# Sustainable Water Use in Arid Agricultural Areas Based on System Dynamics and Water Footprint: a Case Study of Zhangjiakou City, China

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## Declaration by the Author

I declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree. Except where states otherwise by reference or acknowledgment, the work presented is entirely my own.

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## Summary

The water resource is an indispensable natural capital for human production and life. On the one hand, insufficient water resources and uneven temporal and spatial distribution in arid agricultural areas are the objective reasons for restricting social and economic development and fragile ecological environment. On the other hand, socio-economic development occupies a large amount of ecological water, especially the unscientific planning and unreasonable expansion of irrigated agriculture, which makes a large amount of water wasted. Therefore, in this study, Zhangjiakou, China, a city with less than 400 $m^3$ of water per capita per year, was taken as a case study area to explore the sustainable use of water in arid agricultural areas from the perspective of blue water (surface water and groundwater) and green water (soil water). First, a complex system dynamics model, reflecting the relationships between the water resources subsystem and other socioeconomic subsystems in Zhangjiakou City, was established using Vensim PLE to simulate water demand (2015-2035) in four designed alternative development scenarios: the Current Development Scenario (CDS), the Economic Priority Scenario (EPS), the Water-saving Priority Scenario (WPS), and the Balanced Development Scenarios (BDS). Secondly, with the help of CropWat 8.0, the water footprint and its spatiotemporal characteristics and variations of the main crops in Zhangjiakou City for 2005, 2010, and 2015 were estimated. Furthermore, an in-depth analysis of blue water, green water, and food productivity and economic benefits of water footprint was further investigated by introducing three new indicators, i.e., green water footprint occupancy rate, blue water footprint deficit, and virtual water consumption per GDP. Finally, from the perspective of the ecological zone, the spatiotemporal matching characteristics of agricultural water footprint and socioeconomic factors were analyzed using the Gini coefficient and imbalance index. The main findings are as follows:

The variables related to irrigation farmland are the main driving factors of water demand, especially the area and the average water consumption of irrigated land. Therefore, reducing the area of irrigated farmland and improving the efficiency of agricultural irrigation water will be the main direction of water-saving in Zhangjiakou City. But it is vital to consider various factors, e.g., agricultural GDP and farmers' income, to determine the degree of reduction of irrigation area. Besides, in the four development scenarios, regardless of which development model is chosen, the water demand per ten thousand yuan GDP will eventually fall to around 20 $m^3$ in 2035. Therefore, reducing water demand only by slowing down economic growth cannot improve the efficiency of water use, and even result in inefficiency of water supply capacity. Zhangjiakou City should adopt a dynamic and efficient water-saving model that not only sustains regional socio-economic development but also protects ecological security in the whole Beijing-Tianjin-Hebei region.

The total water footprint requirement of Zhangjiakou City increased from 1.671 billion $m^3$ in 2005 to 1.852 billion $m^3$ in 2015, of which the ratio of green water to blue water was around two. The total water footprint requirement in the counties of the mountainous Bashang area is lower than those of the Baxia area, and the gap between them was further expanding. The green water footprint occupancy rate in counties of the Bashang area was 43%-49%, with an average of 44%, while it was 51%-59% in counties of the Baxia area, with an average of 54%. The highest green water footprint occupancy rate in a year was from May to August, at 58%-83%. In terms of blue water footprint deficit, in general, it was lower in the Bashang area than in the Baxia area. The changing trends in food production and economic benefits of water footprint were not always the same. Therefore, it is necessary to consider them simultaneously when developing policies from the perspective of water footprint.

The agricultural water footprint of Zhangjiakou City increased from 3.61billion $m^3$ in 2005 to 5.30 billion $m^3$ in 2015, an increase of 1.69 billion $m^3$, of which the water footprint of animal products increased by 1.59 billion $m^3$. Therefore, in addition to continuing to optimize the planting structure, implement efficient water-saving irrigation measures, and control the water footprint of crops, the government needs to strictly prohibit overload grazing and develop modern animal husbandry to reduce the water footprint of animal products, especially in counties of high-altitude ecological zones I, II and IV. The Gini coefficient and the imbalance index of agricultural water footprint and socioeconomic factors indicate that the spatial distribution of agricultural water footprint and planting area, population, agricultural GDP was relatively balanced, but there were still some significant differences. It means that the adjustment of the agricultural structure in each county requires a comprehensive consideration of multiple socioeconomic factors.

**Keywords:** Arid agricultural areas; System dynamics; Water footprint; Blue water; Green water; Zhangjiakou City

## Zusammenfassung

Die Wasserressourcen sind ein unverzichtbares natürliches Kapital für die Produktion und das Leben der Menschen. Einerseits sind unzureichende Wasserressourcen und deren ungleichmäßige zeitliche und räumliche Verteilung in ariden landwirtschaftlichen Gebieten die objektiven Ursachen für die Einschränkung der sozialen und wirtschaftlichen Entwicklung und des fragilen ökologischen Umfelds. Andererseits nimmt die sozioökonomische Entwicklung eine große Menge an ökologischem Wasser in Anspruch, insbesondere durch die unwissenschaftliche Planung und die unangemessene Ausweitung der Bewässerungslandwirtschaft wird eine große Menge Wasser verschwendet. Daher wurde in dieser Studie Zhangjiakou, China, eine Stadt mit weniger als 400 $m^3$ Wasser pro Kopf und Jahr, als Fallbeispielsgebiet herangezogen, um die nachhaltige Nutzung von Wasser in semiarid-ariden landwirtschaftlichen Gebieten aus der Perspektive von blauem Wasser (Oberflächenwasser und Grundwasser) und grünem Wasser (Bodenwasser) zu untersuchen. Zunächst wurde mithilfe von Vensim PLE ein komplexes Systemdynamikmodell erstellt, das die Beziehungen zwischen dem Teilsystem Wasserressourcen und anderen sozioökonomischen Teilsystemen in der Stadt Zhangjiakou widerspiegelt, um den Wasserbedarf (2015-2035) in vier alternativen Entwicklungsszenarien zu simulieren: das Current Development Scenario (CDS), das Economic Priority Scenario (EPS), das Water Saving Priority Scenario (WPS) und das Balanced Development Scenario (BDS). Zweitens wurden mit Hilfe von CROPWAT 8.0 der Wasserfußabdruck sowie seine raumzeitlichen Eigenschaften und Variationen der Anbaukulturen in der Stadt Zhangjiakou für 2005, 2010 und 2015 geschätzt. Darüber hinaus wurde eine eingehende Analyse der Produktivität von blauem Wasser, grünem Wasser und Lebensmitteln sowie des wirtschaftlichen Nutzens des Wasserfußabdrucks untersucht, indem drei neue Indikatoren eingeführt wurden: die Belegungsrate des grünen Wasserfußabdrucks, das Defizit des blauen Wasserfußabdrucks und der virtuelle Wasserverbrauch pro BIP. Schließlich wurden für ökologische Zonen die raum-zeitlichen Übereinstimmungsmerkmale des landwirtschaftlichen Wasserfußabdrucks und sozioökonomische Faktoren unter Verwendung des Gini-Koeffizienten und des Ungleichgewichtsindex bestimmt. Die wichtigsten Ergebnisse sind die folgenden:

Die Variablen im Zusammenhang mit der Bewässerung von Ackerland sind die Hauptfaktoren für den Wasserbedarf, insbesondere die Fläche und der durchschnittliche Wasserverbrauch von bewässertem Land. Daher werden die Reduzierung der bewässerten Ackerfläche und die Verbesserung der Effizienz des landwirtschaftlichen

Bewässerungswassers die Hauptrichtung der Wassersparmaßnahmen in der Stadt Zhangjiakou sein. Es ist jedoch wichtig, verschiedene Faktoren zu berücksichtigen, z. B. das landwirtschaftliche BIP und das Einkommen der Landwirte, um den Grad der Verringerung der Bewässerungsfläche zu bestimmen. Außerdem wird in den vier Entwicklungsszenarien, unabhängig davon, welches Entwicklungsmodell gewählt wird, der Wasserbedarf pro zehntausend Yuan BIP im Jahr 2035 auf etwa 20 $m^3$ sinken. Ein reduzierter Wasserbedarf nur durch die Verlangsamung des Wirtschaftswachstums wird die Effizienz der Wassernutzung nicht erhöhen; vielmehr kann das sogar zu vermehrter Ineffizienz der Wasserversorgung führen. Die Stadt Zhangjiakou sollte ein dynamisches und effizientes Wassersparmodell einführen, das nicht nur die regionale sozioökonomische Entwicklung unterstützt, sondern auch die ökologische Sicherheit in der gesamten Region Peking-Tianjin-Hebei schützt.

Der Gesamtbedarf des Wasserfußabdrucks der Stadt Zhangjiakou stieg von 1,671 Milliarden $m^3$ im Jahr 2005 auf 1,852 Milliarden $m^3$ im Jahr 2015, wovon das Verhältnis von grünem Wasser zu blauem Wasser bei etwa zwei lag. Der Gesamtbedarf des Wasserfußabdrucks in den Landkreisen des bergigen Bashang-Gebietes war geringer als in dem Baxia-Gebiet, und der Abstand zwischen ihnen wurde weiter vergrößert. Die Auslastung des grünen Wasserfußabdrucks in den Bezirken des Bashang-Gebiets betrug 43% bis 49% mit einem Durchschnitt von 44%, während sie in den Bezirken des Baxia-Gebiets 51% bis 59% mit einem Durchschnitt von 54% betrug. Die höchste Auslastung des grünen Wassers in einem Jahr lag zwischen Mai und August bei 58% bis 83%. In Bezug auf das Defizit an blauem Wasser war es im Gebiet von Bashang im Allgemeinen niedriger als im Gebiet von Baxia. Die sich ändernden Trends der Lebensmittelproduktion und die wirtschaftlichen Vorteile des Wasserfußabdrucks waren nicht immer gleich. Daher müssen sie gleichzeitig berücksichtigt werden, wenn Strategien unter dem Gesichtspunkt des Wasserfußabdrucks entwickelt werden.

Der landwirtschaftliche Wasserfußabdruck der Stadt Zhangjiakou stieg zwischen 2005 und 2015 von 3,61 Milliarden $m^3$ auf 5,30 Milliarden $m^3$, ein Anstieg von 1,69 Milliarden $m^3$, wovon der Wasserfußabdruck für tierische Produkte um 1,59 Milliarden $m^3$ zunahm. Daher muss sich die Regierung neben der weiteren Optimierung der Anbaustruktur, der Umsetzung effizienter wassersparender Bewässerungsmaßnahmen und der Kontrolle des Wasserfußabdrucks von Kulturpflanzen widmen sowie die Überweidung strikt verbieten und eine moderne Tierhaltung entwickeln, um den Wasserfußabdruck tierischer Produkte zu verringern, insbesondere in den hoch gelegenen ökologischen Zonen I, II und IV. Der Gini-Koeffizient und der Ungleichgewichtsindex des landwirtschaftlichen Wasserfußabdrucks

sowie sozioökonomische Faktoren weisen darauf hin, dass die räumliche Verteilung des landwirtschaftlichen Wasserfußabdrucks und der Anbaufläche, der Bevölkerung und des landwirtschaftlichen BIP relativ ausgeglichen war, es jedoch immer noch einige signifikante Unterschiede gab. Dies bedeutet, dass die Anpassung der Agrarstruktur eine umfassende Berücksichtigung mehrerer sozioökonomischer Faktoren erfordert.

**Keywords:** Arid agricultural areas; System dynamics; Water footprint; Blue water; Green water; Zhangjiakou City

# 1. Introduction

## 1.1 Problem Statement

The water resource is an indispensable natural capital for human production and life (Tuninetti et al., 2019). However, with the rapid growth of the global population, the transformation of human lifestyles, consumption patterns approaching high-water-consuming foods, and unreasonable ways of water extraction and utilization, as well as climate change, water resources are under increasingly severe pressure (Karandish et al., 2020; Liu et al., 2017; Ma et al., 2020a; Sun et al., 2013). The shortage of available water resources not only restricts sustainable socioeconomic development but also poses a serious threat to ecological and environmental security (Liu et al., 2015; Vorosmarty et al., 2010). The water resource crisis has evolved into one of the most concerning resources and environmental issues in the world, which is considered to be the biggest challenge facing mankind in this century (Vogel et al., 2015). Therefore, “ensure water availability and sustainable development” is set as one of the 2030 sustainable development goals (SDGs) (Ma et al., 2020b; van Vliet et al., 2017). It is predicted that 47% of the population will live in countries and regions with severe water shortages by 2030 (Connor, 2015), due to the extremely unequal distribution of global freshwater resources. In this context, “virtual water” has been heralded as the answer to this imbalance (Whitney and Whitney, 2018), which has aroused great interest of scholars in the fields of water resource management, agricultural production, environmental assessment, etc.

The complex system that humans rely on for survival can be divided into two major systems: the socio-economic system and the eco-environment system (Choi et al., 2017; Liu, Jianguo et al., 2007). The optimal allocation of water resources is to regard the human-nature system as an organically connected whole, and rationally allocate the water demand or consumption of the socio-economic and eco-environment system, so as to ensure the healthy development of the social economy while satisfying the self-repair ability of the ecological system (Elshafei et al., 2015; Sivapalan et al., 2012). On the one hand, insufficient water resources and uneven temporal and spatial distribution in arid agricultural areas are the objective reasons for restricting social and economic development and fragile ecological environment (Elshafei et al., 2015). On the other hand, the subjective reason for the shortage of water resources is that the economic development occupies a large amount of ecological water (Lund, 2015), especially the unreasonable development of irrigated agriculture, which makes a large amount of water wasted (A and Dall'erba, 2020; Zhang and Guo, 2016). Therefore, a scientific and reasonable analysis of the utilization of local water resources and a reasonable allocation of industrial, agricultural, domestic, and ecological water among the limited water resources are the fundamental way out to solve the above problems (Bekchanov et al., 2017; Wang et al., 2018), which leads to an increasing application of system dynamics in integrated water resource management (Zomorodian et al., 2018).

## 1.2 State of the Art

### 1.2.1 System dynamics

The relationships between human and natural systems are bi-directional (Srinivasan et al., 2013). The impact of human activities on natural systems is changing the way we view and manage the earth’s resources (Winz et al., 2008; Yang et al., 2018). With the challenges of population expansion, rapid urbanization, and climate change, water resources, as an irreplaceable resource for human-nature systems, are becoming increasingly scarce (Jiang, 2015). This will not only significantly affect regional sustainable development but also poses a serious threat to the well-being of future generations (Brown et al., 2015; Kotir et al., 2016; Yang et al., 2017). The contradiction between water supply and water demand has become a global challenge for human beings for a long time now and in the future, especially in developing countries and regions with large population sizes and dry climates (Zhang et al., 2020).

The research on water resources can be roughly summarized into two categories (Sun et al., 2017): surface and ground water, and sustainable utilization of water resources (David and Tobin, 2017; Döll and Fiedler, 2008; Larson et al., 2009). First, studies of surface water and groundwater are mostly related to climate change, overexploitation of groundwater, and the impact of water supply projects on the hydrological environment. Hagemann et al. (2013) studied the Colorado River basin using a global climate-hydrological model and found that climate change was not the only factor affecting the hydrological cycle. Hashemy Shahdany et al. (2018) taking the Zayandeh-Rud River basin in Iran as a case, discussed the effect of improving operational performance in irrigation canals to overcome groundwater overexploitation. Zhang (2009) evaluated the environmental impactions of the South-to-North Water Diversion Project and concluded that the Chinese government must establish a long-term environmental monitoring network. Second, the evaluation methods of sustainable use of water resources mainly include water poverty index (WPI), water stress index (WSI), and water resources carrying capacity (WRCC). WPI, first used by Sullivan (2002), is measured using five components “Resources”, “Access”, “Capacity”, “Use”, and “Environment”. It has been widely used as a holistic tool to assess water resources available at different scales from international and national scales (Jemmali, 2018; Jemmali and Matoussi, 2013; Jemmali and Sullivan, 2014) to district and basin (Manandhar et al., 2012; Van Ty et al., 2010) scales. WSI can be used to assess the extent of water scarcity faced by the region's society, economy and environment systems, such as Han and Ruan (2002) selected nine indicators from these three systems and conducted a comparative analysis of the water resources pressure in 31 administrative regions of mainland China. WRCC refers to the maximum human activity level that available water resources can support without causing ecological and environmental degradation while maintaining an adequate standard of living (Naimi Ait-Aoudia and Berezowska-Azzag, 2016). A number of studies have been carried out in this aspect, especially in areas where there is a negative gap between water supply and water demand (Li et al., 2016; Ren et al., 2016; Yang et al., 2015).

