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Water Footprint of Animal Breeding Industry and Driving Forces at Provincial Level in China

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Abstract: Agriculture significantly contributes to the global water footprint (WF) with the animal breeding industry accounting for over 33% of agricultural water consumption. Since 2000, rapid development in animal breeding has intensified the pressure on water resources. Forecasts indicate a projected 70% increase in freshwater usage in the meat industry by 2025 compared to 2000, particularly in developing countries, such as China, yet comprehensive studies regarding China's animal breeding industry WF remain limited. This study aimed to assess the variations in the green, blue, and gray WF of pork, beef, milk, eggs, and chicken meat across 31 provinces in China from 2000 to 2017. Additionally, a driving force analysis using the Kaya equation and LMDI method was conducted. Findings revealed that the total WF of animal products increased from 1049.67 Gm^3 (in 2000) to 1385.05 Gm^3 (in 2017) in China, and pork exhibited a significantly higher WF compared to other animal products, contributing 64.49% to China's total animal product WF. The sharp rise in the green WF demonstrated regional disparities in water consumption efficiency within the animal breeding industry. The increase in the blue WF was associated with rising livestock numbers and China's efforts to conserve water. The increase in the gray WF indicated that increased consumption of animal products heightened wastewater treatment pressures, particularly in economically developed provinces. The augmentation in China's animal product WF was primarily influenced by policy and economic effects, with increased agricultural equipment funding and enhanced production efficiency identified as effective strategies for WF reduction. This study suggests that the promotion of technology, combined with scientific policies, can alleviate the pressure on water resources in the animal breeding industry in developing countries.

Keywords: water footprint assessment; animal products; agricultural water consumption; logarithmic mean divisia index (LMDI); driving force analysis; Kaya equation

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1. Introduction

Agriculture represents a major contribution to the water footprint (WF) of humanity, and most of this contribution is linked to the animal breeding industry, which represents more than 33% of agricultural water consumption [1]. There is more pressure on water resources caused by the animal breeding industry. The growing need for livestock products, their substantial water usage, and their significant direct influence on aquatic environments have placed immense pressure on finite water resources. [2]. Predictions show that freshwater consumption in the meat industry will have a 70% increase by 2025 compared to

2000 [3]. Since the beginning of the new century, significant advancements in the animal breeding industry have been witnessed in developing nations. There is an imperative to enhance water productivity within this sector to mitigate its impact on water resources and the environment, thereby fostering the sustainability of animal production.

The WF [4] stands as a comprehensive indicator assessing both water consumption and its environmental ramifications. It quantifies direct and indirect water use by source and identifies polluted water according to the type of pollution, offering distinct spatiotemporal trends that reveal the impact of diverse human activities on water resources [3]. The water usage within the animal breeding industry is elucidated through the evaluation of the WF of animal products. This term encompasses the complete amount of direct and indirect freshwater utilized and contaminated due to livestock feeding practices. Direct water usage incorporates water utilized for drinking and for services like cleaning sheds [5]. Additionally, it encompasses water utilized to mitigate pollutant concentrations arising from animal excreta, commonly referred to as the gray WF. Indirect water consumption is the WF generated in the process of feed production over the lifetime of livestock. The green WF denotes the usage of green water, specifically rainwater that does not transform into runoff. Meanwhile, the blue WF signifies the consumption of blue water resources, including surface and groundwater, throughout the livestock product supply chain. Lastly, the gray WF quantifies water pollution, signifying the volume of freshwater needed to assimilate a pollutant load based on natural background concentrations and established ambient water quality standards [5].

The WF of animal products has been widely studied worldwide and provides the basis for the projections of global future demand for animal products [1,6–9]. Technology and economic development levels and populations are not considered for different countries at the global level. Therefore, the national WF of animal products has recently begun to be intensively analyzed. Most of these studies analyzed the environmental impact of a single WF of animal products in developed countries [2,8–16]. However, the WF of a single animal product has little impact on water resources for a country. The WF of the entire animal breeding industry enables an analysis of the future development of the industry and the impact on the development of a country. There are limited studies that are representative for developing countries, such as China, which is the one of the biggest producers of animal products in the world. China accounted for 46.25% of global pork and 39.13% of egg production in 2017 [17]. The main animal products consumed in China are pork, eggs, milk, poultry meat and beef. The production of these animal products in 2017 was 36.10%, 45.05%, 323.44%, 77.66%, and 25.56% higher than that in 2000, respectively. Water scarcity limits the expansion of animal production. Therefore, large quantities of animal products must be imported into China. China imported 3048.61 thousand tons of meat products in 2018 [17]. However, few studies have examined the driving forces of growth in the WF of the animal breeding industry in China. China's demand for animal products is rapidly increasing with economic development, which corresponds to a highly uneven agricultural development. For its future sustainable development, it is necessary to investigate the impact of the WF of the animal breeding industry on China's water resources.

