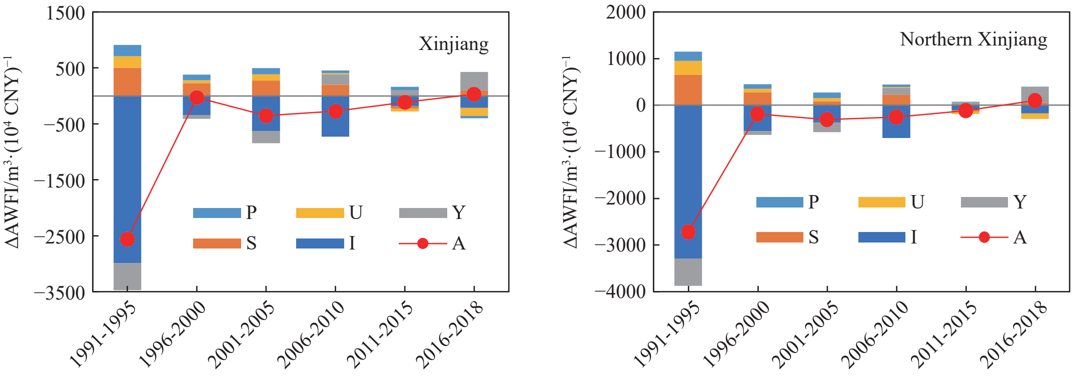
4.4 Analysis of the driving factors result

The analysis results of driving factors in Xinjiang and each scribed area are calculated by The Logarithmic Mean Divisia Index. Table 1 and Figure 6 show the results of the analysis of factors influencing the AWFI in Xinjiang. As shown in Figure 6, except for southern Xinjiang, the regional changes in AWFI were consistent with that for the whole of Xinjiang. The AWFI in Xinjiang and three major sub-regions declined rapidly from 1991 to 1995. Water-saving technology played a key role in the decline in the AWFI

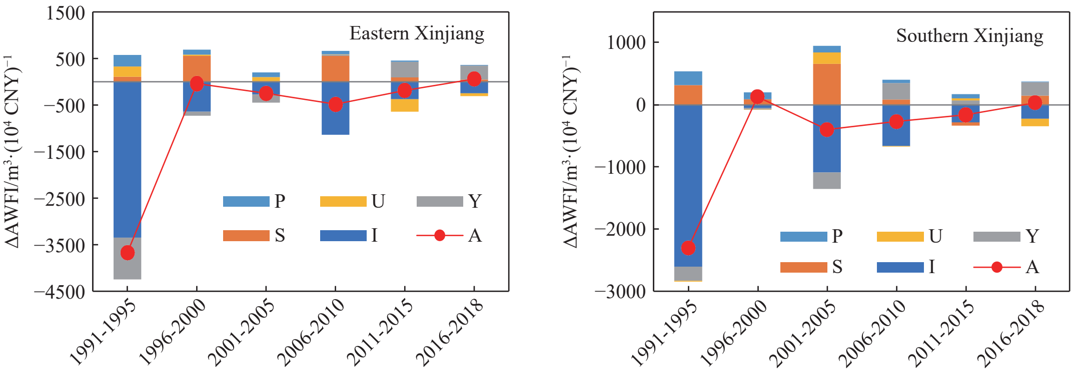
Table 1 Contribution of each influencing factor to the reduction in agricultural water footprint intensity (AWFI) in Xinjiang, China

Region	I	S	Y	U	P
Xinjiang	154.03%	−37.98%	4.61%	−5.97%	−14.70%
Northern Xinjiang	149.91%	−36.93%	11.68%	−10.03%	−14.64%
Eastern Xinjiang	136.60%	−34.63%	11.23%	0.07%	−13.27%
Southern Xinjiang	171.09%	−45.27%	−0.04%	−4.88%	−20.91%

Note: “I” represents water-saving technology; “S” represents the planting structure; “Y” represents the production scale; “U” represents the urbanization rate; “P” represents the population; “A” represents the average change in the intensity of the agricultural water footprint in the period.



a. Xinjiang (b) Northern Xinjiang



(c) Eastern Xinjiang (d) Southern Xinjiang

Note: “P” represents the population; “U” represents the urbanization rate; “Y” represents the production scale; “S” represents the planting structure; “I” represents water-saving technology; “A” represents the average change in the intensity of the agricultural water footprint in the period.