In recent years, the interaction between social, environmental, and water systems has become more intense and complex due to the explosive demand for water resources (Blair and Buytaert, 2016; Brown et al., 2015; Choi et al., 2017; Ghodsvali et al., 2019). In this context, for a better understanding of the dynamic relationships of the coupled human-environmental system, the system dynamics (SD) model is becoming more and more popular in water resources planning and management, because many other models based on linear causality cannot provide the mental and structural framework to solve complex problems in multiple systems (Duran-Encalada et al., 2017; Fang et al., 2019; Ghashghaie et al., 2014). SD was initially proposed by Forrester (1958) for simulating industrial and urban dynamics. It not only enables users to understand the extent to which each variable affects the system and subsystems but also can capture the interaction of various model components (Zomorodian et al., 2018). According to Zomorodian et al. (2018), the application of SD in water resources mainly falls into two categories: predictive simulation models and descriptive integrated models. The former focuses on the water resources system itself but lacks mutual feedback from economic, ecological, and social subsystems (Hoekema and Sridhar, 2013; Safavi et al., 2009; Teegavarapu and Simonovic, 2014). The latter focuses on the impact of factors from various subsystems on the water supply and demand systems, such as climate change, urbanization, economic development, and population growth (Gao et al., 2016; Hagemann et al., 2013; Qi and Chang, 2011).

### 1.2.2 Virtual water and water footprint

Virtual water (VW) refers to the freshwater consumed by a product or service in its place of origin, and which is then traded and transported to another region embedded in these products or services (Allan, 1993). The volume of global trade has continued to expand since the 20th century, resulting in an increasing amount of virtual water exchange through commodities (Shtull-Trauring and Bernstein, 2018). VW theory has thus laid a solid foundation for accurately measuring the real water consumption of a country or region. Meanwhile, by seeing water itself as an internationally traded commodity, it also offers an alternative way for water-poor regions to effectively solve the shortage of water resources by importing "freshwater" through international trade (Allan, 1998).

However, VW has received relatively little attention until "water footprint (WF)" was proposed and introduced to international researchers (Hoekstra, 2003). Based on VW theory, WF represents the total amount of water consumed by a country (region or individual) in a given period, including the water contained in all products and services, which is an analog to the concept of ecological footprint proposed by the Canadian economist Willian E. Rees in the early 1990s (Hoekstra, 2017; Hoekstra et al., 2019). WF is a supplement to traditional measurement indicators of water consumption due to the following features it possesses: (1) It made a connection between physical water and VW, and extended VW assessment from the geographical scale (country, region, and watershed) to the individual and product scale. (2) It expanded the boundary of water resources research from the consumption of blue WF to green WF and gray WF (Chapagain et al., 2006; Qian et al., 2019). Blue WF means water comes from surface water or groundwater; Green WF means water comes from precipitation which is stored in the soil; Gray WF means water used to assimilate pollutants (Hoekstra et al., 2011). By doing this, the problems of insufficient research on green water and independent evaluation of water quality and quantity have been solved, thereby broadening the evaluation system and connotation of water resources (Qian et al., 2019). (3) It linked water resources assessment with human consumption patterns (Song et al., 2020; Wang et al., 2019). Calculating the real occupancy of water resources from the perspective of consumption, which can help people understand the meaning of VW and increase their awareness of saving water (Hoekstra and Mekonnen, 2012). Because of the above advantages, WF has been widely concerned by scholars around the world since its introduction and has become one of the important indicators for measuring and evaluating the environmental impact of human activities.

The research methods of VW and WF are similar, which can be summarized as two types of “bottom-up” and “top-down” (Lovarelli et al., 2016; Vanham and Bidoglio, 2013). The "bottom-up" methods are mainly used in the agricultural sector, that is, using crop growth models such as CropWat (Hoekstra and Hung, 2002; Ma et al., 2020b; Zeng et al., 2012), EPIC

(Liu, Junguo et al., 2007), AquaCrop (Chukalla et al., 2015; Zhuo et al., 2016), and LPJmL (Fader et al., 2011) to calculate crop growth water footprint, including blue WF and green WF. The “top-down” approaches, similar to life cycle assessment (LCA), are mainly based on the inter-sector input-output (IO) tables. Input-output models are used (including single-region input-output models and multi-regional input-output models) to measure direct and indirect WFs and VW flow between all sectors. Therefore, the bottom-up approach is mainly suitable for estimating the WF of agricultural products. A large body of physical water from irrigation is consumed during the growth of crops. The top-down approach can take the VW (indirect water resources) contained in the raw materials between sectors into account, it is thus suitable for estimating the regional water consumption of all sectors and VW flows between countries and regions.

The research on VW and WF has extended from the initial global, national, or regional level to small watersheds, cities, and single products, and from a single annual evaluation to inter-annual comparative research. As for the research content, it has gone from quantitative accounting of crop WF, regional VW flow, to qualitative analysis of WF sensitivity and inter-regional VW flow driving factors. In general, VW and WF research has developed rapidly in the past two decades, which has attracted the increasing attention of international scholars. In addition to research articles, there are also some reviews, which qualitatively elaborate and explain VW and WF research in terms of conceptual interpretation, research content, research objects, and research scale (Vanham et al., 2019).

However, few academic endeavors have been made from the perspective of bibliometric statistics. As far as I know, only Zhang et al. (2017) conducted a bibliometric study of WF in 2006-2015, but it did not include VW. The WF mostly refers to water consumed in the local production process, and the VW refers to the water embedded in the product being transported to other regions, that is, the WF has a feature of ‘static’, while the VW has a feature of ‘dynamic’. The essence of WF accounting is still VW accounting, and it can even be said that VW accounting is the basis of WF accounting (Hoekstra and Chapagain, 2006). Therefore, the two concepts complement each other and it is necessary to analyze both at the same time. For this reason, please see Chapter 2 for the bibliometric analysis of virtual water and water footprint research.

## 1.3 Research goals and objectives

### 1.3.1 Research goals

*Provide scientific support for coordinating conflicts between regions and industrial sectors is a general scientific goal.* Due to the scarcity of water resources in arid areas, there are often conflicts in the demand for water resources between upstream and downstream areas or between industrial sectors. It is unlikely to solve the water shortage only by transferring water from outside, which requires coordination and cooperation between upstream and downstream areas and different industrial sectors within the region. Based on system dynamics and water footprint theory, exploring the demand for water resources under different industrial layouts and agricultural planting patterns will provide a scientific basis for achieving coordinated and balanced development of the entire region.

*Provide scientific support for regional sustainable development is another general scientific goal.* In the process of social and economic development, blindly pursuing economic benefits and ignoring the relationship between water resources and ecological environment systems are the root causes of many problems such as deterioration of the ecological environment, forest degradation, loss of biodiversity, and groundwater overexploitation. Despite the shortage of water resources in arid areas, the water consumption per unit of GDP is often higher than the national average. Also, in arid areas, there are always unsound water resources protection laws and regulations, which leads to poor water resources management. Research on the sustainable utilization of water resources is of great significance to the conservation of water resources and to alleviate the deterioration of the ecological environment in arid areas, thereby providing a strong guarantee for regional sustainable development.

### 1.3.2 Research objectives

Zhangjiakou City is located in the northwest of Hebei Province, China, with an annual per capita water resource of less than 400 $m^3$. The shortage of water resources not only severely restricts the local economic development but also poses a threat to the ecological security of the capital of Beijing, because it is the geo-ecological protection barrier and water source for Beijing. This research thus takes Zhangjiakou City as an example, and the main research objectives are as follows:

(1) Based on the “Two-zone Planning” of Zhangjiakou City, a system dynamics model will be established to simulate the water demand of various departments in Zhangjiakou City from 2020 to 2035 under different development scenarios.

(2) According to water footprint theory, the water footprint requirement of the main crops in Zhangjiakou City will be estimated with the help of CropWat 8.0, and its characteristics of spatial distribution and dynamic changing trends for 2005, 2010, and 2015 will be identified. Besides, water footprint food productivity and water footprint economic benefits will be investigated.

(3) For the first time, from the ecological zone perspective, the distribution and matching characteristics of agricultural water footprint and socioeconomic factors (planting area, population, and agricultural GDP) in each county (district) using mathematical models, i.e., Gini coefficient and imbalance index will be analyzed, and the suitable measures and policies for sustainable agricultural development for counties (districts) will be proposed accordingly.

## 1.4 Research approaches

(1) *Literature reading and data collection.* Mastering the following aspects by reading a large number of Chinese and English literature is the basis for this research: a) analyzing the main content and main methods of research in arid agricultural areas; b) clarifying system dynamics and water footprint research methods and their applications; c) identifying the problems facing Zhangjiakou's water resources; d) collecting relevant policy documents and data needed by the research

(2) *Scenario analysis.* Based on the current situation and future planning of Zhangjiakou City, this study sets four development scenarios from the perspectives of water supply and demand, and the water demand and water use efficiency in these four scenarios are evaluated.

(3) *Quantitative analysis.* The Vensim PLE, CropWat 8.0, and Gini coefficient models are used to quantitatively estimate and analyze Zhangjiakou's water demand, agricultural water footprint, and the matching features between agricultural water footprint and socioeconomic factors.

(4) *Comparative analysis*. Many research results, e.g. water demand and agricultural water footprint, in this study have undergone comparative analysis from the different spatial and temporal scales.

## 1.5 Research structure and framework

### 1.5.1 Research structure

This research is divided into seven chapters, as follows:

Chapter 1 is the introduction. This chapter mainly introduces the research background, state of the art, research goals and objectives, research approaches, and technical framework.

Chapter 2 is the bibliometric analysis of virtual water and water footprint. Given the significance of water footprint theory in this study, this chapter conducts a detailed quantitative analysis of the past and current status of virtual water and water footprint research using CiteSpace, and the future research trends are further discussed.

Chapter 3 is the introduction of the study area. This chapter introduces the basic situation of Zhangjiakou City, including geographical location, topography, social and economic development, and the current status of water resource utilization.

Chapters 4–6 are the results of this research. Chapter 4 firstly identifies the sensitivity factors of water resource utilization in Zhangjiakou City and then conducts scenario simulations on the water resources demand of different departments in Zhangjiakou City from 2020 to 2035. Chapter 5 investigates the temporal and spatial distribution characteristics of crop water footprints in Zhangjiakou City from 2005 to 2015, and then the food production and economic benefits of crop water footprints are discussed. Based on the Gini coefficient, Chapter 6 investigates the temporal and spatial matching characteristics of agricultural water footprint and socio-economic indicators (planting area, GDP, and population).

Chapter 7 is the section of conclusions and future work. This chapter mainly summarizes the conclusions of the whole research and proposes future research directions.

### 1.5.2 Research framework

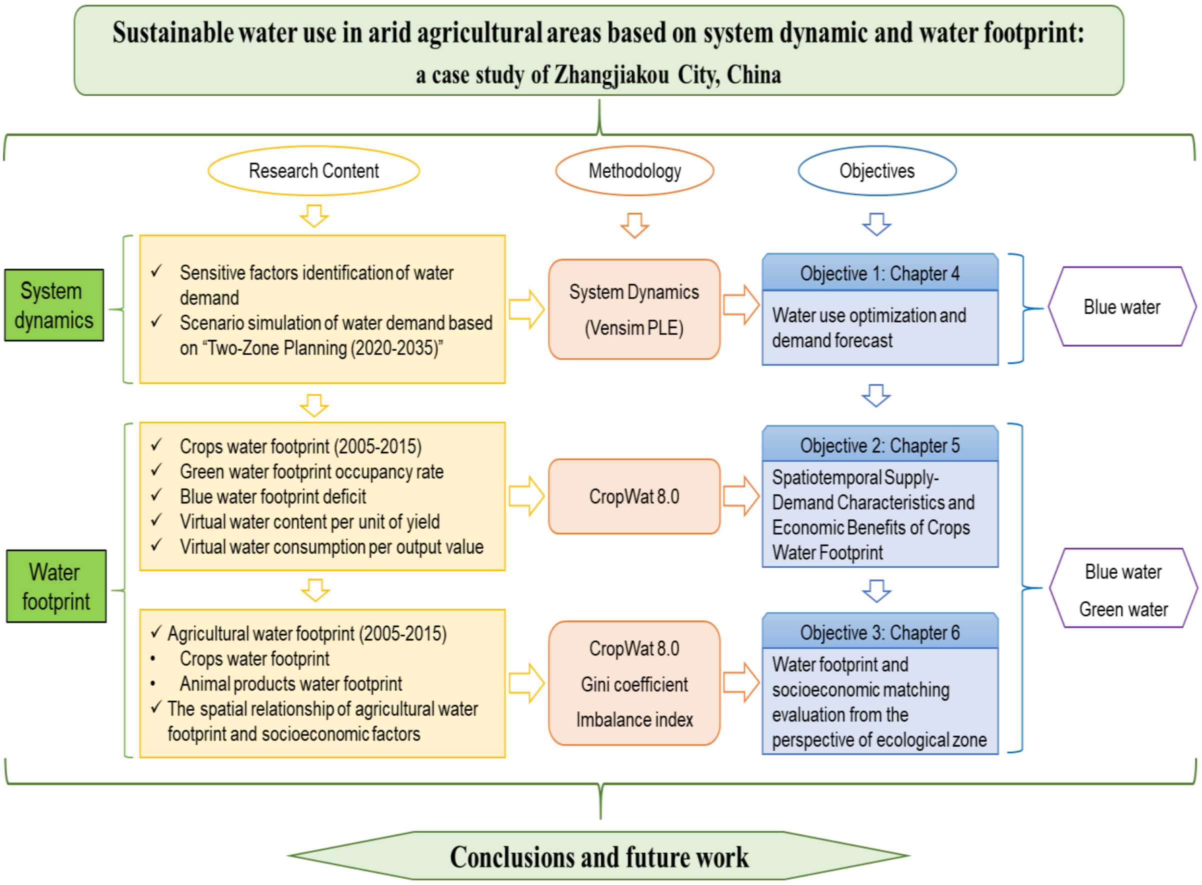

Figure 1.1 Research framework

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# 2. Past, present, and future of virtual water and water footprint

In the face of a huge amount of literature, the qualitative literature analysis method has certain limitations of subjectivity and one-sidedness, and cannot comprehensively, objectively, and intuitively reflect the research trends and dynamic development of a field. The application of modern scientometrics and information metrology technology can conduct a multivariate and historical dynamic analysis of massive literature. Mapping Knowledge Domains is one of the important methods of document analysis and visualization (Wu et al., 2019). In recent years, the development of literature analysis tools represented by CiteSpace has provided an effective way for the big data measurement analysis and visual display of literature (Chen, 2018). CiteSpace can identify research frontiers, detect research characteristics and evolution trends, and identify the interactive relationship between different research topics through co-citing literature and collaborative network analysis. Since its release, the software has been widely used in document measurement and analysis and data visualization (Zhang et al., 2020). At present, it has been gradually applied in the fields of geography, ecology, and the environment (Fang et al., 2017; Hu et al., 2019; Zhang et al., 2017; Zhang et al., 2020).

## 2.1 Research objectives

With the help of CiteSpace, this study attempts to use the knowledge map to display the research literature of VW and WF, find out the key literature, and make a further summary and analysis of the VW and WF research since they were proposed. It aims to reveal the development path and research trend of VW and WF more objectively, provide a new perspective for the exploration of research frontiers and hot spots in this field, and deliver some innovative clues and suggestions for future research.

The main research objectives are to (1) investigate the development trajectory of VW and WF research, including the number of articles and research fields; (2) clarify the team and distribution of VW and WF research, including major countries, institutions, and research teams; (3) summarize the temporal and spatial dynamics of the research topics and research hotspots of VW and WF; and (4) explore the current deficiencies and future development directions of VW and WF research.

## 2.2 Materials and methods

### 2.2.1 CiteSpace

CiteSpace was developed by Chen (2014) to analyze and visualize scientific literature. It can extract and analyze the hidden information of keywords, topics, authors, institutions, cited documents, cited authors, cited journals, and other information, and visually present relevant information with the help of visual knowledge maps. Through the convergence of this information, it can show the development path of a field and the relationships of interdisciplinary fields in a certain period, and fully reveal the research status of this field, which helps to understand and predict research hotspots and frontiers. In addition to information science and library science, CiteSpace has been increasingly used in economics, sociology, geography, and environmental science (Chen, 2018).

In the knowledge map of CiteSpace, N represents the number of network nodes, and the color and size of the nodes represent the year and quantity. E represents the number of connections. Modularity is a reflection of network structure. When the value of the modularity larger than 0.3, it means that the network community structure is remarkable. The value of silhouette is an index for measuring network homogeneity. When it is greater than 0.5, indicating that the clustering result is reasonable. Regarding the Keyword Co-appearance Analysis map, Li et al. (2017) believe that frequency is the number of occurrences of words in the analyzed documents. The distribution of keyword frequency can reflect the frequency of citations or the number of articles published in a certain field. The fields with the most published articles or the most frequently cited articles are often research hotspots.

