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Risk Assessment and Pressure Response Analysis of the Water Footprint of Agriculture and Livestock: A Case Study of the Beijing–Tianjin–Hebei Region in China

Chen Cao [1,2], **Xiaohan Lu** [1,2] **and Xuyong Li** [1,2,*]

[1] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

[2] University of Chinese Academy of Sciences, Beijing 100049, China

* Correspondence: xyli@rcees.ac.cn; Tel.: +86-10-62849428

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Abstract: Excessive water consumption, associated with regional agriculture and livestock development and rapid urbanization, has caused significant stress to the ecological health and sustainable use of water resources. We used the water footprint theory to quantify the spatiotemporal characteristics and variation in the water footprint of agriculture and livestock (WF-AL) in the Beijing–Tianjin–Hebei region of China (2000–2016). We predicted the spatial distribution and sustainability of regional water resources at different levels of annual precipitation. Results showed that the average county WF-AL rose from 8.03×10^8 m^3 in 2000 to 10.89×10^8 m^3 in 2016. There was spatial heterogeneity compared to the average city WF-AL. The WF-AL varied between the mountains and the plains. The scale of the WF-AL was one of the main reasons for differences in the consumption and distribution of water resources. The development of regional water resources deteriorated from a stable state to an unstable state from 2000 to 2016. Only 5.8% of the areas maintained a stable state of water resources. Even in the predicted wet years, no improvements were found in the instability of water resources in four areas centered on the counties of Xinji, Daming, Luannan, and Weichang. To achieve a medium and long-term balance between WF-AL development and water resource recovery, the WF-AL should be limited and combined with reservoir and cross-regional water transfer.

Keywords: water footprint; the Beijing-Tianjin-Hebei region; agriculture and livestock; water resource

1. Introduction

The consumption of freshwater resources is an integral part of modern society but it has gradually become a limiting factor for society [1]. According to the 2017 United Nations World Water Development Report, 60% of the world’s population live in water-deficient areas, and by 2030 the global freshwater demand will grow by 50% compared with current demand [2–4]. China is one of the countries suffering the most severe water shortages worldwide, and problems related to the uneven spatial distribution of water resources and excessive water consumption are extremely serious in this country [5–7]. The Beijing-Tianjin-Hebei (BTH) region in China’s semi-arid and semi-humid areas typifies these problems. In 2017, the BTH region had per capita water resources of 286 m^3/person, less than 30% of the international minimum standard [8,9]. Urbanization of the BTH region has reached 64.9%, and 2.35% of the land area has to bear 7.24% of the population’s living security and 10.36% of the socio-economic aggregate. The siphon effect of urbanization will increase the scale of regional agriculture and livestock development in the non-core urban areas of the BTH region, further increasing the demand for water resources [10,11]. However, 65% of the surface rivers in the BTH region are facing a shortage of water resources due to seasonal flows, as well as water shortages because of agricultural non-point source pollution and secondary pollution from transferred ecological water [12,13]. Regional agriculture and livestock development has caused significant stress on the ecological health of river water and the sustainable use of water resources in the BTH region [14].

With regard to the scarcity of regional water resources, the governments in the BTH region have adopted water-saving control measures to deal with the impact of water shortages [15–17]. However, the control measures focus on cross-regional water resource regulation in the core urban areas, or small-scale agricultural water-saving demonstrations and experiments in the non-core urban areas; no effective measures have been taken to restrict the over-exploitation of water resources in regional agriculture and livestock production [18,19]. Given the current climatic conditions, which are relatively stable, it will be difficult to change the trend of regional water shortages in the short to medium term [20]. It is, therefore, necessary to maintain a dynamic balance between the development of agriculture and livestock production and the conservation and recovery of water resources [21].

The water footprint theory was proposed in 2002. Because of its simple and easy application, this theory has been extensively used in research into the consumption and evaluation of water resources at macro scales, such as national and regional levels [22–27]. Researchers have explored the impacts of land use, typical crop production, pollution risk, demographic change, and socioeconomic fluctuations on regional water resources at province and city levels in the BTH region [15,18,28–31]. However, existing studies rarely involved small-scale horizontal comparisons between counties, which weakens the analysis of spatial differences in the water footprint and affects the feasibility of implementing recommendations. Temporally, previous studies have not analyzed the long-term cumulative effects of changes in the water footprint, and have ignored the analysis of regional water resources under different precipitation conditions. Regional evaluation studies also reduce the effect of natural differences in the distribution of agriculture and livestock development caused by factors such as terrain and urbanization.

In the present study, we estimated the water footprint of agriculture and livestock (WF-AL) in 155 counties (including districts) in the non-core urban areas of the BTH region from 2000 to 2016 based on typical agriculture and livestock production. We then analyzed the distribution of the WF-AL based on precipitation and terrain characteristics across different areas. The main objectives of this study were: (1) to quantitatively evaluate the spatiotemporal variation of the WF-AL in the BTH region in 2000–2016; (2) to estimate the response pressure of agricultural and livestock development on water resources in the BTH region across different levels of annual precipitation; and (3) to provide recommendations and plans for adjusting the distribution of agriculture and livestock industries and improving the allocation of water resources. The results can help to optimize water resource allocation and implement a sustainable medium and long-term development plan for agriculture and livestock in the BTH region. The study also provides a reference for research into the conservation of water resources in similar semi-arid and semi-humid areas.

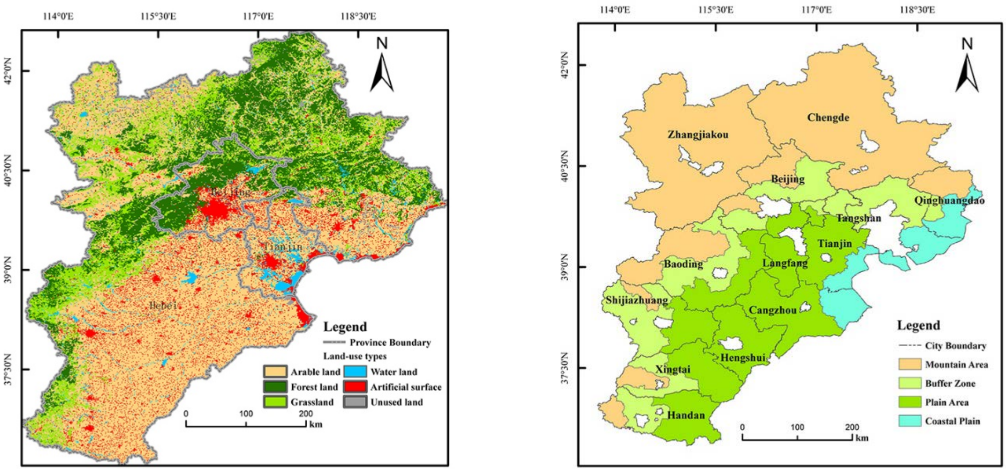
2. Materials and Methods

2.1. Study Region

The BTH region is located in the Haihe River Basin in northern China. This region is comprised of the Beijing municipality, Tianjin municipality, and Hebei Province, with a total area of approximately 216,000 km^2. The terrain is complex, generally tilting from the northwest to the southeast, consisting of a mountain area, a buffer zone (mountain–plain transition zone), a plains area, and a coastal plain (Figure 1). The BTH region has a temperate continental monsoon climate. The average annual precipitation range is between 400 and 600 mm from north to south and the precipitation is mostly concentrated in June–September, which is typical for a semi-arid and semi-humid area.