Figure 6 Results of analysis of factors driving the agricultural water footprint intensity (AWFI) in Xinjiang, China during this period, followed by the scale of production. The urbanization rate, population, and planting structure partly offset the decline, although the combined effect of these factors was relatively small. The AWFI in southern Xinjiang rose slightly from 1996 to 2000, whereas AWFI declined slightly in the other regions. During this period, the effects of various factors on AWFI in southern Xinjiang were not obvious. In contrast, the increase in AWFI in northern and eastern Xinjiang was almost completely offset by the decrease in AWFI resulting from water-saving technology and production scale, resulting in a stable AWFI. All districts in Xinjiang showed a downward trend in AWFI from 2001 to 2015, although the overall decline was greatly reduced, except for eastern Xinjiang. The direction of influence of driving factors changed frequently during this period, except for the reduction effect of water-saving technology. AWFI showed a very weak upward trend from 2016 to 2018 which could be attributed to the effects of water-saving technology and urbanization, although the effect was completely offset. The total impact of AWFI in Xinjiang decreased in all periods except for an increase of 27 $m^3/10^4$ CNY from 2016 to 2018. The decrease in AWFI mainly occurred from 1991 to 1995, with a decrease of 2561 $m^3/10^4$ CNY. The decreases in AWFI during the other periods in descending order were 2001 to 2005 (351 $m^3/10^4$ CNY), 2006 to 2010 (274 $m^3/10^4$ CNY), 2011 to 2015 (116 $m^3/10^4$ CNY), and 1996 to 2000 (30 $m^3/10^4$ CNY). The trends in AWFI were similar among northern, eastern, and southern Xinjiang, mainly manifested by the most rapid decline from 1991 to 1995, with average annual decreases of 2721 $m^3/10^4$ CNY, 3669 $m^3/10^4$ CNY, and 2302 $m^3/10^4$ CNY, respectively.

Water-saving technology was the main factor influencing the reduction in the AWFI during the entire study period from 1991 to 2018, whereas planting structure and the total population were the main factors hindering the reduction in AWFI, and urbanization rate and production scale had little impact. Among the influencing factors, the contributions of water-saving technology and planting structure to the change in the AWFI in Xinjiang from 1991 to 2018 were 154.03% and −37.98%, respectively. The total contribution to AWFI of the total population, urbanization rate, and production scale was −16.06%. The rank of the different regions of Xinjiang in terms of the impact of water-saving technologies on decreasing AWFI was: southern Xinjiang (171.09%)>northern Xinjiang (149.91%)>eastern Xinjiang (136.60%). The rank of the regions of Xinjiang in terms of the impact of planting structure on increasing AWFI was southern Xinjiang (−45.27%)>northern Xinjiang (−36.93%)>eastern Xinjiang (−34.63%). The rank of the different regions of Xinjiang in terms of the combined effect of the total population, urbanization rate, and production scale on increasing AWFI was southern Xinjiang (−25.82%)>northern Xinjiang (−12.99%)>eastern Xinjiang (−1.97%). These results show that although the contribution of water-saving technology to decreasing AWFI has been the highest in southern Xinjiang, these decreases in AWFI have been offset by increases in AWFI due to the largest changes in planting structure in Xinjiang. Therefore, southern Xinjiang experienced the smallest rate of decline in the AWFI among the regions of Xinjiang. Figure 7 and Table 2 show the results of the analysis of the factors influencing AWFI among the 14 prefectures in Xinjiang.

As shown in Figure 7 the changes to AWFI amongst all prefectures in Xinjiang besides Karamay, Urumqi, and Kashgar were consistent for those of Xinjiang as a whole. The AWFI at the prefecture level, besides Karamay, decreased rapidly from 1991 to 1995. There were significant increases in the AWFI in Karamay and Kashgar from 1996 to 2000, whereas there were significant decreases in AWFI in Altay and Tacheng, and the changes in other regions were not significant. Besides a slight increase in AWFI in Bayangol from 2011 to 2015, 13 regions showed a downward trend in AWFI from 2001 to 2005, from 2006 to 2010, and from 2011 to 2015, with an overall large decline in AWFI. Besides Turpan and Hotan, the other regions showed a weak upward trend in AWFI from 2016 to 2018.