The main indicators used in this article include betweenness centrality and burst terms. Betweenness centrality is an indicator that reflects the importance of a node, indicating that the node serves as the number of shortest paths between the other two nodes. The higher the betweenness centrality of a node, the greater its influence in the network. Generally, nodes whose betweenness centrality is greater than or equal to 0.1 are regarded as key nodes. Burst terms refer to research terms that appear to have a sudden and rapid increase in frequency, and it can more accurately reveal research frontiers than keywords due to their dynamic change characteristics over time. The emergence of burst terms indicates that scholars have discovered new research fields and research perspectives during this period, and thus appear as academic frontiers, which are often shown in red in the knowledge map.

### 2.2.2 Data collection

The Web of Science Core Collection (WOSCC) is considered as a reliable database for visual analysis (Hu et al., 2019). Water footprint and virtual water usually appear in the title of research in this field in the form of fixed phrases. Therefore, we first searched for all publications containing the phrases “virtual water” or “water footprint” in the title from 1993 to 2020, and then we manually removed publications unrelated to virtual water and water footprint research. Finally, a total of 1,592 publications were retrieved on 22 July 2020.

## 2.3 Results

### 2.3.1 Characteristics of publication outputs

In general, the number of annual publications can reflect the importance of a particular field and the degree of attention it receives. As shown in Figure 2.1, although VW was proposed as early as 1993, the first publication retrieved was in 1998. This is an editorial in which Allan (1998) explained the strategic significance of VW from the perspective of “the definition of water deficit, the relationship between water and food, and water resources and politics”, and VW could be a global way to address regional water deficits. He argued that reducing the rate of population growth and water-intensive food consumption is the fundamental solution to water shortages.

It was not until the WF theory was developed in 2002 that clarify the team and distribution of VW and WF research gradually began to receive more attention. As of July 2020, there were a total of 1,592 publications on VW and WF, showing an increasing trend overall. Among them, the annual average number of publications was only 7.4 in 1998–2008, while it was 126.5 in 2009–2019. It indicates that after 2008, the year that Allan won the Stockholm Water Award for virtual water, the research on VW and WF grew rapidly.

These publications were classified into 12 types, of which there were 1,252 articles, accounting for 79%; 143 proceedings papers, accounting for 9%; 35 reviews, accounting for 2%; and 162 other publications, accounting for 10%.

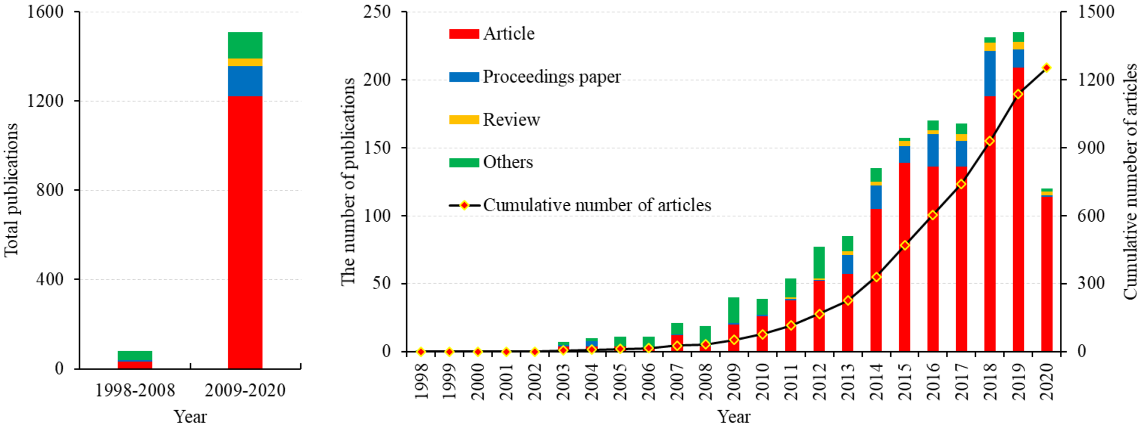

Figure 2.1 The number of publications of virtual water and water footprint

In terms of disciplines, although VW and WF are concerned with the sustainable use of water resources, there are up to 618 publications in the field of environmental science, accounting for 46% (Figure 2.2), followed by water resources (371, 28%), engineering environmental (241, 18%), and green sustainable science technology (235, 17%). This shows that VW and WF have become important methods and indicators in the field of environmental impact assessment, and WF has therefore been regarded as one of the environmental footprint indicators.

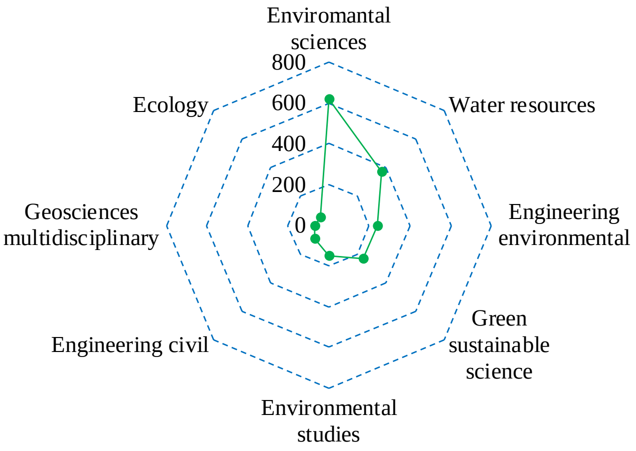

Figure 2.2 The number of publications on different subjects

### 2.3.2 Cooperative network analysis

#### 2.3.2.1 Contribution of country analysis

As shown in Figure 2.3, a total of 84 countries have published articles in the field of VW or WF, and the density of cooperation networks among countries is 0.0813. In terms of publication time, the United States published the earliest article in 2001. Other countries with earlier publication times include Japan (2002), the United Kingdom (2003), Italy (2003), France

(2003), Sweden (2004), the Netherlands (2005), China (2005), and India (2005). China is the most productive country with the largest number of 344 articles, accounting for 27%, followed by the United States (245, 20%), the Netherlands (139, 11%), and Italy (105, 8%).

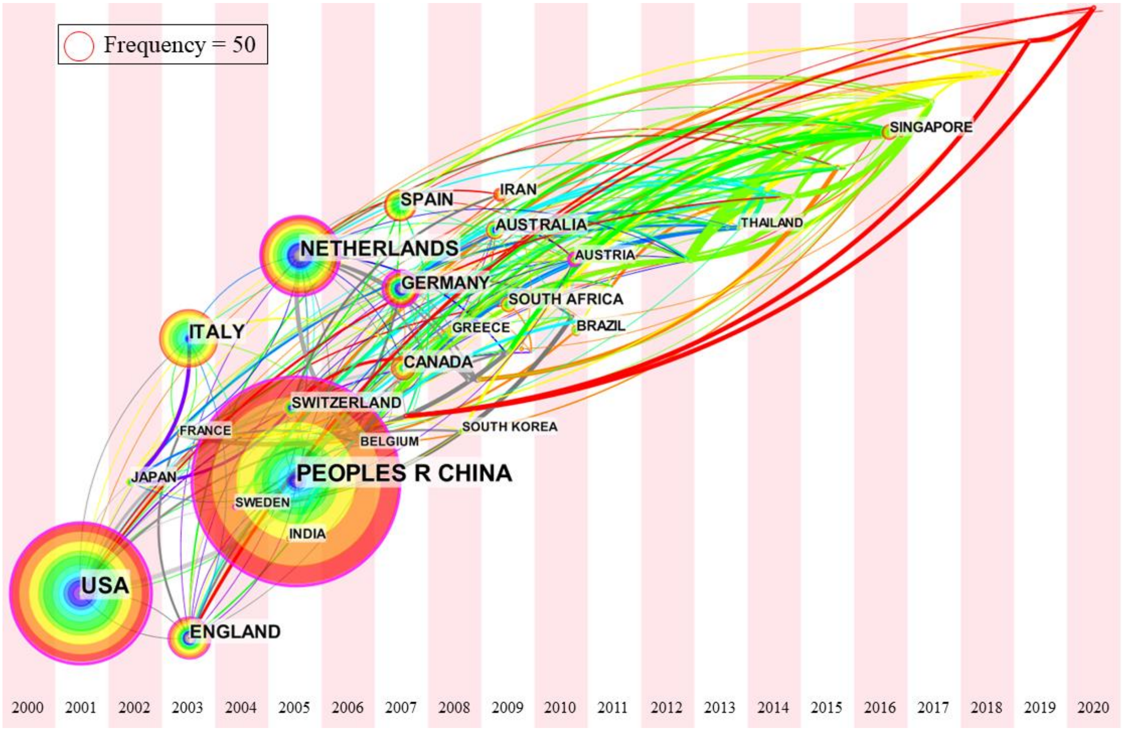

Figure 2.3 Cooperative network among countries (the size of the node represents the number of articles, and the location of the node represents the time when the earliest article was published)

In terms of influence, the betweenness centralities of the Netherlands (0.33), USA (0.29), China (0.23), Germany (0.22), Sweden (0.11), and the United Kingdom (0.10) are higher than or equal to 0.1, which indicates that these six countries played the most influential role in the field of VW and WF research. Although the number of articles published in the Netherlands is smaller than that of China and the United States, the betweenness centrality is greater than that of China and the United States, highlighting the leading role of the Netherlands in this field.

Through further analysis, a total of 414 funds have supported research on VW and WF over the past ten years, of which 377 funds came from China, accounting for 91%, while only 37 funds came from other countries or institutions, accounting for 9%. This could explain why research on VW and WF developed rapidly in China after 2010.

### 2.3.2.2 Contribution of the institutions

In terms of research institutions, of the 11 institutions in the top 10 in terms of the number of articles, there are eight in China, and one in the Netherlands, Singapore, and Japan. As shown in Figure 2.4, the institution that published the most articles was the University of Twente (94).

The institutions ranked second to tenth are the Chinese Academy of Sciences (80), Beijing Normal University (55), Hohai University (39) and Northwest Agriculture and Forestry University (33), University of Chinese Academy of Sciences (28), National University of Singapore (26), China Agricultural University (19), Beijing Forestry University (19), Shanghai Jiaotong University (14) and the National Institute for Environmental Studies, Japan (14). In terms of influence, only the betweenness centralities of the Chinese Academy of Sciences (0.22) and University of Twente (0.17) were higher than 0.1, reflecting the key role of these two institutions in the field of VW and WF research. The betweenness centralities of Beijing Normal University (0.09) and Hohai University (0.08) were close to 0.1, which is expected to become the core institution of VW and WF research. Overall, the density of institutional cooperation networks is only 0.0099, indicating that cooperation among institutions is relatively low. Through further analysis, it can be seen that closely cooperating institutions are often in the same country or city.

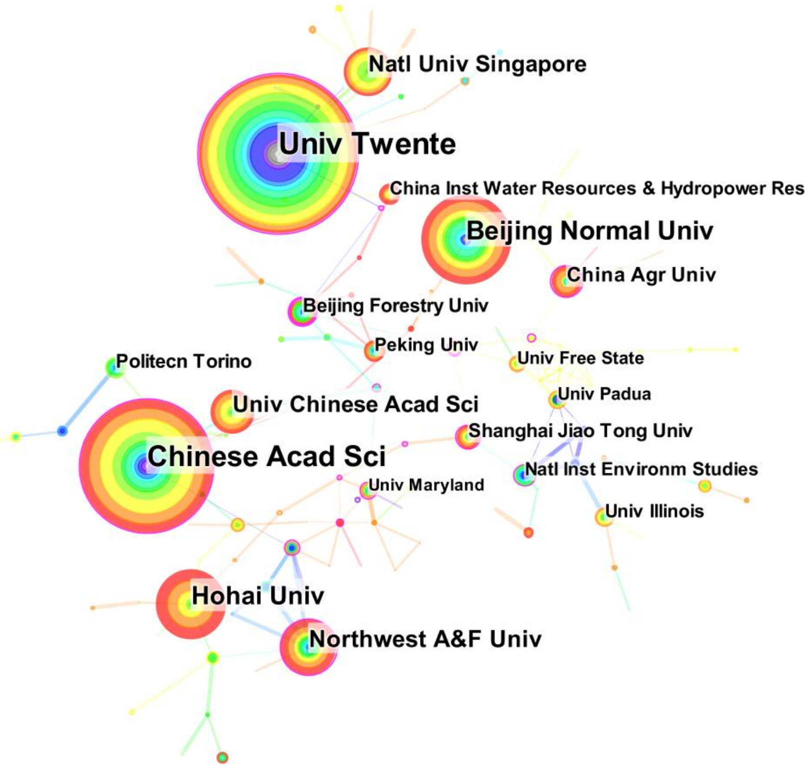

Figure 2.4 Cooperative network among institutions

### 2.3.2.3 Contribution of authors

The authors' co-occurrence analysis can identify cooperation and mutual citation relations between core figures and other researchers. In total, 40 authors have published more than 5 articles (Figure 2.5). Among them, A Y HOEKSTRA published 82 articles, far ahead of second-place P T WU (25), which exemplifies the dominant status of Hoekstra, the introducer of the water footprint. The authors with the third, fourth, and fifth place are M M MEKONNEN (21), A K CHAPAGAIN (18), and LA ZHUO (13). It can be seen that the cooperation between the authors is generally poor, mainly concentrated in the same country and department, and presents a relatively fixed cooperative relationship. The two most prominent research groups are led by A Y HOEKSTRA and P T WU. LA ZHUO is the link between the two groups because she has studied in these two institutions. Therefore, strengthening the exchange and learning among researchers will help to improve the international cooperation and influence of VW and WF research.

Figure 2.5 Collaborative network among authors

### 2.3.3 The evolution of the frontier on VW and WF research

#### 2.3.3.1 Keywords analysis

Keywords represent the core topics of the article and can better reflect the research hotspots. Visual analysis of keywords in a certain field can intuitively present the research frontier and dynamic evolution path. As shown in Figure 2.6, in the keywords network for VW and WF research, there are 149 nodes, 265 connections, and a density of 0.024. Among them, there are 31 keywords with an occurrence frequency greater than 50.

The largest node is “water footprint”, which has appeared 408 times. The nodes closely connected to it are virtual water (269) and flow (122), indicating that the WF is the development and continuation of VW theory. The second-largest node is “consumption (348)”. The main nodes connected to it are resource (248), trade (201), impact (189), environmental impact (78), energy (98), and food (69), indicating that research of VW and WF focuses on the consumption of resources, especially energy and food, and its environmental impact has also received increasing attention.

In terms of influence, the node “agriculture” has the highest betweenness centrality of 0.44, and it has entered the top 50 keywords since 2004, reflecting that VW and WF research has been mainly concentrated in the agricultural sector. Land had the second-highest betweenness centrality of 0.40, which entered the top 50 keywords for the first time in 2012. This is because the land is another important resource in agricultural production, and agricultural water resources research cannot conduct without consideration of factors such as land productivity. Climate change (0.29) and sustainability (0.17) also had a greater influence in the keyword network, reflecting that research on virtual water and water footprint was increasingly concerned with sustainable development in the context of climate change.