The BTH region covers 13 cities, from which the specific areas studied here were selected according to the “Beijing-Tianjin-Hebei Collaborative Development Plan” and the “13th Five-Year Development

Plan" of each city, as well as the development trends of counties and their differences in industrial and agricultural development (as of 2018). After excluding the core urban areas of each city, a total of 155 county-level administrative areas were selected to form the study region for WF-AL in the BTH region. These included 31 counties in the mountain area, 37 counties in the buffer zone, 80 counties in the plains area, and 7 counties on the coastal plain.



(**a**) study area (**b**) terrain types

Figure 1. Study area and terrain types.

Yield data for major agricultural and livestock products and area data for administrative divisions in the 155 county-level administrative areas from 2000 to 2016 were derived from the relevant statistical yearbooks and socioeconomic statistical bulletins of Beijing, Tianjin, and Hebei (2000–2017) (http://www.nlc.cn/). The data on precipitation and water resource use were derived from province/city water resource bulletins and city statistical yearbooks (2000–2017). Classification of the terrain and watersheds was based on the 30-m digital elevation model of China (2010).

2.2. WF-AL Analysis

2.2.1. Calculation Methods

The water footprint refers to the sum of water resources contained in direct or indirect goods and services consumed by humans per year within a certain area [32]. Agriculture and livestock production and subsequent product consumption are an integral part of human production and livelihoods, as well as one of the most important forms of water consumption [33]. The water footprint of agriculture and livestock (WF-AL) refers to the total water consumption during the life cycle of agricultural production and livestock breeding, in which the life cycle of agricultural and livestock products is generally one year [34]. Currently, there are two main methods for the calculation of WF-AL: the top-down evaluation method and the province/city-level bottom-up accumulation method [35,36].

A third method, the county-level bottom-up accumulation method, is based on county-level sub-units, while the data are dependent on county statistical yearbooks. The county-level method is superior to the two methods mentioned above in terms of its use for the quantification, evaluation, and optimal management of small and medium-sized watershed units across administrative areas. Therefore, the county-level bottom-up accumulation method was adopted to calculate WF-AL and its spatial density in our study region. The calculation methods are expressed as follows:

$$WF - AL = \sum P_{\mathrm{i}} \times VW \quad (1)$$

where WF-AL represents the total WF-AL in a region, which quantifies the water consumption of regional agriculture and livestock; P_{i} represents the mass of an agriculture and livestock product consumed in the corresponding region; and VW represents the virtual water content per unit mass of the agricultural and livestock products in the corresponding region.

$$\rho_{[WF-AL]} = \frac{WF-AL}{\rho_{H_2O} \times \text{Area}} \quad (2)$$

where $\rho_{[WF\text{-}AL]}$ represents the spatial density of WF-AL in a region, which measures the spatial variation of WF-AL per unit area in the region; ρ_{H2O} represents the density of water (ρ_{H2O} = 1000 kg/m^3); and Area represents the area corresponding to the region.

$$L_{[WF-AL]} = \rho_{[WF-AL]} - P = \frac{WF-AL}{\rho_{H_2O} \times \text{Area}} - P \quad (3)$$

where $L_{[WF\text{-}AL]}$ represents the difference between the spatial density of WF-AL and the annual precipitation in a region, which measures the development intensity and surplus or loss of water resources for agriculture and livestock in the region and P refers to the annual precipitation in the region. $L_{[WF\text{-}AL]}$ < -200mm indicates that the development of regional water resources is in a healthy state, while $L_{[WF\text{-}AL]} \in (-100{,}100)$ mm indicates a relatively balanced state and $L_{[WF\text{-}AL]}$ > 400mm indicates an unstable state [37].

$$K_{[WF-AL]} = \rho_{[WF-AL]} \times \frac{1}{P} = \frac{WF-AL}{\rho_{H_2O} \times \text{Area}} \times \frac{1}{P} \quad (4)$$

where $K_{[WF\text{-}AL]}$ represents the ratio between the spatial density of the WF-AL and the annual precipitation in a region, which measures the response relationship between regional agriculture and livestock development and precipitation.

2.2.2. Virtual Water Content of Agriculture and Livestock Products

The WF-AL per unit mass is numerically equivalent to its virtual water content, which is determined by water consumption during the production process of crop planting/livestock rearing. In the non-urban industrial areas, agriculture and livestock products form the most important part of regional water consumption. There are two main methods for calculating the virtual water content of agricultural products (VW_c): estimation based on the measured evapotranspiration of crops, and estimation based on the inversion of products. For estimation of a long-term series of virtual water content for agriculture and livestock, the former method is applied to single small watersheds with station observation experiments, while the latter method is applied to watersheds with limited empirical data and a large area.

Limited to the measured meteorological data in the BTH region, the actual evapotranspiration of agricultural products is difficult to obtain. Here, we adopted the inversion of products method to estimate the VW_c of agricultural products. We selected agricultural products with a total yield > 5% throughout the study region. These products included eight food crops and cash crops. Their VW_c values are listed in Table 1 [38–41]. The virtual water content of livestock products (VW_a) refers to the water consumption in the life cycle of livestock production during feeding. Because large-scale farming is the dominant method for the main livestock products in the study region, we selected six typical livestock products based on the results of similar studies in this region. Their VW_a values are given in Table 1 [14,32,42–48].

Table 1. Virtual water consumption of agriculture and livestock products in the Beijing–Tianjin–Hebei (BTH) region (m^3/kg).

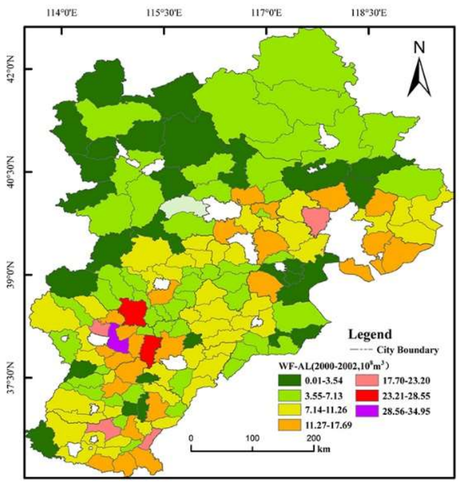
Region	Agricultural and Livestock Products													
	Grain Crops				Cash Crops				Livestock Products					
	Wheat	Maize	Paddy	Tubers	Peanut	Cotton	Vegetable	Fruit	Pork	Beef	Mutton	Poultry	Egg	Milk
Hebei	1.38	1.19	2.19	1.2	1.2	5.5	0.1	0.68	3.6	18.1	19.98	3.50	8.65	2.2
Beijing	1.23	0.84	1.4	0.7	1.5	4.4	0.2	0.58						
Tianjin	1.25	0.76	1.19	0.88	1.5	5.22	0.1	0.48						