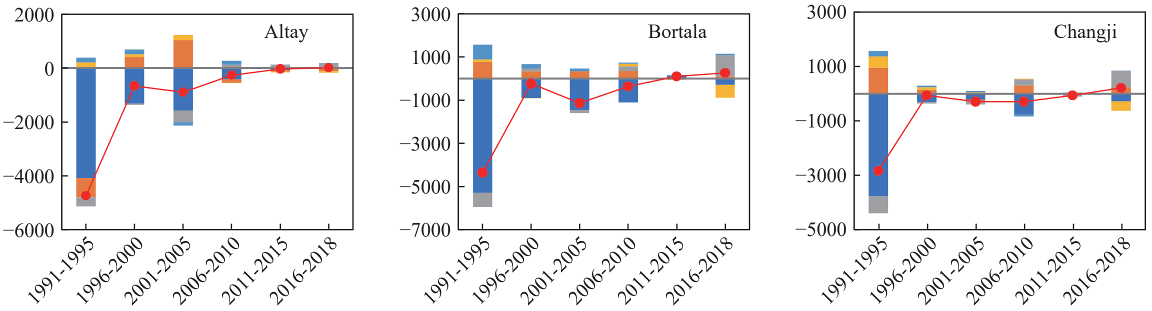
Water-saving technology was the main contributor to the reduction in AWFI and the improvement in agricultural water use efficiency. The changes to planting structure were the main driver offsetting the decline in AWFI, resulting in the overall rate of decline in AWFI plateauing over time. Water-saving technologies reduced AWFI during the 28-year study period in Altay, Tacheng, Urumqi, Bayangol, Kashgar, Kizilsu, Hami, and Turpan, indicating a continual increase in the efficiency of agricultural water use. There was a slight increase in AWFI in Karamay, Aksu, and Hotan between 1996 and 2000, indicating a slight decrease in water consumption efficiency. The efficiency of water consumption in these areas increased during other periods. There was a slight increase in AWFI in Bortala and Changji from 2011 to 2018, indicating a slight decrease in water use efficiency. The efficiency of water consumption in these areas increased during other periods. The agricultural planting structure mainly increased AWFI during the study period. However, the planting structure decreased AWFI in the seven states of Bortala, Tacheng, Ili, Aksu, Bayangol, Hotan, and Kashgar during the later stage. The planting scale promoted the decline in the AWFI in most areas during the early stage of the study period, whereas the planting scale had the opposite effect during the later stage. The rate of urbanization increased AWFI overall, besides Karamay and Bayangol. Karamay had a particularly important effect on changes to AWFI during the study period. This result could be attributed to Karamay being an urban area with an industry dominated by oil development and processing, with almost a complete absence of agriculture and a rural population close to zero. Therefore, the results obtained for Karamay are not representative, and the present study does not focus on an analysis of the results for Karamay. The contribution of water-saving technology to reducing AWFI among the 13 prefectures (cities) ranged from 117% to 188%, whereas the contribution of planting structure to offset the reduction in AWFI ranged from 57% to 12%. The effect of population growth on offsetting the reduction in AWFI ranged from 28% to 6%. The scale of production and the rate of urbanization had little effect on the changes in AWFI.

5 Discussion

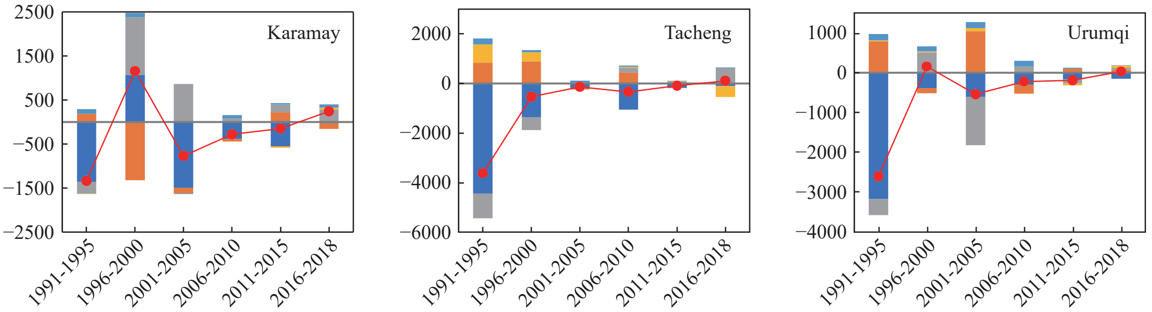
5.1 Reasons for the rapid growth of agricultural water footprint

The agricultural water footprint of Xinjiang has shown a trend of overall growth during the past 30 years, with a relatively gradual increase before 2005, after which it increased sharply. The water footprint of crops is related to factors such as climate, agricultural input, and planting structure. The method of calculating the crop water footprint indicated the factors directly influencing the crop water footprint to be crop planting area, planting structure, and crop yield.