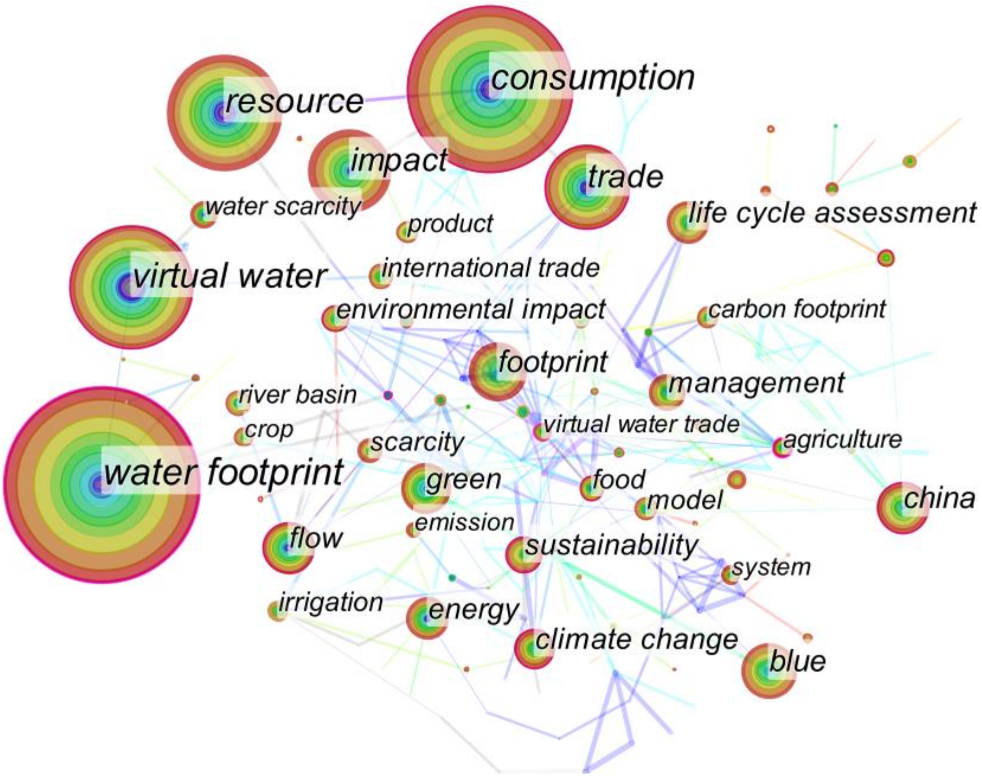

Figure 2.6 Keywords with a frequency of more than 50

#### 2.3.3.2 Burst terms analysis

Burst terms are extracted from keywords, titles, abstracts, etc., which are often used to judge the development trajectory and trend of a field. As shown in Table 2.1, there were 24 burst terms in the field of VW and WF. These burst terms can be divided into three time periods (2003–2010, 2011–2015, and 2016–2020). The three burst terms with the highest strength are virtual water (11.34), water resources management (6.90), and environmental impacts (6.85), which respectively represent research hotspots in different periods.

In 2003–2010, The burst terms reflected that the research hotspots at this stage were mainly based on VW theory, focusing on water-food nexus and international trade. The input-output analysis was the representative method. In 2011–2015, the burst terms reflected that the research hotspots at this stage were dominated by WF theory, mainly focusing on the estimation of crop water footprint, environmental impact assessment. Research on the combination of water footprint and other footprint indicators at this stage began to attract attention. In 2016–2020, the burst terms reflected that research hotspots at this stage were more closely integrated with sustainable development, and researchers were trying to apply VW and WF to traditional water resources management. The LCA method has received more and more attention at this stage. However, the overall duration of each prominent word was relatively short, reflecting that systematic research in these fields has not yet been formed.

Table 2.1 Burst terms of virtual water and water footprint research

| Burst Terms | Strength | Begin Year | End Year | 2003—2020 |
|---|---|---|---|---|
| virtual water | 11.34 | 2003 | 2008 | ■■■■■■□□□□□□□□□□□□ |
| food security | 5.33 | 2004 | 2008 | □■■■■■■□□□□□□□□□□□ |
| food production | 5.75 | 2005 | 2014 | □□■■■■■■■■■■□□□□□□ |
| water supply | 3.91 | 2007 | 2013 | □□□□■■■■■■■□□□□□□□ |
| global water resources | 3.52 | 2007 | 2012 | □□□□■■■■■■□□□□□□□□ |
| input-output analysis | 3.68 | 2009 | 2011 | □□□□□□■■■□□□□□□□□□ |
| international trade | 6.26 | 2010 | 2012 | □□□□□□□■■■□□□□□□□□ |
| greenhouse gas | 3.52 | 2011 | 2012 | □□□□□□□□■■□□□□□□□□ |
| crop water footprint | 3.26 | 2013 | 2015 | □□□□□□□□□□■■■□□□□□ |
| Water footprint assessment | 3.53 | 2014 | 2016 | □□□□□□□□□□□■■■□□□□ |
| environmental impacts | 6.85 | 2014 | 2016 | □□□□□□□□□□□■■■□□□□ |
| water productivity | 6.11 | 2014 | 2016 | □□□□□□□□□□□■■■□□□□ |
| water demand | 3.13 | 2014 | 2016 | □□□□□□□□□□□■■■□□□□ |
| agricultural production | 4.36 | 2015 | 2017 | □□□□□□□□□□□□■■■□□□ |
| water requirement | 4.70 | 2015 | 2016 | □□□□□□□□□□□□■■□□□□ |
| irrigation | 5.11 | 2015 | 2016 | □□□□□□□□□□□□■■□□□□ |
| water stress | 5.90 | 2016 | 2017 | □□□□□□□□□□□□□■■□□□ |
| water resources management | 6.90 | 2016 | 2018 | □□□□□□□□□□□□□■■■□□ |
| water pollution | 6.67 | 2016 | 2017 | □□□□□□□□□□□□□■■□□□ |
| sustainable development | 6.26 | 2017 | 2020 | □□□□□□□□□□□□□□■■■■ |
| grey water footprint | 3.84 | 2017 | 2020 | □□□□□□□□□□□□□□■■■■ |
| total water footprint | 5.85 | 2018 | 2020 | □□□□□□□□□□□□□□□■■■ |
| water scarcity footprint | 5.48 | 2018 | 2020 | □□□□□□□□□□□□□□□■■■ |
| life cycle assessment | 6.11 | 2018 | 2020 | □□□□□□□□□□□□□□□■■■ |

### 2.3.4 Co-citation analysis

As shown in Figure 2.7, 30 publications have been cited more than 50 times by these 1,252 articles, of which Hoekstra is the first or corresponding author of 15 articles. In terms of the number of citations, the book "The water footprint assessment manual" published in Earthscan by Hoekstra et al. (2011) has the highest citations of 421. The book introduces in detail the "Goals and Scope of WF Evaluation", "WF Account", "WF Sustainability Evaluation" and how different stakeholders, such as consumers, farmers, enterprises, and governments, can reduce WFs.

In terms of time, the earliest publication with citations of more than 50 is a book of "Water footprints of nations", which was published by Chapagain and Hoekstra (2004). It is also the most influential publication with a betweenness Centrality of 0.6. The book estimated the WF of each country in 1997–2001 and concluded that the WF of a country is mainly affected by climate conditions, agricultural structure, and consumption patterns.

In addition to the research group of Hoekstra, the most influential publication is "national water footprint in an input-output framework: A case study of China 2002" with third-place of betweenness Centrality (0.35), which was published by Zhao et al. (2009). In this article, the national WFs of all industry departments were calculated, which was divided into 23 sectoral units per the input-output table. On this basis, a new indicator of national WF intensity was proposed to evaluate the intensities of water use in different sectors for an accurate water-saving strategy.

In addition to the research group of Hoekstra, the most cited publication is "Assessing the environmental impacts of freshwater consumption in LCA", ranking eighth with 88 citations, which is published by Pfister et al. (2009). Based on LCA, this paper has developed a method to assess the impact of freshwater consumption on the environment from the three dimensions of human health, ecosystem production, and water resources, which is also very useful for researchers to assess the environmental impacts of VW and WF.

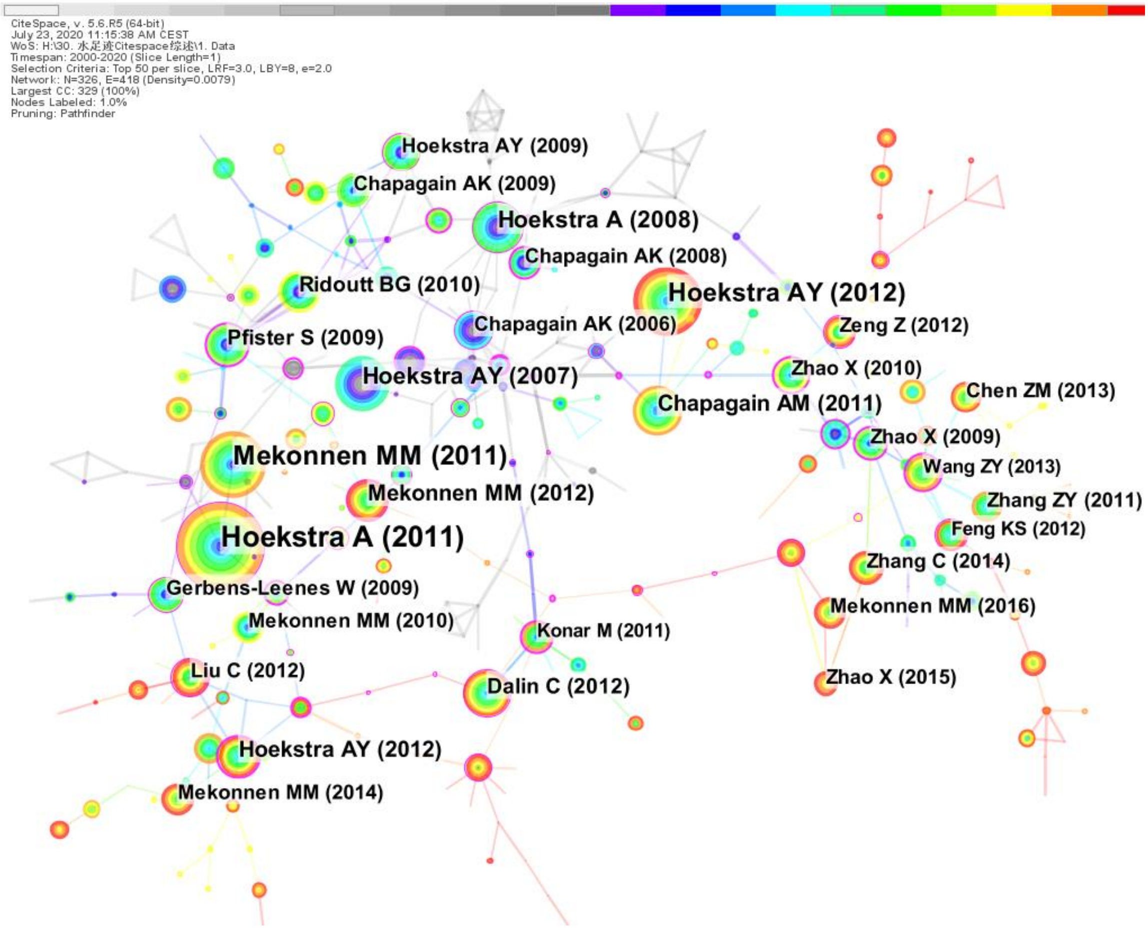

Figure 2.7 Publications cited more than 50 times by these 1,252 articles

## 2.4 Discussion

### 2.4.1 Problems

In recent years, research on VW and WF has received extensive attention (Hoekstra et al., 2019; Zhang et al., 2017). However, it can be known from this study that most of the research is mainly conducted in a few nations of China, the United States, and the Netherlands, and even in individual institutions and research groups in these countries, and there is little cooperation between them. In theory, research of VW and WF should be given more attention in water-scarcity countries and regions, such as the Middle East, Central Asia, and Africa, because the original intention of VW is to provide an alternative method for solving water shortages in water-scarce regions (Allan, 1998). It is thus necessary for international academic groups to strengthen exchanges and cooperation, especially between developed and developing countries, water-rich and water-poor countries (regions), to further promote the development of VW and WF.

Currently, most research on VW and WF is published in journals in the field of ecological environment and sustainable development (Hoekstra, 2017). This reflects that research on VW and WF is still in the stage of theoretical exploration and improvement, and has not been widely adopted in the optimal allocation of water resources utilization. It is well known that VW, as an intangible but actually existing resource, always participates in the flow of water resources. It should be incorporated into the water conservancy planning together with physical water to promote the rational planning and management of water resources, so as to better meet the needs of economic development. “VW flow” is essentially the circulation of the water resources “embedded” in the product in the socio-economic system, including blue water and green water. Although it is estimated that 80% of water consumption in agricultural production comes from green water, green water has not received corresponding attention in traditional water resources research. We believe that the “VW flow” phenomenon can be regarded as the secondary distribution of water resources, especially for precipitation. Therefore, it should become one of the focuses of social water cycle research, and only by incorporating it into the social water cycle can VW and WF research is recognized and funded by policymakers.

The “bottom-up” method has been well applied for calculating crop WF (Lovarelli et al., 2016), while it has been difficult to estimate the WF of animal products and industrial products. This is because various existing hydrological, ecological, and crop models can be directly applied to crop WF calculation, and data acquisition is relatively easy. Although the application of hybrid technology based on the LCA method in recent years has provided novel ideas for solving the VW calculation of animal products and industrial products (Boulay et al., 2013), they are still in the initial stage. The quantification of water consumption of animal products and industrial products is still the frontier of future research on VW and WF. Regarding the “top-down” method, the input-output model is mainly used to investigate VW consumption between different industrial sectors and VW flow between regions. However, because this method requires input-output tables, it is currently only applicable to some countries and large regional studies. Therefore, how to calculate the VW consumption of various industrial sectors in small areas lacking input-output data will still be a challenge for future research on VW and WF.

### 2.4.2 Future research trends

#### 2.4.2.1 Water–food–energy–land–climate nexus

Water, energy, and food (WEF) are indispensable resources supporting human life and socio-economic development (Liang et al., 2019). In recent decades, the use of water, energy, and food, and their interrelationships have received increasing attention due to population growth, urbanization, and changes in the dietary pattern (Conway et al., 2015; Scanlon et al., 2017). The WEF nexus approach is a novel perspective to address the complex interactions and to identify synergies and trade-offs between these sectors (Hanes et al., 2018) (Figure 2.8). It is increasingly prominent on the agenda of policymakers (Li and Ma, 2020), partly related to the SDGs of the post-2015 agenda (Zhang et al., 2019).

However, at present, almost all studies on WEF only consider blue water and ignore green water. As mentioned before, regarding global food production, green water is the main contributor and plays a more prominent role than blue water. In the context of climate change, global warming will affect regional water resources and agricultural patterns through changes in rainfall and its spatial distribution, thereby affecting food production and energy use (Howells et al., 2013).

Land, as an important input element in agricultural production, has also been included in some WEF nexus studies in recent years. Moreover, changes in land use and land cover can contribute to climate change by affecting the biogeochemical and biophysical processes of ecosystems, and then the climate changes land-use patterns by affecting food production and environmental pollution in ecosystems (Arneth et al., 2014).

Therefore, it is essential to continue to explore the dynamic relationship of “water-food-energy-land-climate” from the perspective of WF. For example, in the context of climate change, we can adjust and simulate crop planting patterns based on land resources and water resources endowment (including green water), and explore the relationship between food production, economic benefits, energy consumption, and environmental impacts.

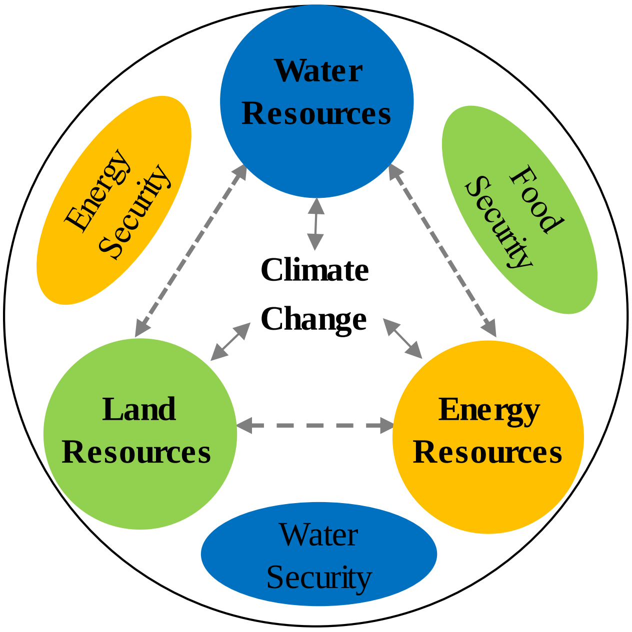

Figure 2.8 The water–food–energy–land–climate nexus

### 2.4.2.2 Footprint family and planet boundary

In the past two decades, the introduction of the concept of the ecological footprint has driven the development of other footprint indicators in the field of resource utilization and environmental impact assessment (Vanham et al., 2019). A series of footprint indicators such as water footprint, carbon footprint, nitrogen footprint, energy footprint, land footprint, and biodiversity footprint came into being (Fang et al., 2015; Mekonnen et al., 2020; Siddik et al., 2020), which have substantially enriched the quantitative assessment indicators of the influence of human activities on the ecosystem (O'Neill et al., 2018).

However, the occupation of various natural capitals by human activities and the interference with ecosystems are not independent of each other. Therefore, Galli et al. (2012) conducted a detailed comparison of ecological footprint, water footprint, and carbon footprint for the first time in 2012, and the concept of footprint family was proposed. The footprint family is a series of index clusters, which track the pressure of human activities on the ecosystem from multiple perspectives. Subsequently, Čuček et al. (2012) reviewed the definition, methods, and measurement units of various types of footprint indicators comprehensively, and proposed a series of social and economic footprint indicators in addition to environmental indicators. Hoekstra and Wiedmann (2014) put forward the concept of maximum sustainable footprint, which provides a reference basis for quantitative assessment of the environmental sustainability of human activities. Based on the theory of LCA, Ridoutt et al. (2015) argued that all footprint indicators should be able to support the comprehensive evaluation of environmental impact characterized by a single value. The concept of footprint family measures the resource occupancy and the environmental impacts of human activities from the perspective of consumption, but most footprint indicators lack corresponding carrying capacity indicators that can be used to assess whether they exceed the threshold of sustainable development.