3. Results

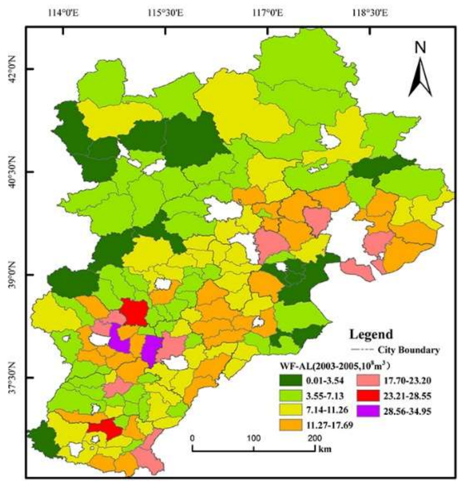
3.1. Structure of the WF-AL

3.1.1. County WF-AL

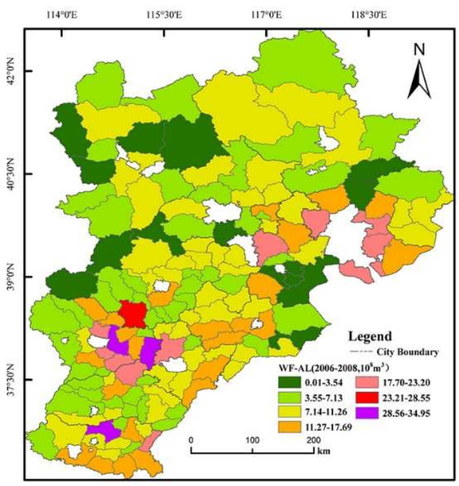
From 2000 to 2016, the average annual county WF-AL (WF-AL$_{county}$) increased from 8.03×10^8 m^3 to 10.89×10^8 m^3. The average annual growth rate of WF-AL$_{county}$ was 1.9%, indicating a slow upward trend. However, for individual counties, there were spatiotemporal differences in WF-AL$_{county}$. From 2000 to 2002, the Chongli District of Zhangjiakou had the lowest value (0.39×10^8 m^3), while the maximum value was found in the Gaogcheng District of Shijiazhuang (31.69×10^8 m^3). In 2015–2016, the Mentougou District of Beijing had the lowest value (0.25×10^8 m^3), while the maximum value occurred in the Xinji County of Shijiazhuang (34.65×10^8 m^3; Figure 2). The average annual growth rate of the Max(WF-AL$_{county}$) was 0.6%, while the Min(WF-AL$_{county}$) had an average annual growth rate of 4.9%. The ratio of Max(WF-AL$_{county}$) to Min(WF-AL$_{county}$) increased from 81.3 in the early stage to 138.6 in the later stage. In regard to spatial distribution, the top 10% of areas in terms of Max(WF-AL$_{county}$) showed an agglomeration effect. Most were located in the plain areas of Shijiazhuang and Handan, or the coastal plain of Tangshan. By contrast, the top 10% of areas in terms of Min(WF-AL$_{county}$) were scattered in the northwest and central east of the BTH region.



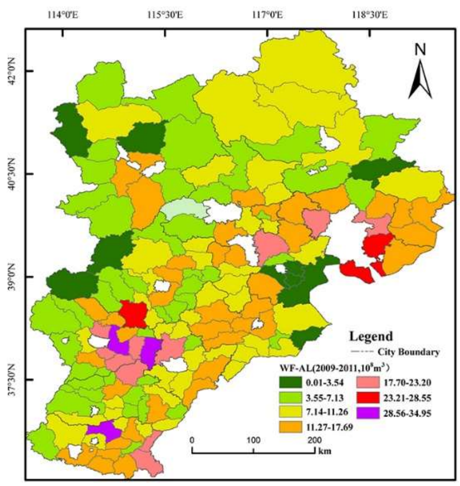
(**a**) 2000–2002



(**b**) 2003–2005

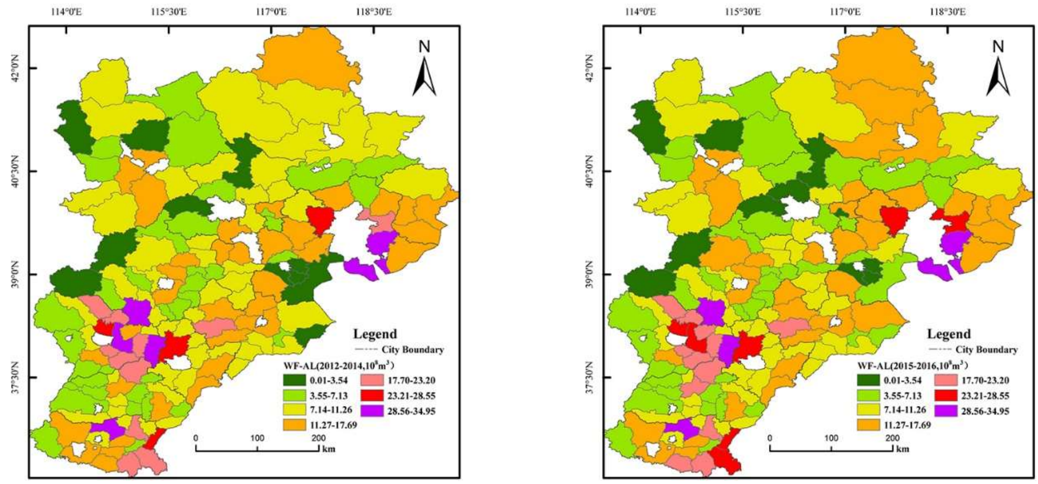


(**c**) 2006–2008



(**d**) 2009–2011

Figure 2. *Cont.*



(**e**) 2012–2014 (f) 2015–2016

Figure 2. County water footprint of agriculture and livestock production (WF-AL_{county}) of the BTH region, 2000–2016.

Based on Figure 2, we selected 30% and 70% of the average WF-AL_{county} as the reference values [49]. Thus, the WF-AL_{county} values 7.13×10^8 m^3 and 11.26×10^8 m^3 were used as the thresholds for regional low–medium, and medium–high water consumption in the BTH region. Table 2 shows that the proportion of counties with low water consumption gradually decreased from 51.6% to 32.9%, while the proportion of counties with high water consumption doubled from 19.4% to 38.1%. The proportion of counties with medium water consumption showed periodic fluctuations, but generally remained unchanged. Spatially, the low water consumption areas which were located in the mountain area and buffer zone became medium water consumption areas, while the medium water consumption areas located in the buffer zone and plains area became high water consumption areas. The water consumption in the BTH region progressively increased from the northwest to the southeast.

Table 2. Proportional distribution of the county water footprint of agriculture and livestock (WF-AL_{county}) in the Beijing–Tianjin–Hebei (BTH) region, 2000–2016.

	2000–2002	2003–2005	2006–2008	2009–2011	2012–2014	2015–2016
Low consumption	51.6%	44.5%	43.2%	36.8%	30.3%	32.9%
Medium consumption	29.0%	27.1%	32.9%	28.4%	34.2%	29.0%
High consumption	19.4%	28.4%	23.9%	34.8%	35.5%	38.1%

3.1.2. City WF-AL

The average city WF-AL (WF-AL_{city}) of Tangshan, Shijiazhuang, Handan, and Qinhuangdao was higher than 11.26×10^8 m^3, which is in the high water consumption category (Figure 3). By contrast, the average WF-AL_{city} of Zhangjiakou was lower than 7.13×10^8 m^3, which is in the low water consumption category. The remaining eight cities were in the medium water consumption category, although Hengshui and Cangzhou were close to the high water consumption category (i.e., WF-AL_{city} was generally within the range of medium–high water consumption). From 2000 to 2016, the average WF-AL_{city} increased from 8.00×10^8 m^3 to 11.05×10^8 m^3, with an average annual growth rate of 2.0%. The average annual WF-AL_{city} of the 13 cities fluctuated in the range of 2.92×10^8 m^3–18.99×10^8 m^3.