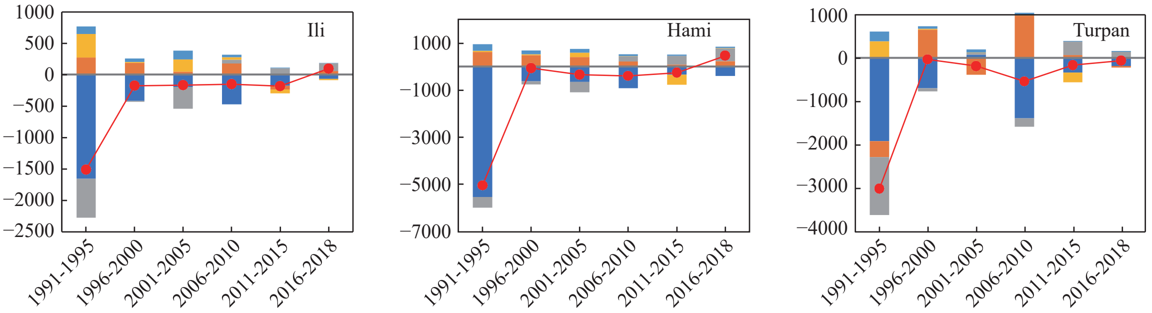
The area of arable land is a key factor driving an increase in agricultural water consumption. There has been a continuous increase in the area of crops planted in Xinjiang, with the area increasing by 3831×10^3 hm^2 from 1991 to 2015 at a growth rate of 144.43%. The expansion of the planting area in Xinjiang can be



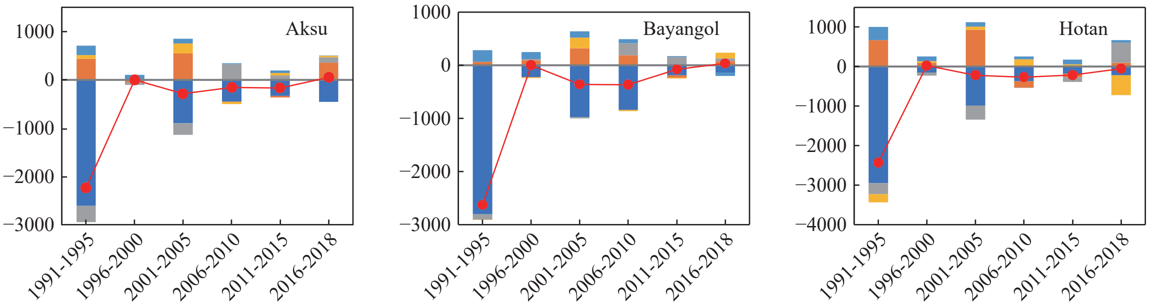
a. Altay b. Bortala c. Changji



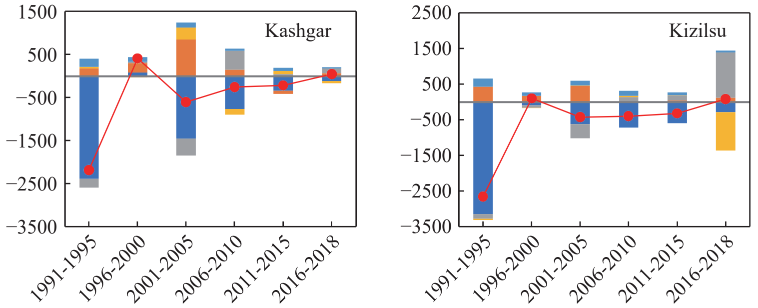
d. Karamay e. Tacheng f. Urumqi



g. Ili h. Hami i. Turpan



j. Aksu k. Bayangol l. Hotan



m. Kashgar n. Kizilsu

Note: The abscissa indicates the year; The ordinate indicates the change in the intensity of the agricultural water footprint.