To explore whether the increasingly serious resource and environmental problems such as carbon emissions, water resource utilization, and climate change have exceeded the sustainable “boundary”, Rockstrom et al. (2009) proposed the concept of planetary boundaries from the perspective of carrying capacity. Based on this concept, the study for the first time clarified the biophysical critical thresholds or tipping points of several global resource and environmental issues and received extraordinary attention and discussion (Erb et al., 2012; Lewis, 2012). The concept of planetary boundary makes up for the shortcomings of environmental carrying capacity indicators that have not been comprehensive enough for a long time. Due to their respective advantages and strong complementarities (Figure 2.9), the combined research of the footprint family and the planetary boundary has gained momentum in recent years (Dao et al., 2018; Li et al., 2019; Vanham et al., 2019).

Therefore, in the future, it is not only imperative to strengthen the research on the integration of WF and other footprint indicators, but also need to measure the “critical threshold” of sustainable water use from the perspective of VW and WF.

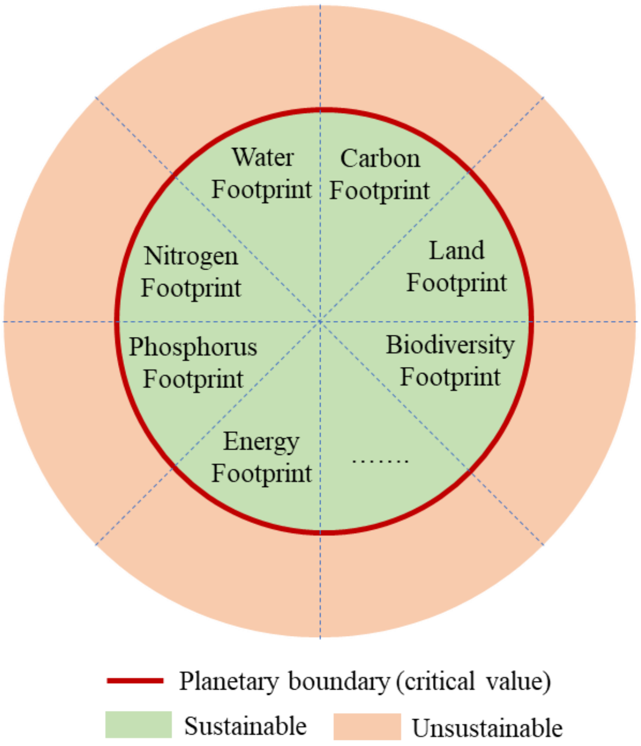

Figure 2.9 Sustainability assessment based on footprint family and planetary boundaries

#### 2.4.2.3 Material metabolism

The interplay between human activities and ecosystems in the given region is likened to a metabolic process of "material exchange and energy transfer" (Wolman, 1965). The most commonly used method of material metabolism research is material flow analysis (MFA), which involves the source, path, and sink of material circulation (Hashimoto and Moriguchi, 2004). Material metabolism research investigates the natural resources entering the socio-economic system and the pollutants discharged into the eco-environment system through material flow analysis, thereby evaluating the interaction between human activities and the natural environment. The material flow account is currently a more systematic account system for measuring the use of human material and its impact on the natural environment. It has been applied at global, national, and city scales (Allesch and Brunner, 2017; Condeixa et al., 2017; Song et al., 2019; Sun et al., 2017) and has formed a relatively complete theoretical method system.

The social water cycle is defined as the circulation process of water in the socio-economic system (Qin et al., 2014), which generally includes four subsystems: water supply, water use, drainage, and sewage reuse. There is a large body of water transfer in the social water cycle is in the form of VW (D'Odorico et al., 2020), and closely related to socioeconomic development. The exploration of the mechanism of VW flow is a pivot of the study of the social water cycle, and it is also the entry point to truly understand the driving mechanism and evolution of the social water cycle.

However, in previous material metabolism studies, VW was basically not considered in the water resource account and the amount of water (gray WF) used to absorb the pollutants carried in industrial wastewater and domestic sewage was not estimated. In fact, physical water consumption only accounts for a small part of the regional water cycle, while VW hidden in products or services accounts for more than 90% (Graham et al., 2020). Therefore, in the future, it is vital to introduce material flow analysis methods into the study of regional VW and WF (Figure 2.10) to make up for the deficiencies of traditional physical water and virtual water separate evaluation. Based on the theory of material metabolism, integrating VW and physical water into the evaluation of the social water cycle, studying the complex coupling mechanism of them, and exploring its driving mechanism will still be the frontiers of VW and WF research.

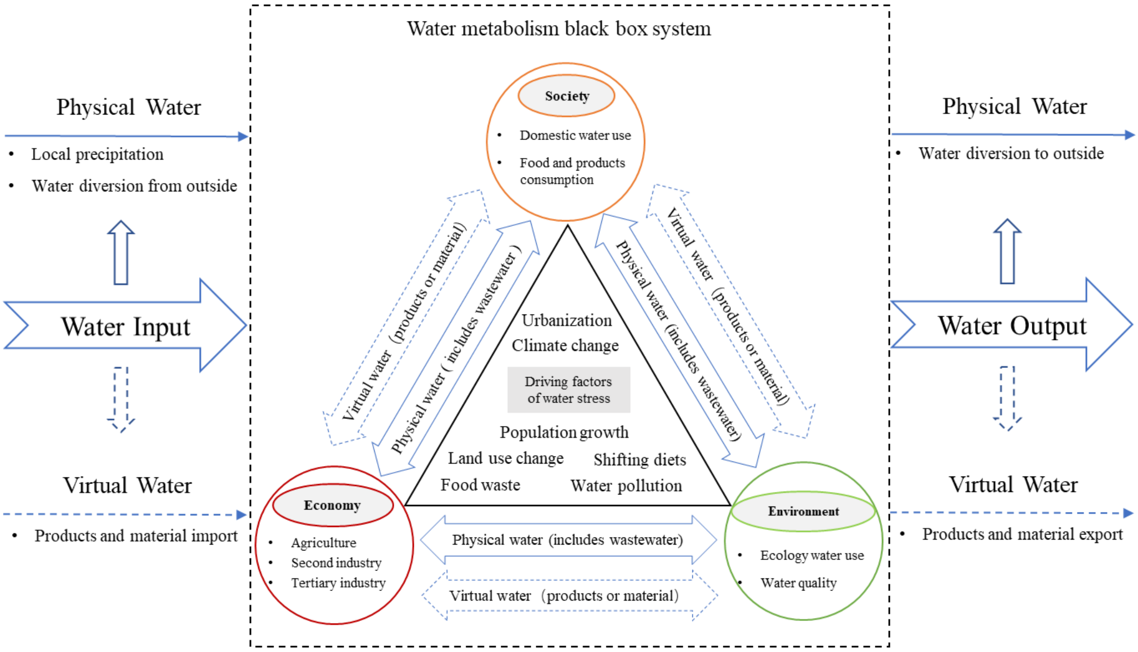

Figure 2.10 The metabolic process of regional physical and virtual water

### 2.4.2.4 Telecoupling sustainability assessment

Sustainable development is the biggest challenge facing humanity in the 21st century (Wu, 2013). It is necessary to comprehensively consider the three dimensions of economy, society, and the environment to measure the sustainable development level of a region (Figure 2.11). With regard to water use, this means not only ensuring the domestic water demand of different interest groups (social equity) and the normal operation of economic production (economic efficiency) but also controlling water pollution within standard thresholds (environmental limits).

In the modern world, distant regions are interconnected and influenced by one another in many ways (Liu et al., 2013), and resource allocation is driven by forces of supply and demand in the market economy system. The “social-economic-environmental” system in a region is inextricably linked to the “social-economic-environmental” system in other regions through trade (Figure 2.11). For example, the China-US trade war has not only led to rising consumption costs for both sides, and it also has caused or would cause major impacts on the agricultural structure, farmers’ income, and ecosystem services in other countries. To understand this kind of interconnected effect, the framework of telecoupling was proposed by Liu et al. (2013), which is employed to evaluate the social, economic, and environmental interactions between distant human-natural systems. This is considered to be a new perspective to solve multidimensional challenges facing global sustainable development (Hull and Liu, 2018).

In terms of VW and WF research, Chapagain et al. (2006) assessed the influence of global consumption of cotton products on water resources in cotton-producing countries from 1997 to 2001 and concluded that about 84% of cotton WF in the EU 25 countries came from outside, with significant effects in Uzbekistan and India. Chapagain and Orr (2009) investigated the impact of Spanish tomato consumption in the EU on Spanish freshwater resources and argued that this impact has local features, which depend on the local agro-climatic characteristics, water resources, and total yield of tomatoes. However, these studies were only based on the perspective of water resource utilization, without considering economic benefits and environmental impacts. Therefore, as the concept of telecoupling has received increasing attention in recent years, it should and will become the new frontier of VW and WF research.

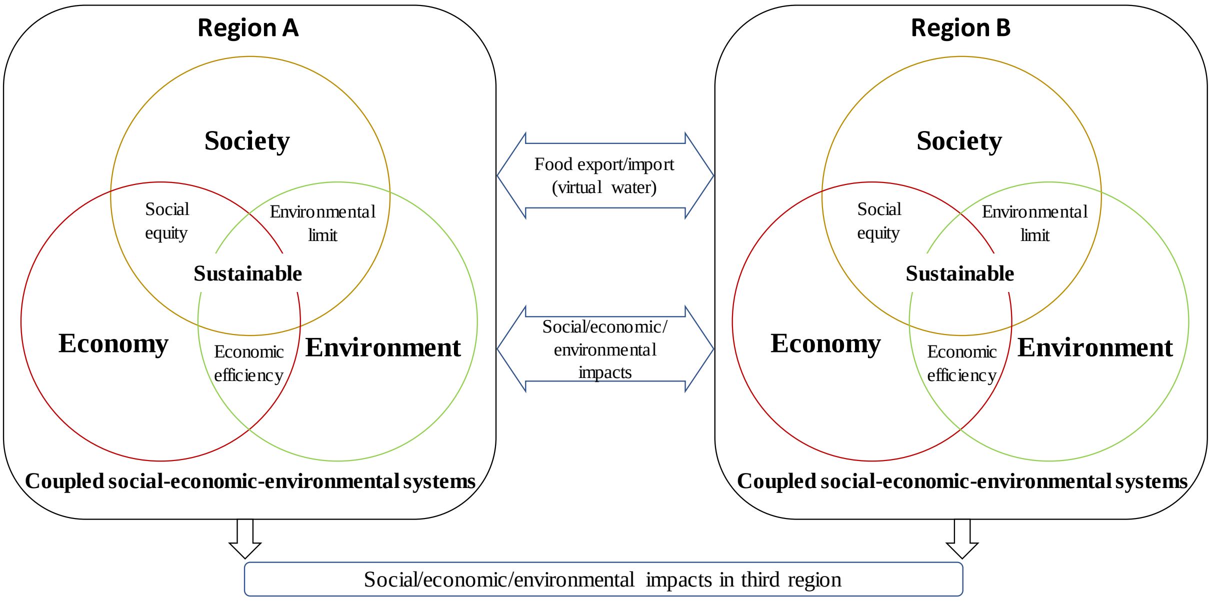

Figure 2.11 Telecoupling framework for research on virtual water and water footprint

## 2.5 Conclusions

Based upon the Web of Science Core Collection, this study employs CiteSpace to quantitatively analyze and visualize information about countries, institutions, and authors that have conducted VW and WF research over the past two decades, and the changing characteristics of research hotspots are analyzed through keywords and burst terms. On this basis, the future research frontiers of VW and WF are further predicted. The main results are as follows:

As of July 2020, there were 1,592 publications on VW and WF, showing an increasing trend overall. The annual average number of publications was only 7.4 in 1998–2008, while it was 126.5 in 2009–2019. Among them, up to 618 publications belong to environmental science, accounting for 46%, followed by water resources (371, 28%), engineering environmental (241, 18%), and green sustainable science technology (235, 17%), which shows that VW and WF have become important methods and indicators of environmental impact assessment.

In total, 84 countries have published research articles on VW and WF. Although China was the most productive country with a total of 344 articles, and 8 of the 11 institutions with the most articles were in China, the Netherlands had the largest influence with a betweenness centrality of 0.33, indicating its leading position. Hoekstra has published 82 articles, far ahead of second-place P. T. WU (25), and he was also the first author, corresponding author, or co-author of half of the publications that have been cited more than 50 times by 1,252 articles, which exemplifies his dominant role in the field of VW and WF.

It is essential to strengthening cooperation between developed and developing countries, water-rich countries (regions), and water-poor countries (regions), and to incorporate VW into social water cycle research. Besides, future research should also be conducted from the perspectives of the “water-food-energy-land-climate nexus”, “footprint family and planet boundary”, “material metabolism theory”, and “telecoupling sustainability assessment”.

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# 3. Study area

## 3.1 Geographic features

Zhangjiakou City is located in the northwest of Hebei Province, China. Its coordinates are 39°30'-42°10'N, and 113°50'-116°30'E (Figure 3.1). The elevation of Zhangjiakou City decreases from northwest to southeast. The Yinshan Mountains divide the city into two different geomorphic units, namely the Bashang area and the Baxia area. The Bashang area is part of the Inner Mongolia Plateau, with an average elevation of 1,368 m. It includes Chabei District, Saibei District, Guyuan County, Kangbao County, Zhangbei County, and the northern part of Shangyi County, with a total area of 11,656 km$^2$, accounting for about 31.5%. The Baxia area includes Qiaoxi District, Qiaodong District, Xuanhua District, Xiahuayuan District, Wanquan District, Chongli District, Huaian County, Huailai County, Yu County, Yangyuan County, Zhuolu County, Chicheng County, and the southern part of Shangyi County, with an average altitude of 681 m. It has a total area of 25,309 km$^2$, accounting for about 68.5%. The Bashang area is characterized by a lower temperature that is suitable for planting crops with a shorter growing time, such as vegetables; while the Baxia area is characterized by a higher temperature that is suitable for planting crops with a longer growing time, such as corn.

There are five water systems in Zhangjiakou City: Yongding River system, Chaobai River system, Daqing River system, Neilu River system, and Luan River system. The Yongding River system has 108 rivers in Zhangjiakou City, with a total drainage area of 17,924 km$^2$, accounting for 48.7%. Yanghe River and Sanggan River are its main tributaries, which are the main water sources for economic development in Zhangjiakou. The Chaobai River system is mainly composed of two tributaries of the Bai River and the Hei River, with a drainage area of 5,763 km$^2$, accounting for 15.6%. The Bai River and Hei River flow into Miyun Reservoir in Beijing after confluence in Yanqing County. The Daqing River Basin covers an area of 1,159 km$^2$, accounting for 3.1%. The Shandian River basin covers an area of 971 km$^2$, accounting for 2.6%. The Neilu River system is distributed in the Bashang area, with a drainage area of 11,021km$^2$, accounting for 29.9%.