The driving force of agricultural water consumption has become a major concern. The impact of population, economic, and intensity effects on agricultural water consumption has been widely analyzed [18–25]. Most of these studies ignored the impact of agricultural machinery inputs, the degree of farm automation, and the efficiency of farm production on the WF of animal products. China has continued to increase its investment in agricultural machinery and improve farming automation in recent years. The impact of these factors on the WF of animal products should be examined.

The present paper quantified and evaluated the interannual variations in the blue, green, and gray WFs of pork, eggs, milk, poultry meat, and beef in 31 provinces in China from 2000 to 2017. A driving force analysis was performed by combining a Kaya equation with the logarithmic mean division index (LMDI) method. Clearly, analyzing the variations and driving forces of the WF under changing economic conditions is important for the efficient utilization of regional water resources and for water management and allocation strategies.

2. Materials and Methods

2.1. Animals and Animal Products

In this study, our focus includes pigs, dairy cattle, beef cattle, broiler chickens, and laying hens, along with their respective products such as pork, milk, beef, chicken meat, and eggs. These animal categories represent significant segments within China's livestock industry, and we have extensively analyzed their WF variations and impact on water resources.

2.2. WF of Animal Products

The WFs of pork, beef, milk, eggs and chicken meat are estimated in this paper. The WF of animal products for category *a* in province *p* (WF; m^3) reflects the feed, drinking water, and service water consumed [1],

$$WF[a,p] = WF_{feed}[a,p] + WF_{drink}[a,p] + WF_{serv}[a,p] \quad (1)$$

where WF_{feed} [*a*,*p*], WF_{drink} [*a*,*p*], and WF_{serv} [*a*,*p*] represent the WF of animal products for category *a* in province *p* related to feed, drinking, and service water, respectively. Service water refers to the water used for maintaining cleanliness and cooling in animal buildings. For beef cattle, pigs, and broiler chickens—animals that yield products after slaughter—we ascertain the WF of the animal at the conclusion of its lifetime, subsequently distributing the total WF among the different products (such as meat and leather). In the case of dairy cattle and layer chickens, the process of determining the animal's WF per year (averaged over its lifetime) and relating this annual animal WF to its average annual production (milk, eggs) is more direct [1].

The WF of animal products related to their feed was calculated as follows (the water used to mix the feed was ignored):

$$WF_{feed}[a,p] = \frac{\sum_{i=1}^{n} \left(Feed[a,c,p] \times WF_{prod}[c] \right) + WF_{mixing}[a,p]}{Pop[a,p]} \quad (2)$$

Feed [*a*, *c*, *p*] denotes the yearly consumption of feed ingredient *c* by animal category *a* in province *c* (m^3/y), WF_{prod} [*c*] stands for the WF of feed ingredient *c* (m^3/ton), WF_{mixing} [*a*, *p*] signifies the water volume consumed during the feed mixing process for animal category *a* in province *p* (m^3/y/animal), and Pop [*a*, *p*] represents the annual count of slaughtered animals or the number of milk- or egg-producing animals in a year for animal category *a* in province *p* [1].

The calculation of WF_{drink} and WF_{serv} is as follows:

$$WF_{drink} = \frac{Drink[a,p]}{Pop[a,p]} \quad (3)$$

$$WF_{serv} = \frac{\sum_{i=1}^{n} Serv[a,c,p]}{Pop[a,p]} \quad (4)$$

where Drink [*a*, *p*] represents the annual amount of drinking water consumed by animal category *a* in province *c* (m^3/y) and Serv [*a*, *c*, *p*] is the water consumed to keep the animal building clean and cool *c* for animal category *a* in province *p* (m^3/y).

2.3. Driving Force Analysis

The driving force analysis was extended to identify the factors influencing the increase in the WFs. While the Kaya equation is commonly employed in analyzing the driving forces of carbon emissions and energy consumption [19,25,26], this paper expands its application to decompose the WF as follows.

$$WF = \sum_i \frac{WF_i}{Y_i} \cdot \frac{Y_i}{FARM} \cdot \frac{FARM}{MAC} \cdot \frac{MAC}{EXP_a} \cdot \frac{EXP_a}{EXP} \cdot \frac{EXP}{GDP} \cdot \frac{GDP}{P} \cdot \frac{P}{W} \cdot \frac{W}{W_a} \cdot W_a \tag{5}$$

where WF_i, Y_i, $FARM$, MAC, EXP_a, EXP, GDP, P, W, and W_a represent the WF of animal product i, the yield of animal product i, the number of farms, the number of agricultural machines and China's financial expenditure on agriculture, total financial expenditure, GDP, populations, water resources, and agricultural water, respectively. The ten driving forces are defined in Table 1.

Table 1. Ten driving forces of the WF of animal products in China.