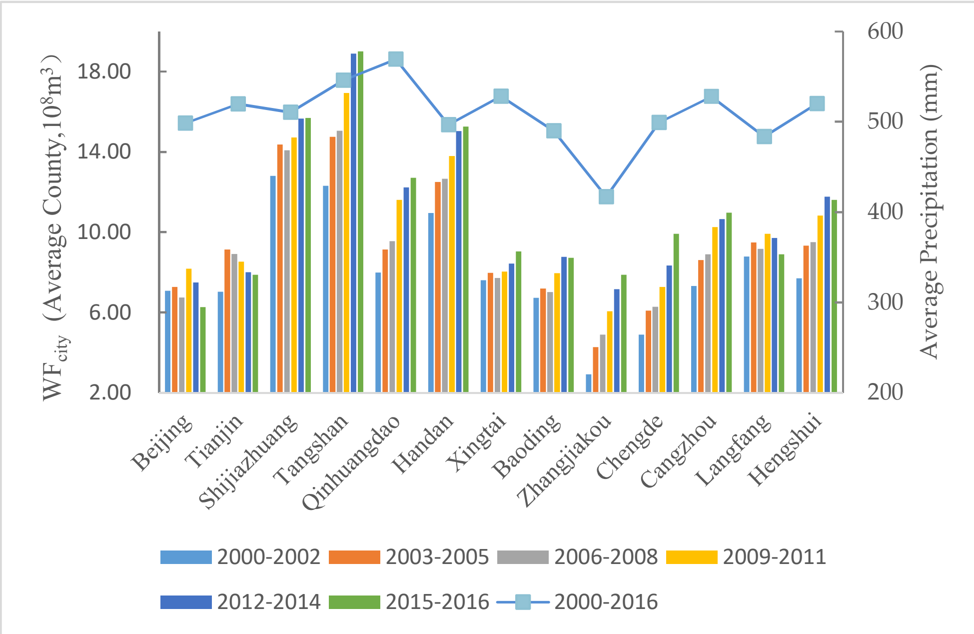


Figure 3. City water footprint of agriculture and livestock (WF-AL$_{city}$) in the Beijing–Tianjin–Hebei (BTH) region, 2000–2016.

After subdividing the water consumption of each city into counties, we found that the WF-AL$_{county}$ showed fluctuations consistent with the corresponding WF-AL$_{city}$ in Tangshan, Hengshui, and Cangzhou (Figure 4). However, there was an increase of WF-AL$_{county}$ in local areas or an overall decreasing trend of WF-AL$_{city}$ found in Zhangjiakou, Baoding, Shijiazhuang, and Handan. Most counties in these four cities were located in the mountain area and buffer zone of the BTH region. This demonstrates that the spatial differences in the WF-AL$_{city}$ were substantially reduced compared with those in the WF-AL$_{county}$.

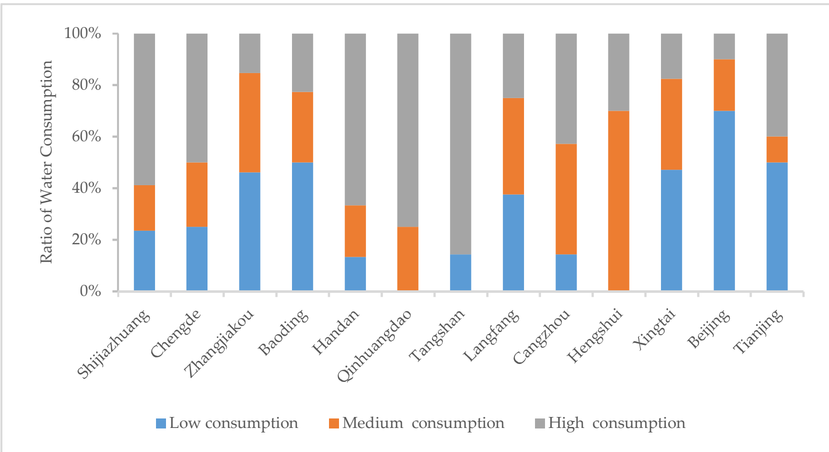


Figure 4. Spatial differences within the city water footprint of agriculture and livestock (WF-AL$_{city}$) in the Beijing–Tianjin–Hebei (BTH) region.

3.1.3. Terrain WF-AL

Because the development of agriculture and livestock varies with terrain, there were considerable differences in the planting structure of crops and the type of livestock. The BTH region can be divided into a mountain area, a buffer zone, a plains area, and a coastal plain (Figure 1). The terrain WF-AL (WF-AL$_{terrain}$) of the buffer zone was generally close to WF-AL$_{county}$, while the corresponding values of the mountain area and the plains area respectively decreased by 21.9% and 7.2%, and the value of the coastal plain markedly increased by 22.4% (Table 3).

Table 3. Distribution of the terrain water footprint of agriculture and livestock (WF-AL$_{terrain}$) in the Beijing–Tianjin–Hebei (BTH) region, 2000–2016 (10^8 m^3).

	2000–2002	2003–2005	2006–2008	2009–2011	2012–2014	2015–2016	County Number
Mountain Area	3.79	4.90	5.44	6.01	6.82	7.53	31
Buffer Zone	8.63	9.53	9.33	10.28	10.95	10.89	37
Plain Area	9.36	10.62	10.44	11.36	11.89	11.91	80
Coastal Plain	8.21	9.81	10.25	12.64	13.67	13.80	7

Under similar climatic conditions, the land area of agricultural planting in the mountain area and the buffer zone was smaller than that in the plain area and the coastal plain due to limitations imposed by the terrain. In contrast, livestock farming was developed on a larger scale in the mountain area and buffer zone compared with the other two terrains. Thus, there were important differences in the development pattern of agriculture and livestock production between these terrains, and their WF-AL ratios were not comparable. The WF-AL ratios of agriculture and livestock products in the mountain area and plain area were much higher than those in the buffer zone and coastal plain (Figure 5). This is because, compared to agricultural products, livestock products require secondary processing with more complex processes of water consumption. The climatic conditions of the semi-arid and semi-humid regions make them unsuitable for large-scale farming of livestock because of limited water resources.