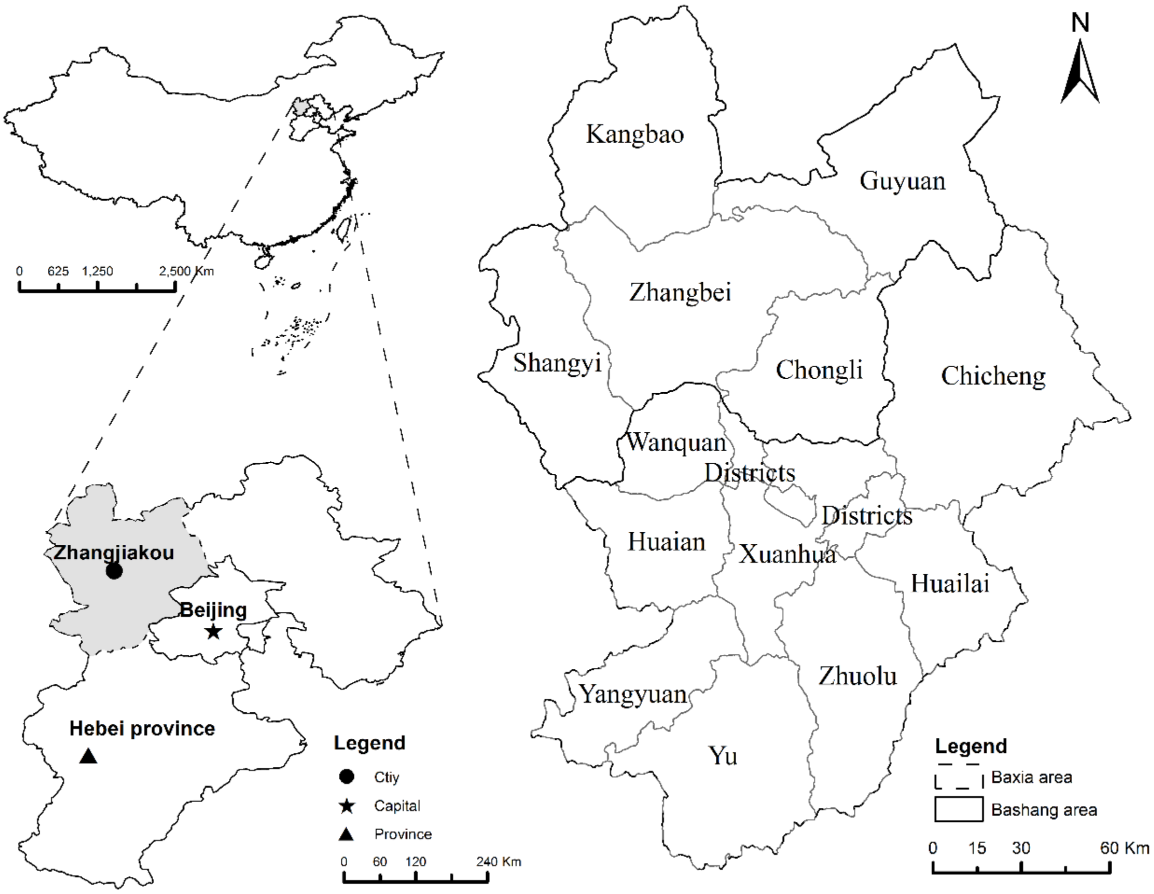

Figure 3.1 The location of Zhangjiakou City

## 3.2 Socioeconomic characteristics

### 3.2.1 Population

From 1949 to 2015, the total registered population of Zhangjiakou City increased from 2.33 million to 4.69 million. Before 2000, the population grew rapidly, with an average annual growth of 43,000, while after 2000, the population growth rate slowed down, with an average annual growth of 13,000. The proportion of the non-agricultural population has been rising, accounting for about 36% by 2015 (Table 3.1). In terms of spatial distribution, the population density of the Bashang area is generally greater than that of the Bashang area (Zhangjiakou Economic Yearbook, 2000-2016).

Table 3.1 Total population (TP) and share of non-agricultural population (SNAP) from 2005 to 2015

| Regions | 2000 | | 2005 | | 2010 | | 2015 | |
|---|---|---|---|---|---|---|---|---|
| | TP | SNAP | TP | SNAP | TP | SNAP | TP | SNAP |
| Qiaodong District | 248,321 | 83% | 263,203 | 84% | 277,707 | 85% | 283,304 | 87% |
| Qiaoxi District | 243,567 | 86% | 234,781 | 86% | 238,111 | 87% | 241,585 | 91% |
| Xuanhua District * | 290,537 | 81% | 299,618 | 82% | 315,270 | 85% | 320,757 | 84% |
| Xiahuayuan District | 68,955 | 54% | 67,806 | 57% | 67,890 | 60% | 66,779 | 64% |
| Xuanhua County * | 299,441 | 8% | 297,731 | 16% | 309,285 | 16% | 307,344 | 19% |
| Zhangbei County | 372,187 | 10% | 372,836 | 17% | 384,322 | 20% | 385,580 | 19% |
| Kangbao County | 283,276 | 8% | 280,630 | 10% | 280,547 | 16% | 274,268 | 16% |
| Guyuan County | 231,334 | 9% | 224,187 | 12% | 232,150 | 13% | 231,512 | 16% |
| Shangyi County | 190,913 | 11% | 189,749 | 14% | 194,338 | 24% | 191,619 | 23% |
| Yu County | 461,284 | 10% | 462,710 | 14% | 488,930 | 16% | 502,841 | 24% |
| Yangyuan County | 276,129 | 10% | 275,120 | 17% | 280,899 | 28% | 274,983 | 31% |
| Huaian County | 246,498 | 11% | 242,013 | 23% | 246,564 | 33% | 246,448 | 31% |
| Wanquan County * | 218,474 | 11% | 219,605 | 19% | 226,253 | 18% | 225,021 | 30% |
| Huailai County | 331,757 | 18% | 338,634 | 28% | 352,526 | 30% | 359,896 | 37% |
| Zhuolu County | 331,177 | 12% | 330,677 | 15% | 345,784 | 16% | 352,159 | 25% |
| Chicheng County | 280,801 | 8% | 280,777 | 9% | 293,867 | 17% | 299,324 | 23% |
| Chongli County * | 123,269 | 12% | 122,824 | 19% | 125,217 | 21% | 126,649 | 24% |
| Zhangjiakou City | 4,497,920 | 24% | 4,502,901 | 29% | 4,659,660 | 33% | 4,690,069 | 36% |

Note: * means that, in 2016, Wanquan County and Chongli County were renamed Wanquan District and Chongli District respectively, and Xuanhua District and Xuanhua County were combined as new Xuanhua District.

### 3.2.2 Economy

From 1949 to 2016, Zhangjiakou's GDP increased from 0.12 billion to 146.6 billion yuan. The share of the primary, secondary, and tertiary industries changed from 64%: 12%: 24% to 18%: 37%: 45%. The rapid development of the tertiary industry enabled it to replace the secondary industry as a pillar industry in Zhangjiakou in 2015 (Table 3.2). In recent years, agricultural development in Zhangjiakou City has made considerable progress. From 2005 to 2016, the output value of the primary industry has increased from 15.3 billion yuan to 26.6 billion yuan (Zhangjiakou Economic Yearbook, 2017).

Table 3.2 GDP of Zhangjiakou City from 1949 to 2016

| Year | GDP (10,000 yuan) | | | | GDP per capita (yuan) |
|---|---|---|---|---|---|
| | Total | Primary | Secondary | Tertiary | |
| 1949 | 12,044 | 7,690 | 1,426 | 2,928 | 52 |
| 1955 | 33,044 | 15,319 | 8,869 | 8,856 | 124 |
| 1960 | 61,646 | 15,018 | 34,924 | 11,704 | 215 |
| 1965 | 46,066 | 20,810 | 13,031 | 12,225 | 151 |
| 1970 | 85,897 | 37,068 | 32,417 | 16,412 | 251 |
| 1975 | 111,665 | 45,547 | 42,066 | 24,052 | 302 |
| 1980 | 123,205 | 33,186 | 58,971 | 31,048 | 321 |
| 1985 | 245,081 | 79,848 | 106,458 | 58,775 | 607 |
| 1990 | 550,216 | 130,803 | 244,895 | 174,518 | 1,313 |
| 1995 | 1,494,939 | 360,403 | 640,417 | 494,119 | 3,448 |
| 2000 | 2,263,400 | 333,833 | 924,669 | 1,004,898 | 5,066 |
| 2005 | 4,258,052 | 651,225 | 1,859,269 | 1,747,558 | 10,185 |
| 2010 | 9,664,158 | 1,529,389 | 4,151,817 | 3,982,952 | 22,517 |
| 2015 | 13,635,443 | 2,436,682 | 5,455,837 | 5,742,924 | 30,840 |
| 2016 | 14,659,911 | 2,660,151 | 5,471,658 | 6,528,102 | 33,142 |

## 3.3 Water resources and water use

### 3.3.1 Water resources

Zhangjiakou City belongs to an arid and semi-arid area. The annual per capita water resources are less than 400 m³, about one-fifth of the national average, which is in an internationally recognized state of extreme water shortage (the annual per capita water resources are less than 500 m³). From 1956 to 2016, the average annual rainfall in Zhangjiakou City was 408 mm, and the amount of evaporation (about 2,000 mm) was 4-5 times that of rainfall. Therefore, the shortage of water resources has become an important factor in restricting its social and economic development.

Surface water resources refer to the dynamic water volume of surface water bodies such as rivers, lakes, and glaciers that are formed by local precipitation and can be renewed year by year, while groundwater resources refer to the dynamic water volume of groundwater that participates in the water cycle and can be renewed year by year. As shown in Table 3.3, according to the "*Water Resources Evaluation Report of Zhangjiakou City, Hebei Province*", from 1980 to 2013, it is calculated that the average surface water resources were 1.162 billion $m^3$ and the average groundwater resources were 1.191 billion m³. Due to the mutual transformation between surface water and groundwater, after deducting the repetitive amount of mutual transformation, the multi-year average water resources of Zhangjiakou City were 1.555 billion m³.

Table 3.3 Multi-year average water resources in Zhangjiakou City

| | Area ($km^2$) | Precipitation (million $m^3$) | Surface water (million $m^3$) | Groundwater (million $m^3$) | Total water resources (million $m^3$) |
|---|---|---|---|---|---|
| Kangbao County | 3,336 | 1,159 | 19 | 68 | 74 |
| Zhangbei County | 4,185 | 1,609 | 74 | 154 | 182 |
| Guyuan County | 3,646 | 1,490 | 69 | 99 | 142 |
| Shangyi County | 2,649 | 1,016 | 72 | 56 | 92 |
| Huaian County | 1,757 | 714 | 55 | 85 | 103 |
| Wanquan County | 1,164 | 473 | 44 | 39 | 54 |
| City area | 780 | 302 | 25 | 19 | 48 |
| Chongli District | 2,347 | 1,072 | 71 | 38 | 63 |
| Xuanhua District | 2,146 | 878 | 66 | 101 | 113 |
| Huailai County | 1,799 | 694 | 69 | 100 | 97 |
| Zhuolu County | 2,802 | 1,251 | 164 | 145 | 150 |
| Yu County | 3,185 | 1,292 | 147 | 108 | 161 |
| Yangyuan County | 1,839 | 687 | 46 | 58 | 59 |
| Chicheng County | 5,330 | 2,500 | 241 | 122 | 214 |
| Zhangjiakou City | 36,965 | 15,127 | 1,162 | 1,192 | 1,555 |

### 3.3.2 Water supply and water use

According to the Zhangjiakou Water Resources Bulletin (2005-2017), from 2005 to 2017, the total water supply in Zhangjiakou City dropped from 1.089 billion $m^3$ to 905 million $m^3$ (Table 3.4). In 2017, the water supply volume of surface water, groundwater, and other water sources were 235, 651, and 20 million $m^3$, respectively, that is, groundwater was the main source of water supply. As shown in Table 3.4 and Figure 3.2, from 2005 to 2017, farmland irrigation water consumption accounted for the largest proportion of Zhangjiakou's total water consumption, but it dropped from 71% to 68%; industrial water consumption dropped from 14% to about 9%; and residential water consumption has increased significantly in recent years, from 7% to 12%.

In general, in terms of water supply, Zhangjiakou City is still facing problems such as the imbalance of the water supply structure and excessive proportion of groundwater sources. In recent years, the planting area of high water-consuming crops has expanded rapidly from 66,800 ha in 2000 to 103,300 ha in 2015. Agricultural irrigation is the main factor of groundwater overexploitation, and the expansion of irrigation area has further aggravated the excessive exploitation of groundwater. In terms of water use, farmland irrigation uses a lot of water, and the proportion of agricultural water use is still higher than the national average, which also means that the agricultural sector has a larger potential for water-saving. Besides, the current per capita domestic water use is relatively low. With the continuous progress of urbanization and changes in residents' lifestyles, it is expected that domestic water demand will increase.

Table 3.4 Water supply and water use in Zhangjiakou City from 2005 to 2017

| Year | Water supply (10,000 cubic meters) | | | | Water use (10,000 cubic meters) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Surface water | Groundwater | Other sources | Total supply | Primary | Secondary | Tertiary | Domestic | Environment | Total use |
| 2005 | 35,774 | 72,121 | 1,036 | 108,931 | 84,292 | 15,302 | 501 | 8,709 | 127 | 108,931 |
| 2006 | 33,801 | 78,373 | 1,321 | 113,494 | 84,955 | 17,406 | 596 | 10,444 | 94 | 113,494 |
| 2007 | 33,918 | 81,401 | 158 | 115,477 | 87,608 | 18,252 | 869 | 8,513 | 234 | 115,477 |
| 2008 | 32,718 | 80,249 | 158 | 113,125 | 85,546 | 17,531 | 1,029 | 8,055 | 964 | 113,125 |
| 2009 | 27,206 | 79,879 | 1 | 107,085 | 82,798 | 14,094 | 898 | 8,822 | 473 | 107,085 |
| 2010 | 27,026 | 77,768 | 1 | 104,795 | 82,466 | 12,500 | 1,056 | 8,144 | 628 | 104,795 |
| 2011 | 28,014 | 77,284 | 1,035 | 106,333 | 82,605 | 13,041 | 1,045 | 9,327 | 315 | 106,333 |
| 2012 | 27,537 | 76,262 | 1,768 | 105,568 | 80,145 | 13,597 | 1,353 | 9,675 | 798 | 105,568 |
| 2013 | 27,535 | 71,846 | 1,710 | 101,091 | 75,437 | 12,942 | 1,948 | 9,663 | 1,102 | 101,091 |
| 2014 | 26,444 | 67,639 | 1,335 | 95,418 | 71,485 | 11,260 | 1,998 | 9,691 | 1,183 | 95,418 |
| 2015 | 24,665 | 67,562 | 1,621 | 93,848 | 70,283 | 10,074 | 1,699 | 10,303 | 1,469 | 93,848 |
| 2016 | 24,764 | 64,988 | 1,593 | 91,330 | 67,530 | 9,522 | 1,588 | 11,225 | 1,465 | 91,330 |
| 2017 | 23,468 | 65,067 | 1,969 | 90,504 | 67,112 | 8,738 | 1,777 | 11,321 | 1,557 | 90,504 |

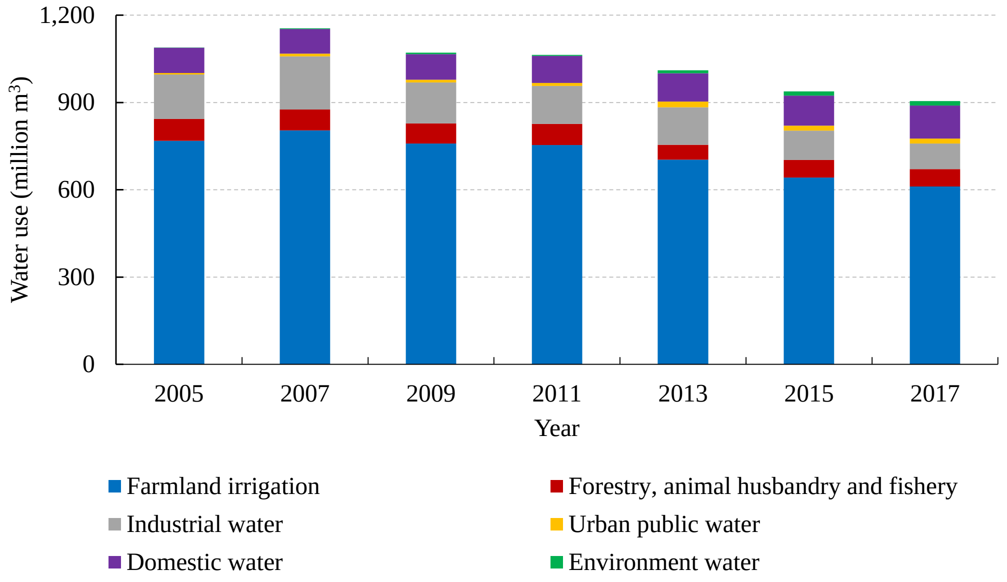

Figure 3.2 Water use of different sectors in Zhangjiakou City from 2005-2017

## 3.4 Future plan of development

Zhangjiakou and Beijing are connected by the Taihang Mountains-Yanshan Mountains. Guanting Reservoir and Miyun Reservoir are two important water sources in Beijing. 96% of the water volume of Guanting Reservoir and 46% of the water volume of Miyun Reservoir comes from the river system located in the upper reaches of Zhangjiakou City. Therefore, the natural geographical pattern determines the important position of Zhangjiakou City in ecological protection, that is, protecting the ecological environment of Zhangjiakou means protecting the ecological environment of the capital Beijing. In January 2017, when Chinese President Xi Jinping inspected Zhangjiakou, he requested that Zhangjiakou be developed into the capital's water conservation functional zone and ecological environment support zone. Since then, on the basis of other regional economic development and environmental protection plans, the government of Zhangjiakou City formulated a future development plan, namely the "*Capital Water Conservation Functional Zone and Ecological Environment Support Zone Construction Planning (2019-2035)*", referred to as the “Two-zone Planning”.