Effect	Decomposition	Symbol	Explanation
Technology Effects	WF_i/Y_i	A	Unit WF content
	$Y_i/FARM$	B	Farm production efficiency
	FARM/MAC	C	Degree of automation on farms
Policy Effects	MAC/EXP_a	D	Funding for agricultural equipment
	EXP_a/EXP	E	National agricultural inputs
	EXP/GDP	F	Scale of national financial expenditure
Economic Effects	GDP/P	G	Agricultural earnings per capita
Endowment Effects	P/W	H	Per capita water resources
	W/W_a	I	Utilization of water resources in agriculture
	W_a	J	Water consumption in agriculture

The study then utilizes the LMDI decomposition method to quantitatively assess the contribution of each influencing factor [27,28]. The LMDI method boasts several advantages, including complete decomposition without residual, a strong theoretical foundation, adaptability, ease of use, and a straightforward interpretation of results [19]. This model aids in analyzing the driving factors within the Kaya equation and their subsequent effects. In accordance with the LMDI method, there exists a variation in the WF between the base year and year t, as illustrated in Equation (6).

$$\Delta WF = WF^t - WF^0 = \Delta WF^A + \Delta WF^B + \Delta WF^C + \Delta WF^D + \Delta WF^E + \Delta WF^F + \Delta WF^G + \Delta WF^H + \Delta WF^I + \Delta WF^J \tag{6}$$

where

$$\Delta WF^A = q \times ln\left(\frac{A^t}{A^0}\right) \tag{7}$$

$$\Delta WF^B = q \times ln\left(\frac{B^t}{B^0}\right) \tag{8}$$

$$\Delta WF^C = q \times ln\left(\frac{C^t}{C^0}\right) \tag{9}$$

$$\Delta WF^D = q \times ln\left(\frac{D^t}{D^0}\right) \tag{10}$$

$$\Delta WF^E = q \times ln\left(\frac{E^t}{E^0}\right) \tag{11}$$

$$\Delta WF^F = q \times ln\left(\frac{F^t}{F^0}\right) \tag{12}$$

$$\Delta WF^G = q \times ln\left(\frac{G^t}{G^0}\right) \tag{13}$$

$$\Delta WF^H = q \times ln\left(\frac{H^t}{H^0}\right) \tag{14}$$

$$\Delta WF^I = q \times ln\left(\frac{I^t}{I^0}\right) \tag{15}$$

$$\Delta WF^J = q \times ln\left(\frac{J^t}{J^0}\right) \tag{16}$$

A, B, C, and D are labeled technology effects, E and F are policy effects, G is the economic effect, and H, I, and J are the endowment effects. After conversion through the application of the LMDI model, the proportion of each of these ten effects is obtained in the explanation for changes in the WF of animal products. If an effect's value is negative, it implies a positive driving factor contributing to the reduction in the WF. The greater the absolute value of this effect, the more pronounced its positive impact as a driving factor. Conversely, a positive effect value indicates a negative driving factor. The magnitude of this effect's value signifies the extent of the impact caused by the driving factor.

q is the logarithmic weight and can be calculated using Equation (17).

$$q = \frac{WF^t - WF^0}{ln\left(WF^T\right) - ln\left(WF^0\right)} \tag{17}$$

2.4. Data

The daily drinking water consumed, daily service water consumed, and feed composition of animals were obtained from Chapagain and Hoekstra [6]. The WF of feed ingredients was obtained from published articles [29,30]. For each province, the annual number of slaughtered animals and production of animal products were obtained, and the number of livestock farms, agricultural machines, financial expenditure on agriculture, total financial expenditure, GDP, populations, water resources, and agricultural water for China were obtained from the National Bureau of Statistics of China.

3. Results and Discussion

3.1. Provincial WF of Animal Products in China

3.1.1. Green, Blue and Gray WF of Animal Products

The green WF of animal products is shown in Figure 1. The results show that a dramatic rise occurred from 2000 to 2017, with a fluctuation of approximately 31.59%. The green WF grew in most provinces, with the exception of Beijing (−45.70%), Shanghai (−63.17%), and Zhejiang Province (−22.57%). The growth rate during the period between 2008 and 2017 (11.53%) was lower than that during 2000–2008 (17.99%), indicating that the demand for animal products is gradually being met as the number of livestock and poultry animals raised in most provinces increases in China.

The regional disparities in the green WF of animal products highlight the diverse efficiency levels in water consumption across provinces within the animal breeding industry. These WFs exhibited notable variations among provinces and underwent significant changes from 2000 to 2017. In 2000, Shandong (67.19 Gm^3), Hunan (64.79 Gm^3) and Hebei (64.45 Gm^3) had higher green WFs, whereas Sichuan (73.95 Gm^3) and Henan (70.67 Gm^3) had the largest green WFs. In 2008, Henan had the largest green WF (86.19 Gm^3). In 2017, Shandong (93.86 Gm^3) surpassed Henan (91.03 Gm^3) and had the largest green WF. Beijing, Shanghai, and Zhejiang had a lower green WF in 2017 than in 2000.