Figure 7 Results of the analysis of the factors influencing agricultural water footprint intensity (AWFI) among the 14 prefectures in Xinjiang

attributed primarily to policies (Figure 8). Xinjiang initiated the “one black and one white” strategy in the 1990s, with “black” referring to petrochemical energy industries such as petroleum and coal and “white” referring to cotton planting and cotton textiles.

Table 2 Contribution of each influencing factor to the reduction in the agricultural water footprint intensity (AWFI) in the 14 prefectures (cities) of Xinjiang

Region	I	S	Y	U	P
Altay	117.85%	−11.62%	6.85%	−6.98%	−6.10%
Bortala	155.49%	−33.30%	−5.55%	3.64%	−20.28%
Changji	156.49%	−45.24%	6.36%	−10.59%	−7.01%
Karamay	256.79%	126.06%	−249.12%	0.71%	−34.44%
Tacheng	162.36%	−48.63%	16.97%	−19.92%	−10.78%
Urumqi	142.54%	−51.50%	32.55%	−3.37%	−20.22%
Ili	142.95%	−32.06%	33.84%	−26.14%	−18.60%
Hami	148.53%	−37.08%	0.05%	3.11%	−14.60%
Turpan	118.49%	−29.46%	26.58%	−3.84%	−11.77%
Aksu	171.57%	−43.72%	3.22%	−12.80%	−18.28%
Bayangol	171.57%	−43.72%	3.22%	−12.80%	−18.28%
Hotan	158.05%	−22.98%	−11.39%	−6.94%	−16.75%
Kashgar	157.61%	−52.04%	18.23%	3.63%	−27.44%
Kizilsu	157.61%	−52.04%	18.23%	3.63%	−27.44%

Note: "I" represents water-saving technology; "S" represents the planting structure; "Y" represents the production scale; "U" represents the urbanization rate; "P" represents the population; "A" represents the average change in the intensity of the agricultural water footprint in the period.

These industries were the pillars of the economy of Xinjiang at the time and the industries for which Xinjiang showed a comparative advantage. The poverty alleviation and other policies implemented by the central government from 2001 to 2010 favored Xinjiang. The national government recognized the need to implement policies to accelerate the development of Xinjiang and proposed the strategy of "stabilizing Xinjiang and rejuvenating Xinjiang, enriching the people and consolidating borders" along with a series of assistance measures. The poverty-alleviation measures implemented in Xinjiang mainly included the construction of farmland water conservancy infrastructure, basic farmland, rural roads, and drinking water infrastructure for humans and animals. National assistance to Xinjiang has been in full force since 2010[31]. Development in Xinjiang is hindered by factors such as a weak industrial base, low technological level, and a long distance from the mainland market. These factors were not conducive to gaining an advantage through industrial development. In contrast, agricultural assistance to Xinjiang required less investment and obtained quicker results. Therefore, much of the national assistance to Xinjiang has involved land reclamation, the construction of high-efficiency water-saving pilot areas, and the development of agricultural science and technology demonstration parks. The influence of policies has resulted in continuous increases in the cultivated land area in Xinjiang. There has been continuous growth in the agricultural water footprint given its positive correlation with the area of arable land. The planting area in Xinjiang increased by 144.43% from 1991 to 2018, with increases in northern, eastern, and southern Xinjiang of 136.95%, 53.72%, and 160.98%, respectively. The change in the planting structure resulting from policy trends and economic drivers represents an additional key factor driving the increase in agricultural water consumption. The large-scale expansion of economic crops with high water consumption during the study period was the main reason for the increase in agricultural water consumption. Wang et al.[10] identified a change in the ratio of grain crops to cash crops (referred to as the "grain economic ratio") from 0.75 to 0.48 in Xinjiang from 1996 to 2015. However, most cash crops consume a larger among of water compared to food crops[23]. Under set conditions, the "grain-to-economic ratio" is inversely related to water consumption.