The plan put forward clear and rigid requirements for the social and economic development and ecological environmental protection indicators of Zhangjiakou City in the next 15 years. The main indicators are shown in Table 3.5. In terms of water resource utilization, agricultural water consumption should be reduced from 650 million $m^3$ in 2018 to 600 million $m^3$ in 2022, and then be controlled within 600 million $m^3$ by 2035. Industrial water consumption should not exceed the level of 2018, and then be firmly controlled within 80 million $m^3$. Domestic water consumption should be controlled within 160 million $m^3$ in 2022 and 200 million $m^3$ in 2035 respectively.

Table 3.5 The main indicators of the “Two-zone Planning” of Zhangjiakou City

| Indicators | | Year | | |
|---|---|---|---|---|
| | | 2018 | 2022 | 2035 |
| 1 | Groundwater extraction volume (100 million $m^3$) | 6.3 | 5.8 | 5.8 |
| 2 | Agricultural water use (10 million $m^3$) | 6.5 | 6 | 6 |
| 3 | Industrial water use (100 million $m^3$) | 0.8 | 0.8 | 0.8 |
| 4 | Domestic water use (100 million $m^3$) | 1.3 | 1.6 | 2 |
| 5 | Other water use (100 million $m^3$) | 0.2 | 0.4 | 0.4 |
| 6 | Total water use (100 million $m^3$) | 8.8 | 8.8 | 9.2 |
| 7 | Forest area (10,000 mu[1]) | 2,157 | 2,760 | 3,035 |
| 8 | Grassland area (10,000 mu) | 1,595 | 1,695 | 1,775 |
| 9 | Wetland area (10,000 mu) | 345 | 346 | 351 |
| 10 | PM2.5 ($\mu g/m^3$) | 29 | 25[2] | 25 |
| 11 | Ammonia nitrogen emissions (10,000 tons) | 0.47 | 0.42 | 0.3 |
| 12 | Surface water quality compliance rate (%) | 100 | 100 | 100 |
| 13 | Urbanization rate (%) | 57.24 | ≥ 60 | - |
| 14 | The per capita disposable income of urban residents (10,000 yuan) | 3.12 | 4 | 10 |
| 15 | The per capita disposable income of rural residents (10,000 yuan) | 1.15 | 1.6 | 4.6 |
| 16 | The share of tertiary industry GDP (%) | 51.5 | 55 | ≥ 60 |
| 17 | Total energy consumption (10,000 tons of standard coal) | 1,445 | 1,623 | 1,879 |
| 18 | Energy consumption per 10,000 yuan GDP (tons of standard coal) | 0.93 | 0.75 | - |
| 19 | Water consumption per ten thousand yuan GDP (ton) | 57.2 | 41 | - |
| 20 | The share of renewable energy in total energy consumption (%) | 23 | 30 | 50 |

Note: 1.1ha = 15 mu; 2. Only for Winter Olympic area

## References

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The People's Government of Zhangjiakou City, 2000-2017. Zhangjiakou Economic Yearbook. *China Statistics Press, Beijing* (in Chinese).

Zhangjiakou Water Resource Bureau, 2005-2017. Zhangjiakou Water Resource Bulletin. *Zhangjiakou Water Resource Bureau.*

# 4. Sensitive factors identification and scenario simulation of water demand

## 4.1 Research problem and objectives

There has been a body of studies on the system dynamics (SD) model in water resources simulation at various scales, from regional (Jeong and Adamowski, 2016; Kotir et al., 2016; Liu et al., 2015; Sahin et al., 2015; Susnik et al., 2012; Wei et al., 2016) to national and global (Duran-Encalada et al., 2017; Kelly et al., 2019; Sun et al., 2017). However, most of the studies have not been closely integrated with the policies and plans of local governments, resulting in poor feasibility of the research results and weak guidance for local sustainable development practices. Therefore, Zhangjiakou, a city with extremely scarce water resources, was selected as the study case in this study to make up this gap.

Zhangjiakou City has less than 400 $m^3$ of water per capita per year, which has not only severely constrained the economic development but also threatened regional ecological security, due to it is the geo-ecological barrier and water sources for the capital Beijing. In 2017, it was identified as “the water conservation function zone and ecological environment support zone of the capital city” by the central government of China. In 2019, the Chinese government further formulated a medium-term plan for the development of Zhangjiakou City (2019-2035), referred to as the “Two-zone Planning”, which placed strict and specific restrictions on water consumption and water use efficiency in various sectors, including agriculture, industry, and households. Moreover, the 2022 Winter Olympic Games will be jointly held in Beijing and Zhangjiakou, making the task of water-saving and water efficiency improvement more important and urgent for the local government policymakers. Therefore, the research objectives of this study are: (1) Identify and analyze the impact of different factors on the water demand of Zhangjiakou City. (2) Establish a system dynamics model to simulate the water demand of various departments in Zhangjiakou City from 2020 to 2035 under the four development scenarios. (3) Estimate the pressure on water resources under the four development scenarios. The research results are expected to provide specific and feasible guidance for the implementation of the “Two-zone Planning”, and to contribute to the sustainable use of water resources in Zhangjiakou City and its surrounding areas. In addition, the research also aims to increase researchers' awareness of integrating with local development policies when simulating water demand, thereby enhancing the practicality of the research results.

## 4.2 Methods and data sources

### 4.2.1 Methods

#### 4.2.1.1 System dynamics simulation

The SD model consists of four types of variables: state variables, rate variables, auxiliary variables and constants, and a series of equations reflecting the relationship between these variables. The simulation process can be summarized as five steps (Figure 4.1): (1) determine the research objective; (2) establish the model, determine the system boundary and the causal relationship between the variables; (3) model validation, qualitative and quantitative test; (4) scenario simulation, determine the control variables (sensitivity analysis) and set different development scenarios; (5) analysis of results.

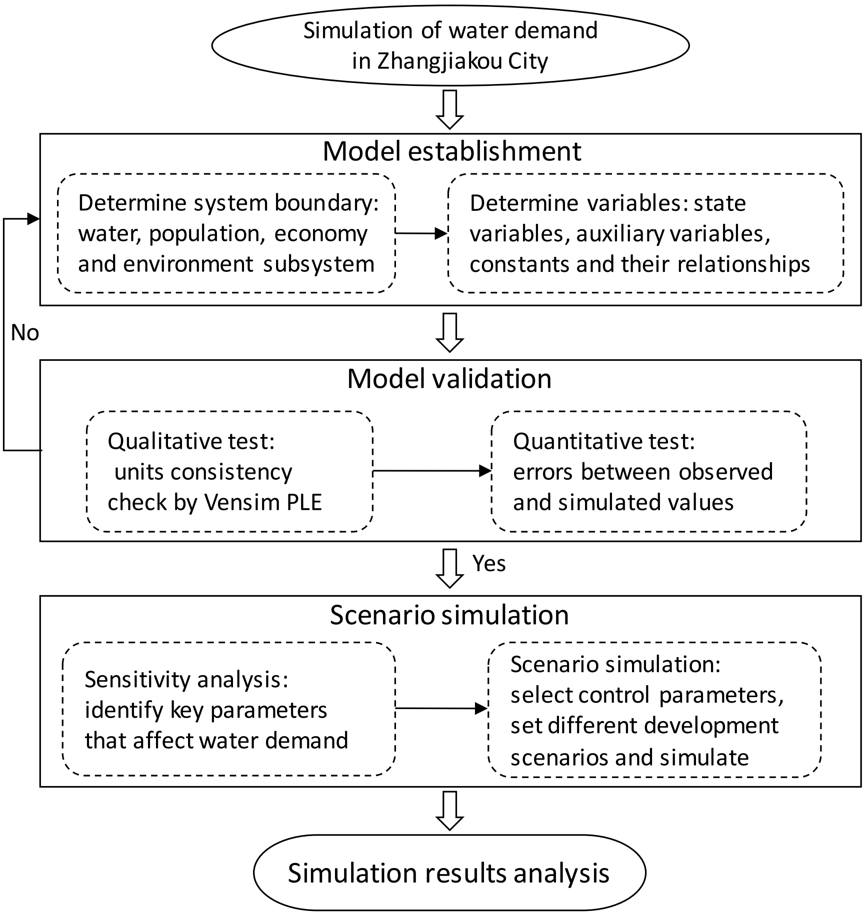


Figure 4.1 The modeling process of system dynamics

#### 4.2.1.2 Zhangjiakou system dynamics model

(1) Water use structure

The water cycle usually consists of water supply, water use, as well as wastewater treatment and reuse. Figure 4.2 simply shows the causal relationship between them in Zhangjiakou City.

Water resources include local water and inbound water, while the available water resources need to be reduced by outbound water and environmental flows. Environmental flow refers to the amount of water that is necessary to maintain the ecological and environmental services of rivers and lakes. Water use mainly includes five sectors from the three sub-systems of population, economy, and ecological environment, that is, domestic, agriculture, industry, urban public, and eco-environment. Finally, some of the wastewater from the population and economic sub-systems can be reused after treatment. All of these components are dynamically interrelated with each other.

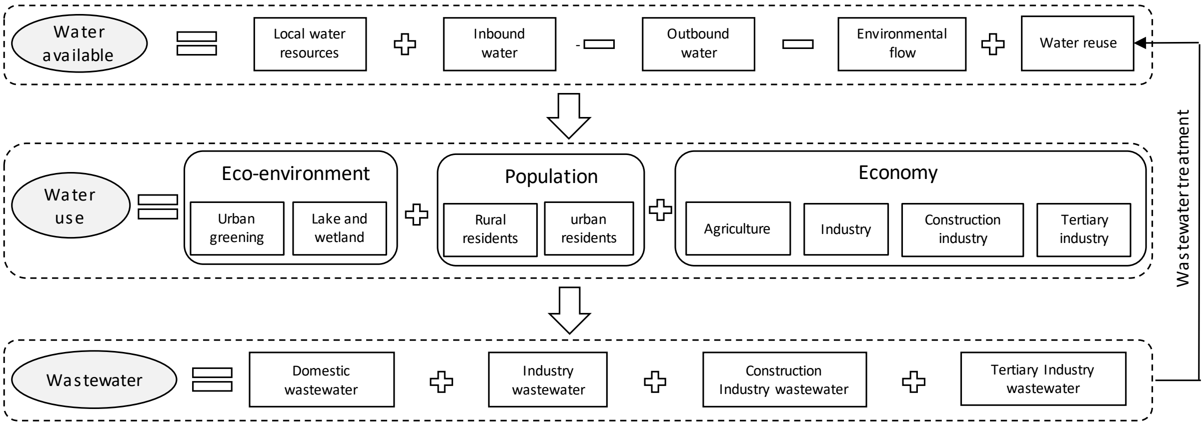


Figure 4.2 Relationships of water resource subsystem and other subsystems in Zhangjiakou City

(2) Establishment of model

Based on the development status and “Two-zone Planning”, Vensim-PLE, a classical software of system dynamics, is used to establish the simulation model of water demand in Zhangjiakou City, abbreviated as ZSD (Figure 4.3). The simulation is from 2005 to 2035, and the modeling time step is 1 year, where the strategic planning time is from 2015-2035. It consists of four subsystems: population, economic, agriculture (irrigation land, forestry, and animal husbandry), and water (water supply, water demand, and water pollution and reuse), including 8 status variables, 7 rate variables, 39 auxiliary variables, 8 table Functions (lookup) and 30 constants, as well as 54 equations. The variables and their relationships can be found in Table S1.

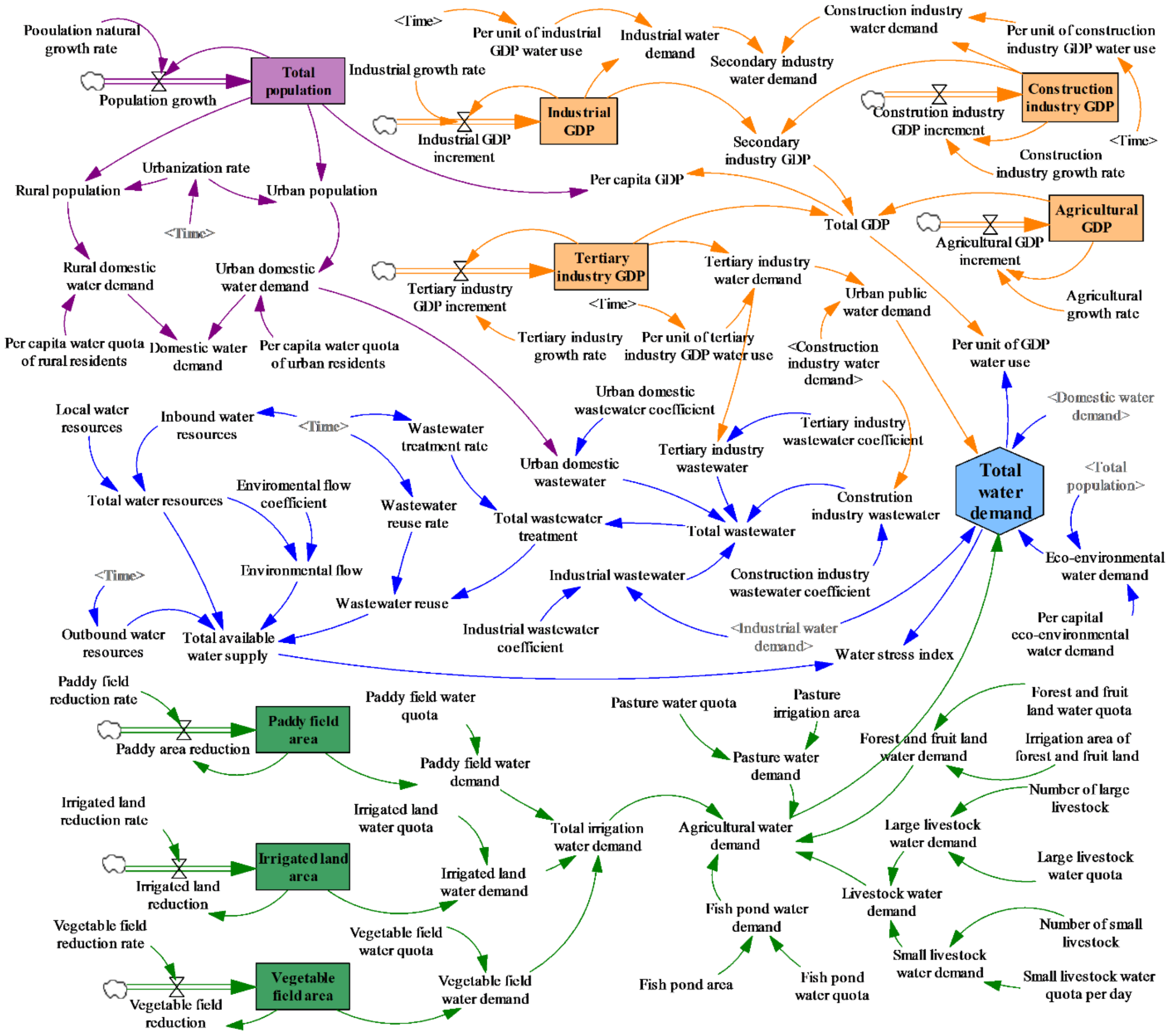


Figure 4.3 System dynamics model of Zhangjiakou City

### 4.2.1.3 Model evaluation and sensitivity analysis

(1) Model evaluation

In this study, the absolute relative error (ARE) is employed for model performance validation.

$$ARE = \left|\frac{(S_i - R_i)}{R_i}\right| \tag{4-1}$$

where $R_i$ and $S_i$ represent the observed value and the simulated value of variable *i*, respectively.

(2) Sensitivity analysis

To identify which variables (constants) in the ZSD model have greater impacts on the water demand of Zhangjiakou City, we use the “univariate” method in the sensitivity analysis function of Vensim DSS, that is, the value of each variable is changed independently, while the values of others are held constant. Sensitivity analysis not only helps us to select key variables for scenario setting scientifically but also to improve the understanding of the relationships between input and output variables in the SD model, which will contribute to the formulation of policies (Susnik et al., 2012).

#### 4.2.1.4 Water stress index (WSI)

There have been many methods for regional water stress assessment. The ratio of water demand to water availability can be a relatively straightforward reflection of whether the number of water resources is surplus or deficit. Therefore, it is used in this study to measure the pressure of water resources in different development scenarios. The formula is:

$$WSI = \frac{TWD}{TAW} \tag{4-2}$$

where *TWD* and *TAW* represent the total water demand and the total available water, respectively. When *WSI* is greater than 1, it means water resources are in a state of deficiency; when *WSI* is less than 1, it means water resources are in the surplus state; when *WSI* is equal to 1, it means water resources supply and demand are just balanced.