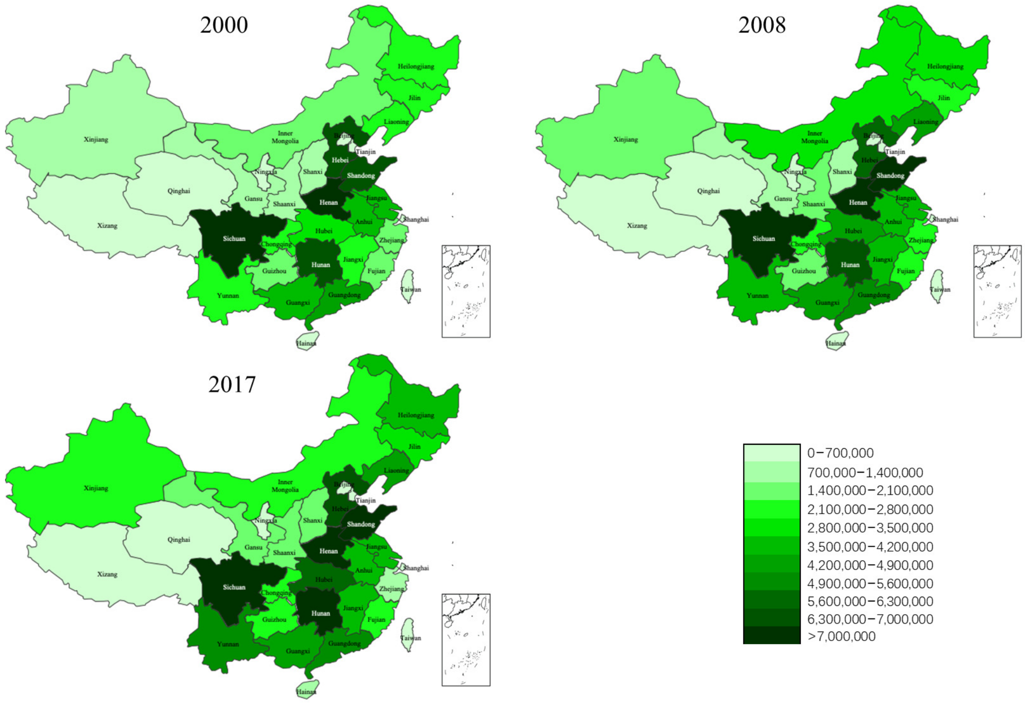

Figure 1. Green WF of animal products in China.

Figure 2 shows the variations in the blue WF of animal products in China over 2000–2017. The blue WF increased by 33.12% during 2000–2017. The blue WF increased in all provinces with the exception of Beijing (−48.69%), Hebei (−0.37%), Shanghai (−67.43%), and Zhejiang (−22.18). The growth rate of the blue WF during 2000-2008 (17.04%) was higher than that during 2008–2017 (13.74%). On the one hand, the increase in the number of livestock and poultry animals led to a larger blue WF, while on the other hand, it can be seen that China made many efforts to save water.

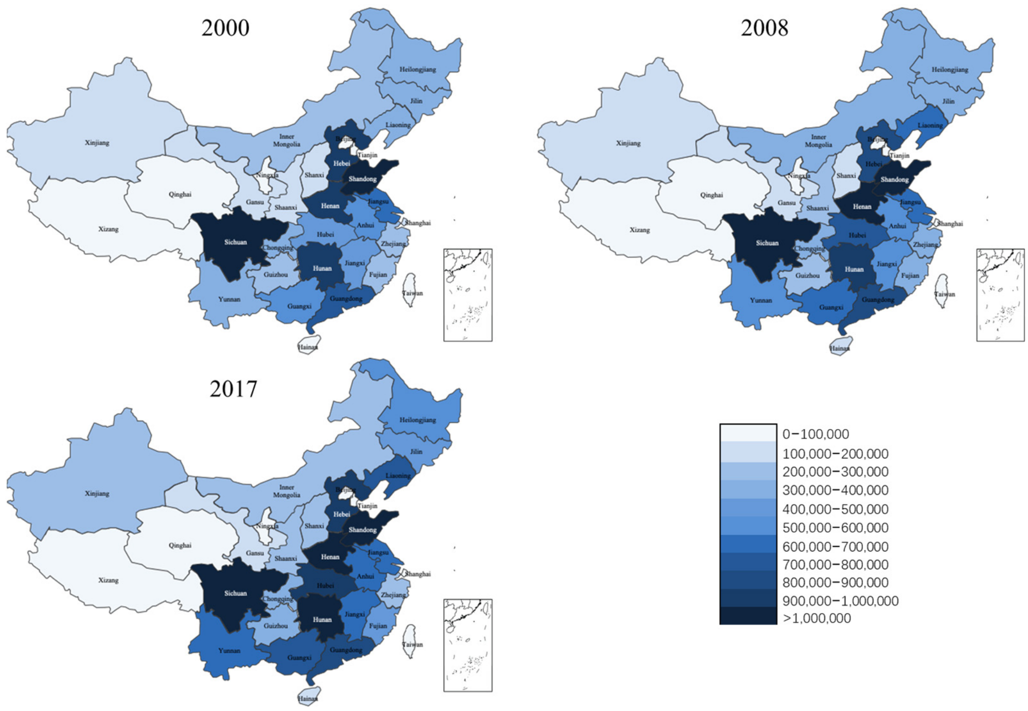

Figure 2. Blue WF of animal products in China.