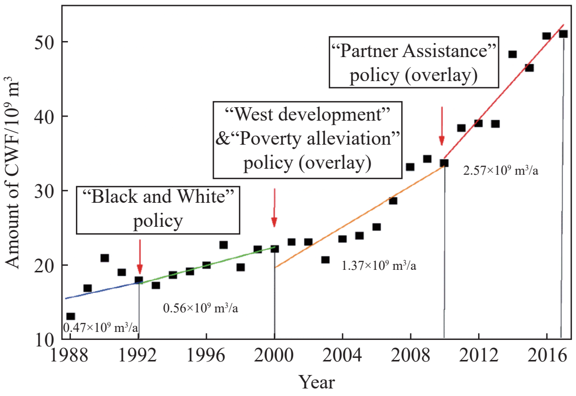


Figure 8 Annual changes in the crop water footprint (CWF) of Xinjiang in relation to policy interventions[22]

5.2 Evolution background of AWFI

The evolution in AWFI can be divided into two stages at a larger scale. There was first a rapid decline in AWFI from 1991 to 1995, mainly resulting from market development, improvement of the irrigation guarantee rate, and improvement of traffic conditions. There was also an improvement in agricultural water-saving technology and the construction of water conservancy projects during this period. These developments resulted in Xinjiang transitioning from a self-sufficient regional economy to a market economy participating in trade exports, the expansion of the scale of production and reproduction, increased added value, rapidly increasing agricultural economic benefits, and a rapidly reducing AWFI[32]. There was then a gradual decline in AWFI from 1996 to 2018. The Chinese government vigorously promoted efficient water saving in Xinjiang in 1996. A field-based water-saving model based on drip irrigation under the film was constructed during the "Tenth Five-Year (2001-2005)" period. The government of Xinjiang decided to vigorously develop high-efficiency water-saving technologies in agriculture in 2008. During this program, a series of policies to support the construction of high-efficiency water-saving agriculture was issued. These policies enabled the rapid promotion of high-efficiency water-saving technologies in Xinjiang. After 2012, the construction of high-efficiency water-saving agriculture transitioned from large-scale expansion to improved quality and efficiency and from high-efficiency water-saving to high-efficiency water use. The strong support of the central government focusing on high-efficiency agricultural water-saving has facilitated considerable progress in water conservancy infrastructure in Xinjiang. Xinjiang currently boasts the largest area under efficient water-saving in China and globally. There has generally been a transition in the AWFI in Xinjiang to a declining trend due to the influences of mechanization, water-saving irrigation, national poverty-alleviation policies, urbanization, crop characteristics, and industrialization. However, the decline in the AWFI is now beginning to plateau.

The spatial evolution of AWFI has mainly manifested as a rapid decline in northern and eastern Xinjiang in 1992 and 2014 that exceeded that in southern Xinjiang. This result could mainly be attributed to the prioritization of efficient water-saving in northern and eastern Xinjiang, whereas the promotion of agricultural high-efficiency water-saving technologies based on drip irrigation was only popularized in southern Xinjiang in 2014.

5.3 Characteristics and influencing factors of Theil index

The Theil index represents the spatial evolution of AWFI and showed an inverted N-shaped Kuznets curve over time, with a decrease from 1991 to 1997, an increase from 1997 to 2003, and a decrease from 2003 to 2018 (Figure 9). This pattern in the Theil index for Xinjiang differed somewhat from the inverted “U” Kuznets curve for the AWFI for China[32]. The inflection points within the evolution of the Theil index for Xinjiang were in 1997 and 2003. The observed pattern of the Theil index for Xinjiang could be attributed to various factors. Before 1997, there was a gradual decrease in the differences in AWFI between regions. This observation could mainly be attributed to the promotion of agricultural technology, and particularly to the second meeting of the Standing Committee of the Eighth National People’s Congress of the People’s Republic of China during which the “Law of the People’s Republic of China on the Promotion of Agricultural Technology” was passed on the 2nd July 1993. The Chinese government promoted and supported the introduction of advanced technology, provided agricultural training, and utilized the deployment of trained farmers to gradually narrow the gap in the AWFI in various prefectures (cities). The implementation of the “one black and one white” program in Xinjiang in 1997 resulted in some regions taking the lead in the increase in the planting area of cash crops due to the influence of geographical advantages, resource endowments, economic foundation, and other factors, especially for cotton. Various aspects of production were transferred and accumulated in the different regions of Xinjiang to maximize profits. This was mainly manifested as a widening of the gap in water use efficiency, leading to an increase in the AWFI Theil index. The AWFI Theil index gradually declined after 2003. In 2000, the central government’s poverty-alleviation policy focused on Xinjiang, with the resulting construction of farmland infrastructure accelerating the increasing economic benefits of water. The Theil index indicated that the regional disparity in the AWFI reached a maximum in 2003. Subsequently, the advantages of the other regions combined with government guidance and support resulted in a decline in the AWFI Theil index in Xinjiang. The inflection point of the AWFI Theil Index in Xinjiang occurred in 2003 due to the delayed effect of poverty-alleviation policies.