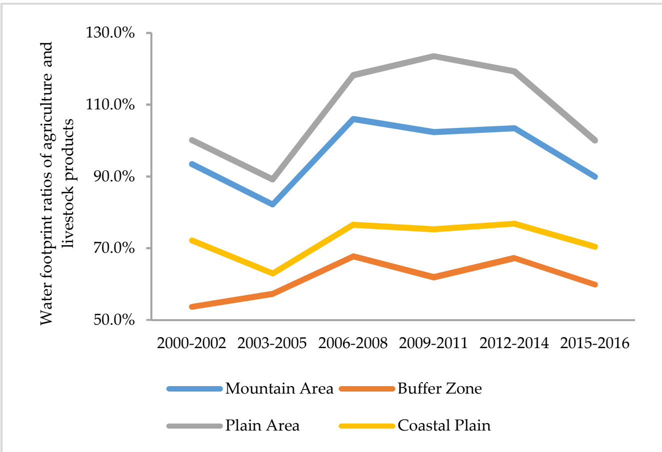
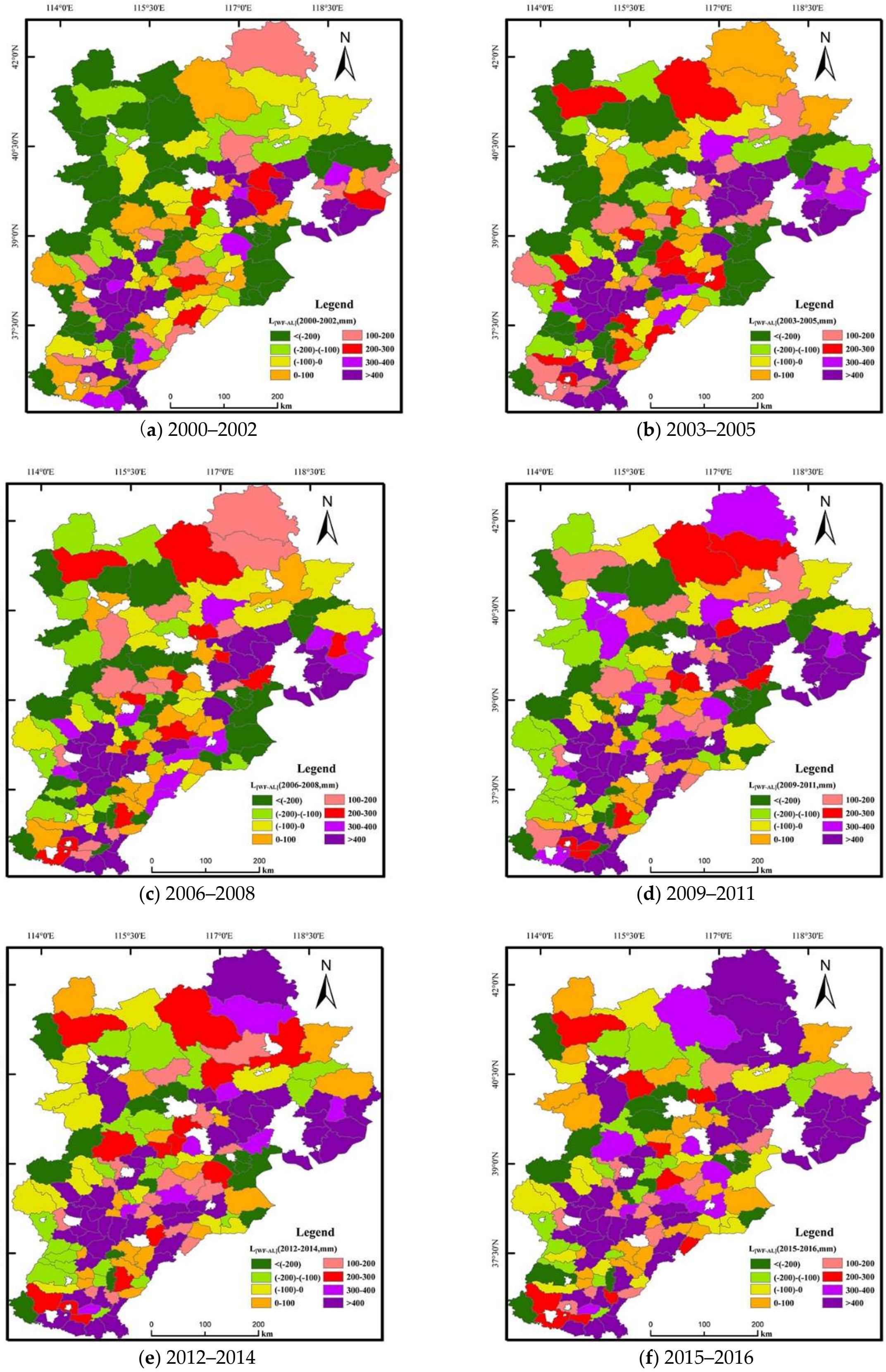


Figure 5. Water footprint ratios of agriculture and livestock products in the Beijing–Tianjin–Hebei (BTH) region.

3.2. Density Variation of the WF-AL

3.2.1. Surplus or Loss of Water Footprint Density

In the northwest and southeast areas of the BTH region (Figure 6), the $L_{[WF\text{-}AL]}$ overall remained < 0 from 2000 to 2008, indicating a healthy and balanced state of regional water resource development. However, a fragmented and patchy trend was found in these areas from 2009 to 2016, with $L_{[WF\text{-}AL]}$ > 400 mm in some counties (e.g., Zhuolu and Huailai of Zhangjiakou). This indicates that regional water resource development shifted into an unstable state. In the west and central areas of the BTH region, the $L_{[WF\text{-}AL]}$ gradually increased from 2000, with periodic fluctuations in local areas. There was no obvious center of surplus or loss for regional water resources, and regional water resource development varied between stable and unstable states.



(**a**) 2000–2002 (**b**) 2003–2005

(**c**) 2006–2008 (**d**) 2009–2011

(**e**) 2012–2014 (**f**) 2015–2016

Figure 6. Differences in the water footprint density of agriculture and livestock ($L_{[WF\text{-}AL]}$) in the Beijing–Tianjin–Hebei (BTH) region, 2000–2016.

Long-term significant losses of water resources were found in the north, central southwest, and central east areas of the BTH region. The $L_{[WF\text{-}AL]}$ was between 100 and 200 mm in local areas only before 2008, while it was > 400 mm in the remaining areas with the Max[$L_{[WF\text{-}AL]}$] close to 2000 mm. Four areas with water resources in an unstable state were formed between 2015 and 2016, which respectively were centered in Xinji County, Shijiazhuang ($L_{[WF\text{-}AL]}$ = 1981 mm) and Daming County, Handan ($L_{[WF\text{-}AL]}$ = 1145 mm) in the plain area, Luannan County, Tangshan in the coastal plain ($L_{[WF\text{-}AL]}$ = 1847 mm), and Weichang County, Chengde in the mountain area ($L_{[WF\text{-}AL]}$ = 618 mm).

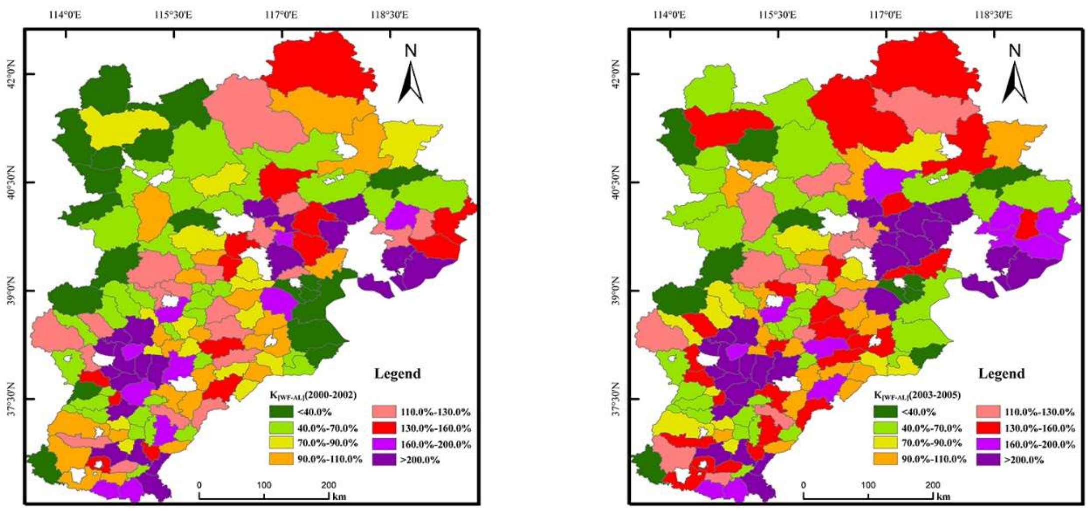
Between 2000 and 2016, $L_{[WF\text{-}AL]}$ showed small fluctuations within the six intervals between –200 mm and 400 mm, while negatively correlated fluctuations were found within the two intervals of $L_{[WF\text{-}AL]}$ < –200 mm and > 400 mm (Table 4). The healthy development areas of water resources sharply decreased during 2000–2014, whereas the unstable development areas rapidly increased in 2003–2005 and 2009–2014. The $L_{[WF\text{-}AL]}$ was relatively stable between 2015 and 2016.