Differences in the water conservation capacity across provinces are reflected in the depletion of the blue WF in 2000, 2008, and 2017. In 2000, Henan (9.74 Gm^3), Hebei (9.53 Gm^3), and Hunan (9.37 Gm^3) had larger blue WFs, whereas Sichuan (10.82 Gm^3) and Shandong (10.33 Gm^3) had the largest blue WFs. In 2008, Sichuan had the largest blue WF (12.56 Gm^3). In 2017, Shandong (14.95 Gm^3) surpassed Henan (14.26 Gm^3) to have the largest blue WF.

This analysis revealed a notably higher WF for pork compared to other animal products. Pork production contributed significantly to the overall WF of animal products in China, accounting for 64.49%. This dominance of the WF of pork highlights its substantial impact on water resources, emphasizing the importance of reducing its water consumption for ensuring the sustainability of water resources in China. The green and blue pork WF was averaged at 705.9 Gm^3 per year, which is much larger than the 225.8 Gm^3 per year in Xie's study [3]. These numbers may be interpreted as the difference between the number of stocked and slaughtered pigs in China. The pork WF may be overestimated, but the annual water consumption of the stocked pigs was not ignored.

The WFs of all five animal products in this study were higher than those in published studies [1,3,8,12–14]. This study concluded that the total WF of animal products needs to encompass all the water consumed by animals annually. The substantial water consumption by living animals should not be disregarded and needs consideration in assessing water resources.

The green and blue WFs are interconnected. Typically, the green WF from feed crop production does not have a notably adverse environmental impact. Nevertheless, globally, minimizing the green WF might be crucial in decreasing the blue WF in crop production. Enhancing rainwater efficiency, such as augmenting yields per unit of rainwater, holds the potential to decrease the blue WF associated with feed crops.

The large animal population requires a greater capacity for manure treatment, especially in the northern provinces of China (Figure 3). In 2017, Shandong (12.89 Gm^3), Henan (12.60 Gm^3), Sichuan (11.80 Gm^3), and Hunan (10.38 Gm^3) had the highest gray WFs, accounting for 37.39% of the total. In contrast, Tibet had the highest growth rate (227.62%) of the gray WF during 2000–2017.

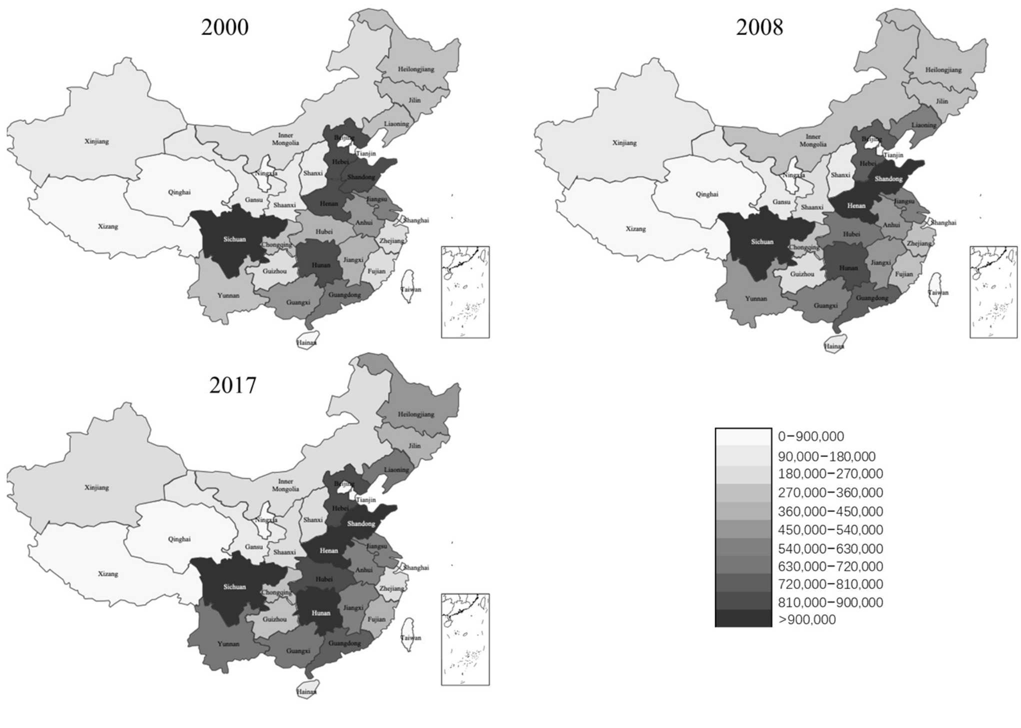

Figure 3. Gray WF of animal products in China.