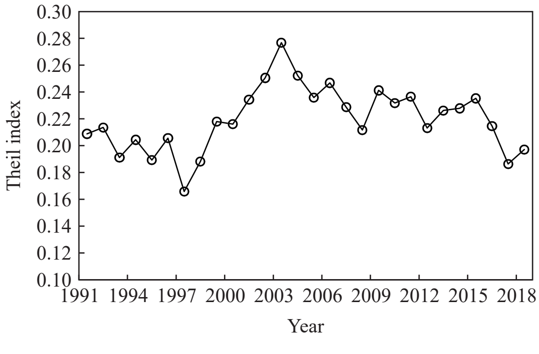


Figure 9 Change in the agricultural water footprint efficiency (AWFI) Theil index from 1991 to 2018 for Xinjiang

5.4 Countermeasures and suggestions based on AWFI driver analysis

The analysis of the impact of water-saving technology, planting structure, production scale, urbanization rate, and population on AWFI showed that water-saving technology (154.03%), planting structure (−37.98%), and population (−14.7%) had the greatest greater impacts on AWFI. In contrast, the overall production scale (4.61%) and urbanization rate (−5.97%) had little effect on AWFI. Water-saving technologies promoted a reduction in the WAFI in the 13 prefectures (cities) except for Karamay, which is dominated by industry. Therefore, the present study mainly focused on the mechanism under which water-saving technology, planting structure, and population influenced AWFI. Although there has been a considerable improvement in irrigation efficiency, there has not been a considerable reduction in irrigation water consumption, particularly in areas in which water resources are scarcer than land resources. Although the effectiveness of efficient water-saving has been questioned, the study by Wang et al.[10] showed that efficient water saving is not the cause of the Jevons paradox of “the more water is saved, the more water is scarce”. High-efficiency water saving in Xinjiang has greatly improved water productivity and has played a role in improving the quality and efficiency of agriculture in the study area. The changes to agricultural planting structure have represented the main obstacle to the reduction in the AWFI. Cotton, wheat, and miscellaneous grains accounted for 31.44%, 23.25%, and 14.39% of the planted area in Xinjiang, collectively accounting for nearly 70% of the total planted area. The water consumption per unit output of cash crops, especially cotton, exceeds that of grain crops by a factor of 5, while the economic benefits of cash crops exceed that of grain crops by only a factor of 3.[33] Therefore, the expansion of the economic crop planting area can be considered to be the main factor hindering the increase in the economic benefits of water. The population of Xinjiang has increased by ~150% during the study period. Agriculture has further attracted the movement of migrant labor into Xinjiang. Agriculture represents the main source of income for local people in Xinjiang. However, as the population continues to increase, the area of arable land will continue to expand. Since there is greater motivation to grow crops with a greater economic return, the grain-to-economic ratio will continue to decrease. Therefore, the population has become another major factor hindering the reduction in AWFI.

The results of the analysis of the factors influencing AWFI in Xinjiang over the 28-year study period showed that the main factors affecting AWFI are water-saving technology, planting structure, and population. On this basis, this present study proposes a series of recommendations to provide a reference for the future development of agriculture in Xinjiang:

1) High-efficiency water-saving technologies for agriculture should continue to be promoted and high-efficiency water-saving facilities should be constructed. Drip irrigation under the film was introduced in Xinjiang in the 1990s and can act as a technical platform for water and fertilizer integration. This technology can supply higher-quality agricultural products while using less water and fertilizer, ultimately achieving water-saving, high-yield, and environmentally friendly targets. China's “13th Five-Year Plan for the Implementation of 100 Million Mu of High-Efficient Water-saving Irrigation Area” clearly states that China aims to add 6.67 million hm^2 of high-efficiency water-saving irrigation area during the 13th Five-Year Plan period. Within this plan, there is a goal to develop an efficient water-saving area of 800 000 hm^2 in Xinjiang with a focus on drip irrigation. Since the national government attaches great importance to high-efficiency water-saving irrigation, there is an opportunity for the construction and development of agricultural water-saving in Xinjiang. A continued reduction in the AWFI and achieving sustainability of agricultural water conservation in Xinjiang requires the promotion of efficient water-saving practices in agriculture.