Table 4. Proportional distribution of the water footprint density of agriculture and livestock ($L_{[WF\text{-}AL]}$) in the Beijing–Tianjin–Hebei (BTH) region, 2000–2016.

$L_{[WF\text{-}AL]}$ (mm)	<−200	(−200,−100)	(−100,0)	(0,100)	(100,200)	(200,300)	(300,400)	>400
2000–2002	27.7%	9.7%	14.2%	14.8%	9.7%	4.5%	4.5%	14.8%
2003–2005	23.9%	11.0%	8.4%	11.6%	10.3%	9.7%	4.5%	20.6%
2006–2008	21.3%	10.3%	12.3%	13.5%	8.4%	8.4%	7.1%	18.7%
2009–2011	16.1%	11.6%	10.3%	12.3%	10.3%	6.5%	7.7%	25.2%
2012–2014	9.0%	14.8%	10.3%	12.3%	10.3%	9.0%	5.2%	29.0%
2015–2016	9.7%	12.3%	10.3%	16.1%	9.0%	6.5%	5.2%	31.0%

3.2.2. Ratio of Water Footprint Density

Owing to the huge terrain differences, microclimate variations are found in local areas of the BTH region, and the precipitation fluctuates substantially at the county level. Therefore, we used the ratio of water footprint density to reduce the spatial differences across the region and quantify the level of regional water resource development and use over time and space (Figure 7).



(**a**) 2000–2002 (b) 2003–2005

Figure 7. *Cont.*

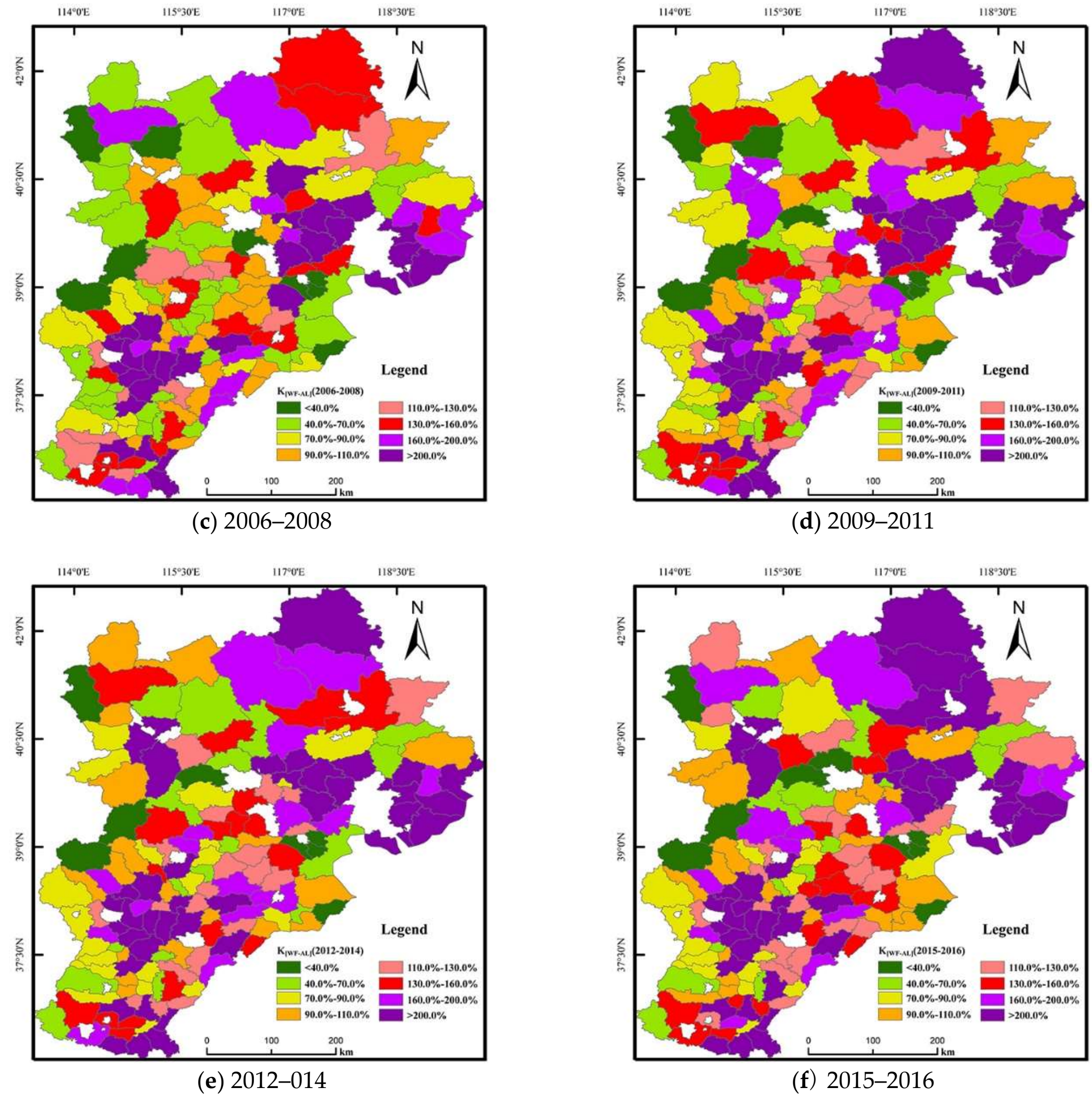


Figure 7. Water footprint density ratio of agriculture and livestock ($K_{[WF\text{-}AL]}$) in the Beijing–Tianjin–Hebei (BTH) region, 2000–2016.

The proportion of counties with $K_{[WF\text{-}AL]}$ < 40% decreased from 12.3% in 2000 to 5.8% in 2008, and then remained almost constant until 2016 (Table 5). The proportion of counties with $K_{[WF\text{-}AL]}$ in the range of 40%–70% decreased from 22.6% in 2008 to 9.0% in 2016. No significant fluctuations were found in the proportion of counties with $K_{[WF\text{-}AL]}$ in the range of 70%–90% or 90%–110%. However, the proportion of counties with $K_{[WF\text{-}AL]}$ > 110% significantly increased from 41.3% in 2000 to 60.6% in 2016, and the increase mostly occurred in the range of >200%.

Table 5. Proportional distribution of the water footprint density ratio of agriculture and livestock ($K_{[WF\text{-}AL]}$) in the Beijing–Tianjin–Hebei (BTH) region, 2000–2016.