The total gray WF increased by 33.12% in 2017 compared to 2000. These results are different from the gray WF estimated by Zhang [19], who indicated that the volume of agricultural gray WF remained relatively stable and only slightly increased during 2003–2015. The differences in the gray WF may be explained by the contradiction between technical progress and consumption growth. The increased gray WF of agriculture was curbed with technical progress in pollution treatment, in recent years. The increased gray WF of animal products indicates that the consumption growth of animal products increased the pressure on wastewater treatment while offsetting the benefits of technical progress. Hence, the gray WF of animal products emerges as a pivotal factor in wastewater management across China. It becomes imperative to enhance the discharge norms for pollutants in the animal breeding sector, especially in economically advanced provinces. Implementing effective strategies to diminish wastewater production on farms and to curtail fertilizer usage in feed crop cultivation remains essential.

3.1.2. Changes in the Total WF in Different Regions of China

For descriptive purposes, China was divided into seven regions based on its livestock characteristics (Figure 4): Qinghai–Tibet Plateau (QTP, Tibet, and Qinghai), Inner Mongolia-Xinjiang Region (IXR, Inner Mongolia, and Xinjiang), Loess Plateau (LP, Shaanxi, Ningxia, and Gansu), Southwest Mountain Region (SMR, Yunnan, Guizhou, Sichuan, and Chongqing), Northeast Region (NER, Liaoning, Jilin, and Heilongjiang), Northern China Region (NCR, Beijing, Tianjin, Hebei, Shandong, Henan, Shanxi, Jiangsu, Shanghai, and Anhui), and Southeast region (SER, Zhejiang, Fujian, Guangdong, Guangxi, Hunan, Hubei, Jiangxi, and Hainan).

Figure 4. Seven regions in China.

Figure 5 shows the total WF for the different livestock animal compositions for the seven regions in 2000, 2008 and 2017. The NCR had the highest WF. The average total WFs of animal products in 2000, 2008, and 2017 were 15.00 Gm^3 $year^{-1}$, 17.67 Gm^3 $year^{-1}$, and 19.50 Gm^3 $year^{-1}$, respectively. The WF of pork accounted for 54.43%, 51.18%, and 54.49% of the total WF in 2000, 2008 and 2017, respectively. The WF of animal products in most regions showed an increasing trend over the period 2000–2017, except for the IXR region. In 2000–2017, the consumption structure of animal products in the LP, SMR, NER, NCR, and SER regions was dominated by pork, and the total WF of pork increased by 33.28% from 678.5 Gm^3 $year^{-1}$ to 904.3 Gm^3 $year^{-1}$, whereas beef had the largest WF in the QTP region, accounting for 62.43% on average.

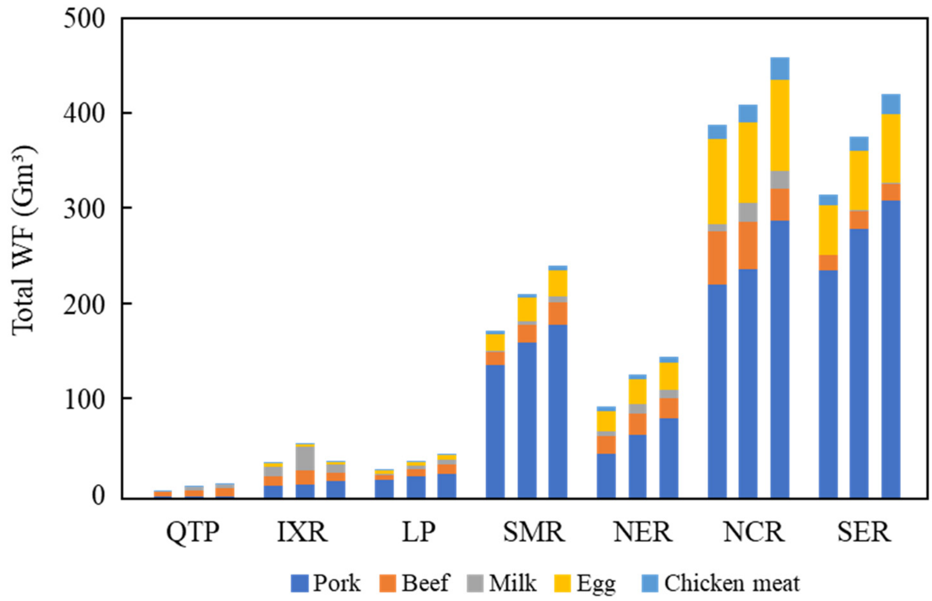

Figure 5. Total WF in different regions of China in 2000, 2008, and 2017.