2) It is recommended that some adjustments to the agricultural planting structure be implemented. Planting structure has a certain impact on agricultural water consumption. For a given arable land area, the proportion of economic crops is positively related to the quantity of water used in agriculture[23, 34-36]. Cotton is a crop with

high water consumption. Some prefectures (cities) in Xinjiang, such as Bortala, Changji, and Karamay, fall within the northernmost part of the upland cotton planting area of China. This area is sub-optimal for the cultivation of cotton. However, the higher economic return of cotton has resulted in a continual increase in the area of cultivated cotton and an overall decline in the quality of cotton in Xinjiang. Therefore, the adjustment of the planting structure is one of the feasible measures that can be used to reduce agricultural water consumption in the future. It is recommended that the area of cotton agriculture in low-yield areas be reduced and that the cotton production capacity in high-quality and high-yield areas be consolidated and increased to optimize cotton production and water usage. The wheat agriculture area should be stabilized and forest and grain intercropping should be rationally allocated to maximize water conservation and crop benefits. Forest, fruit, and pasture planting should be actively developed and the planting of low-water consumption crops such as drought-tolerant, salt-tolerant alfalfa, and silage corn should be encouraged[22].

At the same time, the economy of Xinjiang is characterized as agriculturally focused and export-oriented. The short industrial chain and low added value of the crop economy in Xinjiang have resulted in the expansion of the scale of irrigation and an increase in the use of water to maintain the expansion of the crop economy. The future direction of agricultural development in Xinjiang will involve improving the economic value of primary products and extending the industrial chain to maximize the potential value of agriculture. The results of the present study found that the planting structure of Xinjiang has had a positive impact on the economic benefits of water in recent years. Therefore, there should be further focus on the adjustment of planting structure in Xinjiang while meeting market demand.

Although the overall planting scale in Xinjiang during the study period had little impact on AWFI, intensive management is fundamental to modern agricultural development. Since cultivated land is the basic means of production for agriculture, intensive agricultural management is mainly reflected in the intensive use of cultivated land[37]. Therefore, there should be a focus on promoting the intensive management of cultivated land in Xinjiang. The intensive use of cultivated land plays an important role in national food security, the supply of agricultural products, ecological security, and economic and socially sustainable development. Simultaneously, the intensive management of cultivated land contributes to the improvement of mechanization, reduces manpower, reduces crop planting costs, and improves the economic benefits of agriculture[38,39]. The economic benefits of agriculture should increase under the same water consumption. The most effective way to increase agricultural output under limited water resources and limit environmental pressure is to increase the degree of intensive use of cultivated land[40-42]. Therefore, future studies should further explore the relationship between intensive agricultural production and water efficiency.

6 Conclusions

This study conducted an analysis of the temporal and spatial evolution of AWFI in Xinjiang over the past 30 years and analyzed the influencing factors. The results showed that the AWFI has been decreasing since 1991. The evolution in the AWFI can be divided into two stages: 1) a rapid decline from 1991 to 1995; 2) a gradual decline from 1996 to 2018. There has been increasing the efficiency of agricultural water use in Xinjiang, although the efficiency is now beginning to plateau. Although the efficiency of utilization of water resources in southern Xinjiang was relatively high during the preliminary stage, the AWFI in southern Xinjiang significantly exceeded that in northern and eastern Xinjiang by 2018, with the lowest water use efficiency in the area in Xinjiang. The AWFI Theil index showed an inverted “N” shaped Kuznets curve over time, first decreasing from 1991 to 1997, increasing from 1997 to 2003, and finally decreasing again from 2003 to 2018, with inflection points in 1997 and 2003. Therefore, the spatial difference in agricultural water use efficiency in Xinjiang will continue to shrink in the short term. Water-saving technology was the main factor affecting the reduction of the AWFI. Planting structure and population were the main factors offsetting the reduction in the AFWI. Urbanization rate and production scale had little impact on the AWFI. It should be noted agricultural water-saving technologies are not sufficiently diversified and that the agricultural water rights and water price system in Xinjiang remains imperfect. Therefore, the present study did not explore the difference in AWFI under different agricultural water prices. Further research can explore the effects of different water-saving measures and different water prices on the AWFI.

Acknowledgements

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