$K_{[WF\text{-}AL]}$	<40%	40%–70%	70%–90%	90%–110%	>110%	>200%
2000–2002	12.3%	21.3%	10.3%	14.8%	41.3%	12.9%
2003–2005	7.1%	21.3%	8.4%	12.9%	50.3%	16.8%
2006–2008	5.8%	22.6%	9.7%	15.5%	46.5%	17.4%
2009–2011	5.8%	12.9%	12.9%	11.6%	56.8%	19.4%
2012–2014	5.2%	11.0%	12.9%	11.6%	59.4%	23.9%
2015–2016	5.8%	9.0%	11.0%	13.5%	60.6%	25.8%

Taking the development and use rate of river water resources at 40% as the standard threshold for classifying the carrying capacity of river development, only 5.8% of counties in the BTH region consistently met this standard [50,51]. Most of these areas were distributed in the mountain area (Shangyi County of Zhangjiakou, and Laiyuan and Fuping County of Baoding) and the buffer zone (Mentougou and Changping District of Beijing). This is because the counties of Shangyi, Laiyuan, and Fuping have natural groundwater supplies, with nearly 80% forest and grass coverage, complete surface river systems, and stable wetland, lake, and reservoir ecosystems. By contrast, in the Mentougou and Changping Districts, due to the policy restrictions of Beijing, the development of livestock is under strict control, and the areas suitable for agriculture have been used for urban development, which compensates for the limitations of an insufficient surface water supply and leads to a relatively low development and use rate of water resources. The plain area is concentrated in the Jinnan, Xiqing, and Dongli Districts of Tianjin. These three districts have a higher urbanization rate, with limited areas suitable for agricultural development and production. The livestock production in these counties is mainly based on fisheries, which has little impact on water consumption. In addition, these three counties are close to the estuary of Bohai Bay and receive high precipitation. The recent water supply by the Middle Line Project of South-to-North Water Division also contributes to abundant regional water resources in these counties.

3.3. Prediction and Early-Warning of WF-AL

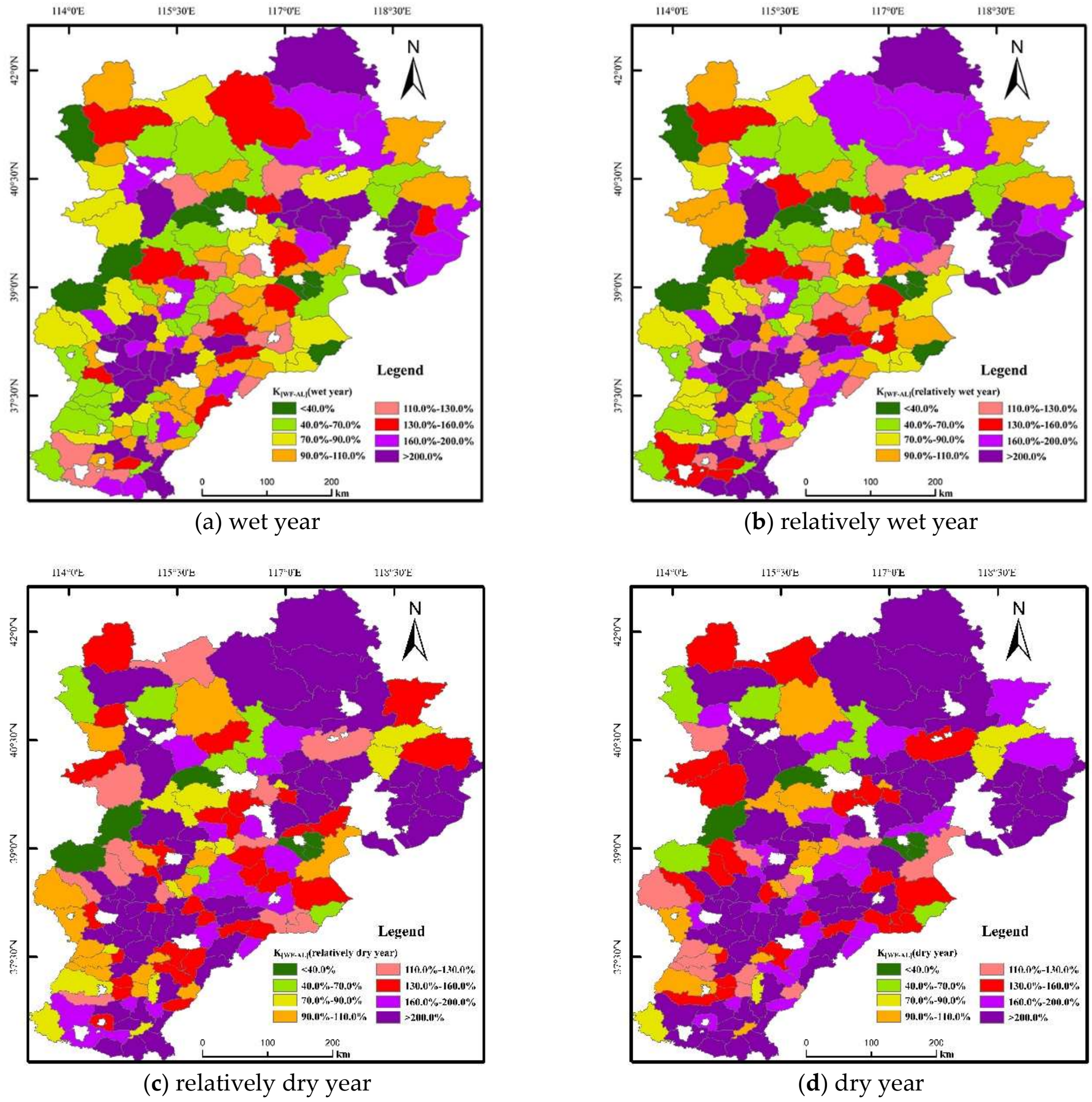
3.3.1. Early-Warning in Different Precipitation Years

We fitted the scenarios for four types of precipitation years (wet, relatively wet, relatively dry, and dry) with the development status of agriculture and livestock in the BTH region between 2015 and 2016 as the baseline (Figure 8) [52]. The simulation was performed without consideration of future control measures such as the transformation of agriculture and livestock or the promotion of water-saving technologies.

In the different precipitation years, the proportions of different terrains with $K_{[WF\text{-}AL]} < 0.4$ were less than 15%. In particular, the proportions of the buffer zone and plains area were less than 5%. Thus, within the range of normal precipitation fluctuations, the development of agriculture and livestock approached or exceeded the threshold for the natural bearing capacity in most of the areas in the BTH region. However, with the $K_{[WF\text{-}AL]}$ of 0.4–0.7 and under the precipitation conditions of relatively wet and wet years, the proportions of the mountain area, buffer zone, plains area, and coastal plain that were stable were 19.4%, 10.8%–24.3%, 12.5%–15.0%, and 0.0%, respectively. This suggests that the water ecosystem health in the mountain area and buffer zone could recover in the short term if the precipitation conditions are suitable and the scale of agriculture and livestock is partially limited.

The proportions of mountain area, buffer zone, and plains area with a of $K_{[WF\text{-}AL]}$ of 0.7–0.9 increased by 10.0%–13.5% during the conversion from dry years to wet years, while increase of the proportion of the coastal plain with this $K_{[WF\text{-}AL]}$ range reached 28.6%. For these areas, the variations in natural precipitation and the scale of agriculture and livestock development have comparable effects on the regional water ecosystems. Thus, the planning of sustainable production of agriculture and livestock should consider different precipitation conditions.

In the wet years, the proportions of mountain area, buffer zone, plains area, and coastal plain with a $K_{[WF\text{-}AL]} > 0.9$ reached 48.4%, 56.8%, 68.8%, and 57.1%, respectively. The mountain area was concentrated in Weichang County of Chengde and Zhuolu County of Zhangjiakou. The buffer zone counties included Luannan County of Tangshan, Dingzhou County of Baoding, and Wu'an County of Handan. The plains area was centered on Gaocheng County of Shijiazhuang and Daming County of Handan. The coastal plain was concentrated in Jinghai District of Tianjin and Changli County of Qinhuangdao. In the abovementioned areas, agriculture and livestock were over-developed, which had considerable negative effects on the enrichment of regional natural water resources. Therefore, while emphasizing the limited production of agriculture and livestock plus the protection of the region's inherent interests, we should consider using the Middle Line Project of South-to-North Water Division as the main trunk to build and connect the branch channels of cross-regional water transfer in the BTH region, thereby constructing a high-speed water network in this water-deficient region.