The contribution of animal products to the total WF varied considerably between different regions. Some provinces produced enormous WFs of animal products and ranked within the top three in 2000, 2008, and 2017. Their enormous WFs were induced by rapid socioeconomic development. These regions are densely populated and have a higher demand for animal products [24,31]. Specifically, a large amount of animal products were produced and consumed in these regions compared to other regions. Provinces in the NCR and NER heavily rely on locally sourced water-intensive animal products and predominantly export feed crops. These areas face severe water stress and grapple with a substantial water scarcity challenge, considering the massive demand for water resources. In these provinces, the animal breeding industry plays a vital role in mitigating the strain on water resources and ensuring sustainable development. Tailoring their development strategies based on local water availability becomes crucial. Therefore, adjusting trade dynamics and relocating a portion of animal product and crop production to regions endowed with abundant water resources could alleviate water scarcity and optimize water utilization in these regions.

The high WF observed in developed areas can be attributed to several factors. Firstly, developed regions often have higher livestock production, leading to increased water consumption due to larger herd sizes and more intensive farming practices. Secondly, these areas tend to rely on more resource-intensive production systems, such as confined animal feeding operations (CAFOs), which require significant water inputs for maintaining livestock health and hygiene. Additionally, the increased use of feed with higher WFs and the reliance on processed feeds might elevate the overall WF in these developed regions. Moreover, the higher demand for animal products in developed areas might drive the need for larger-scale production, contributing to increased water usage throughout the livestock farming process. Lastly, the presence of more advanced but water-consuming technologies and infrastructure in these regions could also contribute to the higher WF associated with livestock farming.

3.2. Driving Force Analysis

In this study, an analysis of the driving forces behind the total WF was conducted. Utilizing the LMDI model, the factors influencing the total WF for each province were categorized into four effects: the technology effect (A, B, C, D), policy effect (E, F), economic effect (G), and endowment effect (H, I, J) (Figure 6).

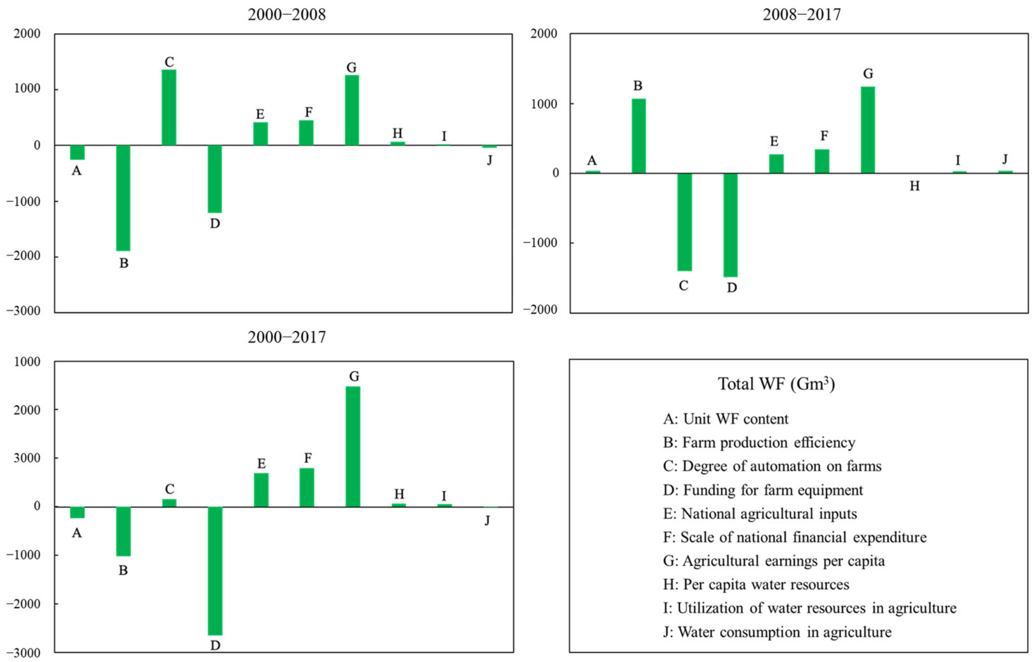

Figure 6. Driving forces of the WFs of animal products in different periods in China.

The results show that G, F, and E were the three most significant driving forces of the total WF increase in the Chinese animal breeding industry. The other driving forces of the increase in the total WF included C, H, and I. The six driving forces contributed 2482.41, 801.97, 696.62, 154.02, 66.29 and 50.93 Gm^3 to the Chinese breeding industry. D was the leading factor in the decline in the total WF, followed by B, A, and J. The four driving forces contributed −2650.51, −1023.00, −237.86, and −5.49 Gm^3 to the total WF of the Chinese breeding industry, respectively.