(a) wet year (**b**) relatively wet year

(**c**) relatively dry year (**d**) dry year

Figure 8. Water footprint density ratio of agriculture and livestock ($K_{[WF\text{-}AL]}$) in the Beijing–Tianjin–Hebei (BTH) region under different precipitation years.

3.3.2. Pressure Response Control of Water Resources

Cross-regional water transfer channels are similar to highway networks, and require comprehensive consideration of land resources and construction costs. Large, medium, and small-sized reservoir systems are well-established in the mountain area and buffer zone of the BTH region. However, the overall water conservation function of natural rivers, which are the links between reservoirs, is still weak in these areas. Only some rivers (Jumahe, Baihe, and Luanhe) can function as water transfer channels. The geological conditions are complex, and it is difficult to construct new artificial water transfer channels in a short period of time. Therefore, the adjustment plan for regional development should be based on limiting the scale of agricultural and livestock development and reservoir water transfer.

Compared to the mountain area and buffer zone, it is obviously advantageous to construct a network of new water transfer channels in the plains and coastal plain areas of the BTH region. In addition to relying on natural rivers, the construction of a new artificial water transfer network is feasible in terms of site selection, construction difficulty, and terrain and geological constraints. Especially in severely water-deficient areas, cross-regional water transfer should be combined with limited agriculture and livestock production to mitigate the regional water shortage.

Therefore, taking into account the current situation of $K_{[WF\text{-}AL]}$ in different areas of the BTH region, we propose the following plan (Table 6, Figure 9) to establish the medium and long-term balance of agricultural and livestock development and water resource recovery.

Table 6. The plan for limited production of agriculture and livestock in the Beijing–Tianjin–Hebei (BTH) region.

$K_{[WF\text{-}AL]}$, Now	$K_{[WF\text{-}AL]}$, Future	Limited Production of Agriculture	Limited Production of Livestock	Water Transfer
0–0.4	Maintain	-	-	-
0.4–0.5	drop to 0.4	-	10%	-
0.5–0.7	Drop to 0.4	10%	30%	-
0.7–0.8	Drop to 0.7	-	10%	Reservoir water transfer
0.8–0.9	Drop to 0.7	10%	10%	Reservoir water transfer
0.9–1.1	Drop to 0.9	10%	15%	Cross-region water transfer
1.1–1.3	Drop to 0.9	10%	30%	Cross-region water transfer
>1.3	Drop to 0.9	30%	30%	Cross-region water transfer

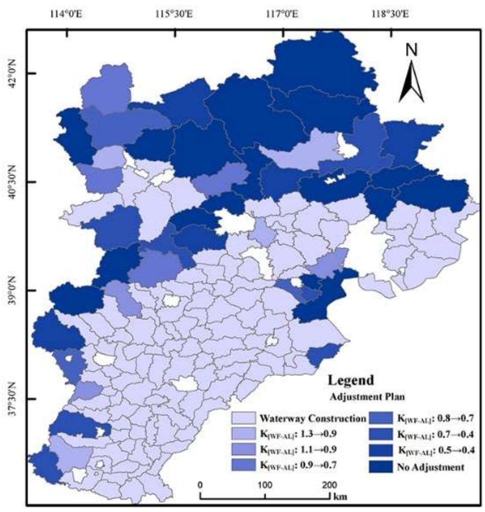


Figure 9. A schematic for limited production of agriculture and livestock in the Beijing–Tianjin–Hebei (BTH) region.

4. Discussion

4.1. Merits and Limitations of the Multi-Scale Study

Based on the classification of WF-AL at different scales, the county-level data can reflect the spatiotemporal dynamics of regional WF-AL more directly than the province/city-level data. Counties also serve as grass-root administrative units in China, which are largely autonomous in the implementation of policies and the adjustment and control of agricultural and livestock locations. This system has great advantages for the development and co-ordination of agriculture and livestock production.

This study identified the following limitations: (1) some county-level administrative units were subjected to slight jurisdictional adjustments or mergers, and in these areas, the WF-AL data showed abnormal fluctuations before and after the year of adjustment, and the interval stability of the data was lower compared with the province/city-level data; and (2) it was difficult to obtain the data for virtual water content per unit mass of agricultural and livestock products, so the use of province/city-level average data to some extent affected the accuracy of the study results.

4.2. Optimization of the Ecological Nodes

In the overlap area at the watershed scale, the county-level administrative units were commonly associated with problems such as abnormal WF-AL compared to adjacent areas or a WF-AL much higher than the water resource capacity threshold. Therefore, it was necessary to adopt composite measurements of water resources according to local conditions: (1) counties with water shortages can be supplied by cross-regional water transfers from the Middle Line Project of South-to-North Water Division, the Yellow River-to-Baiyangdian Water Transfer Project, and the Water Diversion Project from Luanhe River to Tianjin City; and (2) in counties where the development intensity of agriculture and livestock is too high, the scale of agriculture and livestock development can be limited or reduced through detailed classification at the village and town levels and delineation of ecologically sensitive areas for water resources within counties.

5. Conclusions

Urbanization is the main direction of development in the urban agglomeration areas of the BTH region. The non-core urban counties of the 13 cities have therefore taken on part of the existing agricultural and livestock production from the core urban areas. The allocation and restoration of regional water resources has become the focus of regional agriculture and livestock development. Based on 14 typical agricultural and livestock products, we calculated the WF-AL and its density in 155 counties of the BTH region over the period 2000–2016. We also predicted the spatial distribution of the WF-AL across different precipitation years. The results showed that in areas with complex terrain conditions, the spatial differences in the WF-AL at the city level were not significant compared with those at county and terrain levels, thus making it difficult to explain the response relationship of water resources to the development of agriculture and livestock. We found that the WF-AL was clearly affected by terrain. Both the ratio of agriculture and livestock and the average value of the WF-AL were lower in the mountain area and plains area than in the buffer zone and coastal plain. Agriculture and livestock production developed rapidly in the BTH region in 2003–2005 and 2012–2014, along with significant expansion of unstable water resource development areas. In 2015–2016, a desirable balance of water resources was maintained only in Shangyi County, Zhangjiakou, Laiyuan and Fuping County, Baoding, Mentougou and Changping District, Beijing, and Jinnan, Xiqing, and Dongli District, Tianjin. Furthermore, the simulation results in different precipitation years showed that in predicted wet years, the regional water resources generally recovered, but there were still four cross-city regional water-deficient areas in the mountain area, buffer zone, plains area, and coastal plain. Therefore, taking into account the current development for agriculture and livestock in 2015–2016, we constructed a medium and long-term plan for sustainable agriculture and livestock production in the BTH region through a combination of limited development of agriculture and livestock, reservoir water transfer, and cross-regional water transfer. The goal is to achieve a balance between the optimal development of agriculture and livestock and the recovery of water resources in the BTH region. This study is of significance in that it implements quantitative evaluation and constructs an optimal plan for agriculture and livestock development in the BTH region at the county level based on the water footprint theory. It is hoped that the results of this study can effectively influence the optimal development of water resource allocation and provide a reference for the management of the city and county-level agriculture and livestock departments in the BTH region.

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