We decomposed the total WF of the Chinese breeding industry into two different periods to explore the driving forces of the total WF. During 2000–2008, the overall WF increased by 187.11 Gm^3, and C and G had a decisive effect on the increase in WF. The other important driving forces of the increase in total WF were the change in E and F, whereas H and I only marginally affected the total WF. B and D were the leading factors in the decline during this period.

In contrast to the 2000–2008 period, the increase in the total WF of the breeding industry at the national level and the effects of its driving forces differed significantly between 2008 and 2017 in China. B contributed to the increase in total WF, but the positive effects of B notably changed in the two periods. This change may be due to a mismatch between the production of animal products and the increased number of farms. This study finds that D promoted a decline in the total WF during the two periods. The extent of the decrease in 2008–2017 was larger during the two periods since a greater increase in D occurred in 2008–2017. This demonstrates that increased funding for agricultural equipment is effective in reducing WFs. Moreover, G, F, and E were promoted to increase the total WF over the two periods. This promotion could be due to rapid economic growth and a continued rise in the demand for animal products in China. E and F indicate that policy effects may be beneficial to the development of the Chinese breeding industry, while water consumption also increased. The effects of B and C notably changed in the two periods. The change in B occurred because farming productivity was lower during 2008–2017 than in 2000–2008. For example, between 2008 and 2017, the number of farms increased significantly, but the increase in the production of animal products was modest, making 2008–2017 less productive than 2000–2008. The change in C was due to the development of automation on farms. The increase in agro-mechanical equipment has increased the level of automation in farming, and the high level of automation helps to reduce water consumption.

Enhancing farm production efficiency stands as a viable option to alleviate the prevailing pressure on water resources. Namely, the yield of animal products increased under the same conditions of breeding and water consumption, which slowed the expansion of animal breeding scale and reduced water consumption. Despite the advancements witnessed in China's farm production efficiency within the animal breeding industry over the study period, it remained relatively lower in comparison to other industrialized nations, signifying the need for further enhancement. During the past two decades, the substantial expansion of China's animal feeding industry has largely met the demand for animal products among its populace. Efforts are needed create a resource-saving farming model to reduce water consumption while improving production efficiency in the future.

The main drivers behind the increase in the Chinese WF of animal products from 2000 to 2017 were the policy and economic effects, and the technology effects were the main driver of the reduction. Funding for agricultural equipment is increasing via national agricultural inputs and encouraging input from practitioners. The development of the animal breeding industry may be promoted, and the WF of animal products will be reduced. It is more scientific and reasonable to reduce the WF in this manner rather than changing people's consumption habits and continuously expanding the importation of animal products.

3.3. Comparative Analysis

Published studies [2,3,10] broadly addressed the WF of livestock; they mainly concentrated on the overall water resource consumption in specific countries (Korea, the United States) or regions. In contrast, our study focused specifically on the WF of livestock farming in distinct regions of China, undertaking regional and temporal analyses to deeply investigate the variations in WFs across different provinces from 2000 to 2017. This detailed approach provided more specific and concrete data support for managing water resources in the Chinese livestock industry. By conducting an in-depth analysis of the changes in the WF of China's specific regions, including comparisons between different provinces and the impact of various farming scales, our paper provided more precise, practical recommendations and guidance for managing the WF of the livestock industry in specific regions of China.

3.4. Limitations

The study faces certain limitations that could impact the accuracy and comprehensiveness of our findings. Firstly, the diverse regional characteristics of China, including varying climates, economies, and populations, pose a challenge in obtaining representative data for each region, potentially leading to an overestimation of WFs for animal products. Furthermore, our research focused on only five animal species, neglecting other commonly consumed varieties like sheep and duck meat. Expanding the scope of animal products examined could provide a more comprehensive understanding. Additionally, our emphasis on the green WF, while crucial, highlights the necessity to investigate factors influencing water use in the cultivation of feed crops. Future studies should consider delving into the WF of feed crops to offer a more holistic perspective on the overall water impact associated with animal product production.

4. Conclusions

In this study, the WFs of the animal breeding industry were estimated in 31 provinces of China. A driving force analysis of the WF was also conducted by combining a Kaya equation and the LMDI method. The main conclusions were drawn as follows.

The total WF of the animal breeding industry has risen due to the economic development of developing countries. The national total WF of animal products increased 31.95%, from 1049.67 Gm^3 in 2000 to 1385.05 Gm^3 in 2017. The WF of pork constituted the major portion of the total WF in most provinces, consequently being the primary factor contributing to the overall WF increase.

Economically developed regions had higher WFs than less developed regions. The eastern regions of China are more economically developed than the western regions, and the total WF of the animal breeding industry in the eastern regions is higher.

Increasing the funding for agricultural equipment, integrating more small farms, improving production efficiency, and increasing the automation of farms may effectively reduce the WF of animal products.

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