### 4.2.2 Data sources

The basic socio-economic data mainly come from the *Zhangjiakou Economic Yearbooks* (2006-2016) (The People's Government of Zhangjiakou City, 2006-2016), including urban and rural population, output values of various sectors and so on. Water resources, irrigation farmland, and livestock are collected from the *Water Resources Bulletins* (2005-2016) (Zhangjiakou Water Resource Bureau, 2006-2016), including water supply, water consumption and water efficiency in various sectors, and the areas of different irrigation land. In addition, the data required for the simulation phase (2015-2035), except the initial values same as 2015, such as urbanization rates, economic development rates, and water quotas for various departments involved in the model, are set according to government reports, “Two-zone Planning” and local standards “Norm of water intake (2016)” of Hebei Province.

## 4.3 Results

### 4.3.1 Model validation

To conduct the model validation, the water demand from 2005-2015 is simulated, with 2005 as the base year. Table 4.1 shows the absolute relative errors (AREs) between the simulated and observed values for 2010 and 2015. The AREs of most variables are within 10%, indicating that the ZSD model has a good performance to reflect the behavior of the simulated system. Here, the ARE of industrial GDP is greater than 10% in 2015, that is because the industrial GDP used in the *Zhangjiakou Economic Yearbook* (2016) is very likely a mistake. According to the annual government report, the industrial growth rate in 2015 was 4.2%, however, the industrial GDP in the *Zhangjiakou Economic Yearbook* (2016) was 44.17 billion yuan, even lower than 47.56 billion yuan in 2014. If this is adjusted according to the industrial growth rate in the government report, the industrial GDP in 2015 should be 49.56 billion yuan.

Table 4.1 Absolute relative errors (AREs) of the main variables between the simulated and observed values

| Variables | 2010 | | | 2015 | | |
|---|---|---|---|---|---|---|
| | Simulated value | Observed value | ARE | Simulated value | Observed value | ARE |
| Total population ($10^4$ persons) | 462 | 466 | 0.9% | 474 | 469 | 1.0% |
| Rural population ($10^4$ persons) | 309 | 314 | 1.4% | 303 | 298 | 1.6% |
| Urban population（$10^4$ persons） | 152 | 152 | 0.2% | 171 | 171 | 0.1% |
| Total GDP ($10^8$ yuan) | 961.3 | 966.4 | 0.5% | 1495.3 | 1363.5 | 9.7% |
| Agricultural GDP($10^8$ yuan) | 143.1 | 152.9 | 6.4% | 250.2 | 243.7 | 2.7% |
| Secondary industry GDP ($10^8$ yuan) | 399.3 | 415.2 | 3.8% | 655.2 | 545.6 | 20.1% |
| Industrial GDP($10^8$ Yuan) | 338.9 | 352.5 | 3.9% | 544.1 | 441.7 | 23.2% |
| Construction industry GDP ($10^8$ yuan) | 60.5 | 62.7 | 3.6% | 111.1 | 104.9 | 5.9% |
| Tertiary industry GDP($10^8$ yuan) | 418.8 | 398.3 | 5.1% | 589.8 | 574.3 | 2.7% |
| Domestic water demand($10^8$ $m^3$) | 0.8132 | 0.8144 | 0.2% | 1.0435 | 1.0323 | 1.1% |
| Rural domestic water demand($10^8$ $m^3$) | 0.4405 | 0.4426 | 0.5% | 0.4647 | 0.4583 | 1.4% |
| Urban domestic water demand($10^8$ $m^3$) | 0.3727 | 0.3718 | 0.2% | 0.5788 | 0.5768 | 0.4% |
| Agriculture water demand ($10^8$ $m^3$) | 8.2422 | 8.2465 | 0.1% | 7.0342 | 7.0282 | 0.1% |
| Industrial water demand ($10^8$ $m^3$) | 1.2031 | 1.2500 | 3.8% | 1.0882 | 1.0074 | 8.0% |
| Construction water demand ($10^8$ $m^3$) | 0.0357 | 0.0372 | 4.1% | 0.0255 | 0.0244 | 4.7% |
| Tertiary water demand($10^8$ $m^3$) | 0.0712 | 0.0683 | 4.2% | 0.1475 | 0.1455 | 1.3% |
| Environment water demand ($10^8$ $m^3$) | 0.0623 | 0.0628 | 0.7% | 0.1483 | 0.1469 | 0.9% |
| Urban public water demand ($10^8$ $m^3$) | 0.1069 | 0.1056 | 1.2% | 0.1730 | 0.1699 | 1.8% |
| Total water demand($10^8$ $m^3$) | 10.4276 | 10.4794 | 0.5% | 9.4872 | 9.3848 | 1.1% |
| Total wastewater discharge($10^8$ $m^3$) | 0.8228 | 0.8420 | 2.3% | 0.9862 | 0.9357 | 5.4% |

### 4.3.2 Sensitivity analysis

Based on the ZSD model and other studies on water demand simulation (Li et al., 2019; Sun et al., 2017; Wei et al., 2012), twelve constant variables that may have the strongest impacts on the total water demand are selected. To identify the extent of the impacts, these 12 variables are further analyzed using the sensitivity analysis function in Vensim DSS. The initial value of each variable is the same as the observed value in 2015, and its value range is determined through historical data and related planning (especially the “Two-zone Planning”). The results are shown in Figure 4.4, where yellow, green, blue, and gray represent confidence intervals of

0-50%, 50%-75%, 75%-95%, and 95%-100%, respectively. The greater the bandwidth in the graph, the more sensitive the total water demand is to the variables.

It is obvious that different variables have very different impacts on total water demand, which can be divided into four categories:

(1) Per capita water quota. The urbanization rate of Zhangjiakou City was 52% in 2015, and the proportion of the urban population will further increase as the urbanization process continues. In addition, the per capita water quota for urban residents is 50-140 $m^3$/day, while it is only 40-60 $m^3$/day for rural. Therefore, the total water demand is more sensitive to the per capita water quota of urban residents than to that of rural residents.

(2) GDP growth rate. The sensitivities of total water demand to the growth rate of GDP of different sectors from large to small are industry, tertiary industry, and construction. There are two main reasons: First, the output values are significantly different, and the output value of the construction industry is much smaller than that of the industrial and tertiary industries. Second, the water consumption per unit of industrial output value is 12-23 $m^3$ per 10,000 yuan, while it is less than 3 $m^3$ per 10, 000 yuan for the tertiary industry and construction industry.

(3) Irrigation area and water quota per ha. Although the irrigated land and the vegetable field have the same ranges of water quota, both are 1500-4500 $m^3$/ha, and the irrigated land area reduction rate range (-0.05, 0) is smaller than the vegetable field area reduction rate range (-0.1, 0), but the total water demand is more sensitive to the area reduction rate and water quota of irrigated land than to those of the vegetable field. This is because the area of irrigated land is much larger than that of the vegetable field. In 2015, the area of irrigated land was 4.8 times that of vegetable fields.

(4) The number of livestock. The proportion of livestock water consumption is relatively small, which was only 3.4% in 2015, so the total water demand is less sensitive to the number of livestock, whether it is large livestock or small livestock.

In general, irrigated land has the greatest impact on total water demand. Because of the large amount of water use of irrigated land, which was 497 million $m^3$ in 2015, accounting for 53%, resulting in the total demand for water resources being most sensitive to the two variables related to it.

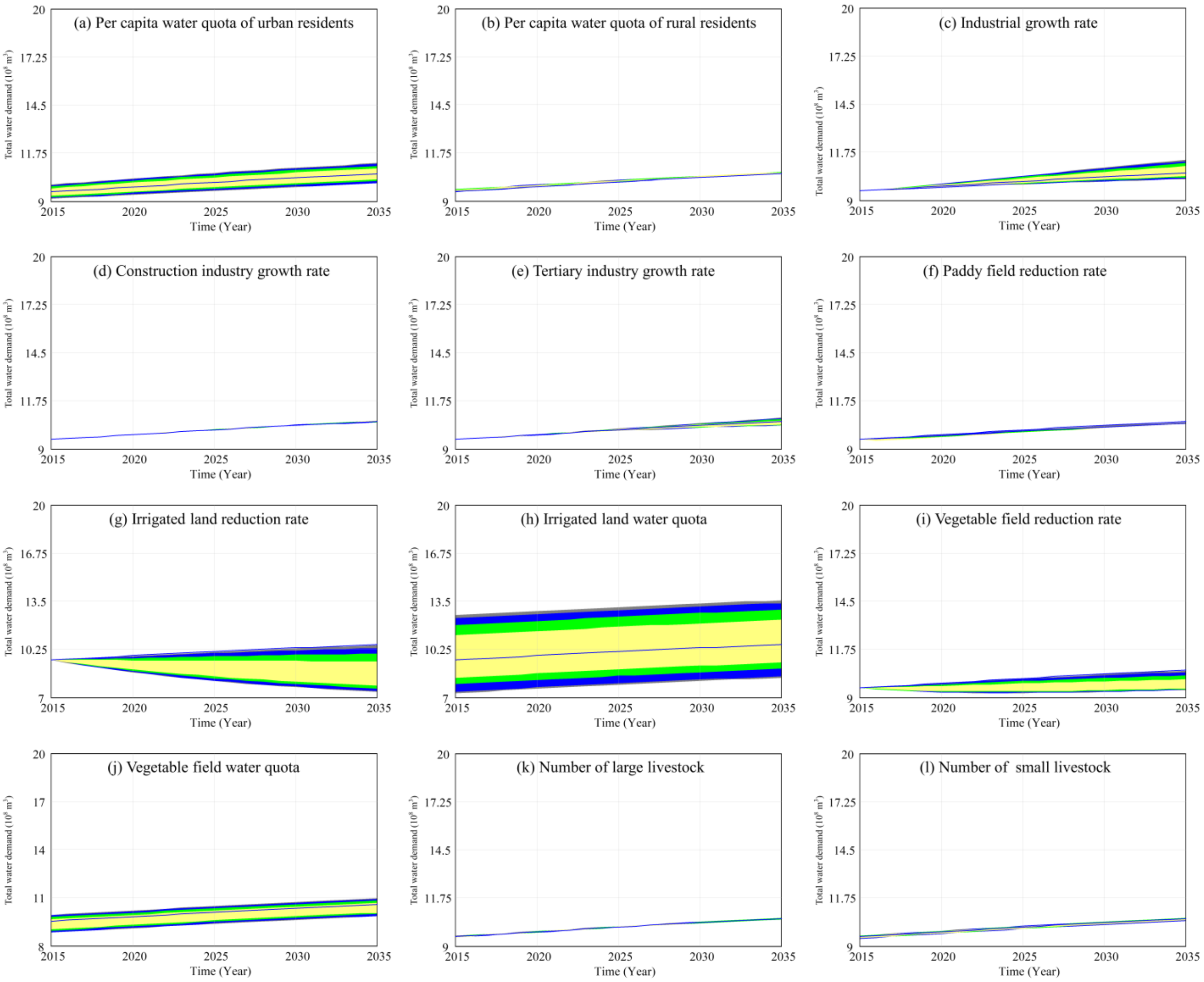


Figure 4.4 Results of sensitivity analysis

### 4.3.3 Scenarios simulation

#### 4.3.3.1 Scenarios setting

In line with the planning period of the two districts of Zhangjiakou City, the simulation time of water demand is 2015-2035, with 2015 as the base year. For most variables, the initial values are derived from the Economic Yearbooks and the Water Resources Bulletins, and for the rest of the variables, they are set based on historical data or reference to relevant government plans (Table S1).

Based on the sensitivity analysis, 15 variables are selected as control variables to set four development scenarios: Current development scenario (CDS), Economic priority scenario (EPS), Water-saving priority scenario (WPS), and Balanced development scenarios (BDS). The main characteristics of each scenario are as follows: (1) In CDS, except for the urbanization rate and industrial GDP water quota, the other variables are consistent with 2015. (2) In EPS, the economic growth rates are higher than the CDS. Moreover, due to the current low water use of per capita and inadequate irrigation of farmland, the per capita water quota and the water quota for all types of irrigated farmland are also set higher than the current situation. (3) In WPS, the economic growth rates and urbanization rates are lower than CDS, and the areas of the three types of irrigated farmland are rapidly reduced. (4) In BDS, the economic growth rates are between EPS and WPS, and the reduction rates of the three types of irrigated farmland are lower than WPS. The values of these 15 variables in each scenario are shown in Table 4.2.

Table 4.2 Values of control variables in four development scenarios

| Variables | Units | Time | CDS | EPS | WPS | BDS |
|---|---|---|---|---|---|---|
| Per capita water quota of urban residents | L/person/day | – | 93 | 120 | 100 | 110 |
| Per capita water quota of rural residents | L/person/day | – | 42 | 60 | 50 | 60 |
| Industrial growth rate | % | – | 4.6 | 5.6 | 3.6 | 5.1 |
| Construction industry growth rate | % | – | 7.3 | 8.3 | 6.3 | 7.3 |
| Tertiary industry growth rate | % | – | 8.1 | 9.1 | 7.1 | 8.1 |
| Agriculture growth rate | % | – | 3.3 | 4.3 | 2.3 | 3.3 |
| Paddy field reduction rate | % | – | 0 | 0 | -50 | -25 |
| Irrigated land reduction rate | % | – | 0 | 0 | -2 | -1 |
| Irrigated land water quota | $m^3$/ha | – | 2,790 | 3,240 | 2,340 | 2,565 |
| Vegetable field reduction rate | % | – | 0 | 0 | -3 | -1.5 |
| Vegetable field water quota | $m^3$/ha | – | 3,450 | 3,900 | 3,000 | 3,150 |
| Number of large livestock | Million | – | 0.75 | 0.95 | 0.65 | 0.85 |
| Number of small livestock | Million | – | 11.59 | 13.59 | 10.59 | 12.59 |
| Urbanization rate | % | 2015 | 52 | 52 | 52 | 52 |
| | | 2020 | 60 | 62 | 58 | 60 |
| | | 2022 | 62 | 65 | 60 | 62 |
| | | 2025 | 65 | 68 | 62 | 65 |
| | | 2030 | 70 | 73 | 67 | 70 |
| | | 2035 | 72 | 75 | 69 | 72 |
| Per unit of industrial GDP water use | $m^3 * 10^{-4}$ $yuan^{-1}$ | 2015 | 22.8 | 22.8 | 22.8 | 22.8 |
| | | 2025 | 18 | 20 | 15 | 18 |
| | | 2035 | 12 | 15 | 10 | 12 |

#### 4.3.3.2 Simulation results

(1) Population subsystem

With a natural population growth rate of 3.07‰, the total population of Zhangjiakou City will increase from 4.69 million in 2015 to 4.99 million in 2035. Meanwhile, the rate of urbanization is also rising, resulting in an increase of domestic water use in every scenario. Domestic water demands from large to small are EPS (191 million $m^3$), BDS (174 million $m^3$), WPS (154 million $m^3$), and CDS (143 million $m^3$) (Figure 4.5a). The gap in domestic water demand between urban and rural will further expand, and the ratio of them will increase from 2.0-2.4 in 2015 to 4.5-6.0 in 2035 (Figure 4.5b).

(2) Economic subsystem

The growth rates of total GDP from high to low are EPS (7.4%), BDS (6.5%), CDS (6.4%), and WPS (5.4%), resulting the total GDP will reach 567 billion yuan, 482 billion yuan, 471 billion yuan, and 390 billion yuan, respectively (Figure 4.5c). The structure of contribution rates of primary, secondary, and tertiary industries to GDP will change from 18%: 40%: 42% in 2015 to 10%: 32%: 58% (CDS, EPS, and WPS) and 10%: 34%: 56% (BDS) in 2035.

The industrial water demands from high to low are EPS (197 million $m^3$), BDS (143 million $m^3$), CDS (130 million $m^3$), and WPS (90 million $m^3$) in 2035 (Figure 4.5d). It shows a declining trend only in WPS. The urban public water demands increase in each scenario, from high to low are EPS (76 million $m^3$), BDS (63 million $m^3$), CDS (63 million $m^3$), and WPS (52 million $m^3$) in 2035 (Figure 4.5e).

(3) Agricultural subsystem

In CDS and EPS, agricultural water demands remain at 704 million $m^3$ and 808 million $m^3$, of which the proportions of farmland irrigation are 91.2% and 91.5%, respectively (Figure 4.5f).

In WPS, the area of paddy fields, irrigated land, and vegetable fields decreased at an average annual rate of 50%, 2%, and 3%, respectively, resulting in a reduction in agricultural water demand from 604 million $m^3$ to 399 million $m^3$, and the proportion of water demand for farmland irrigation will drop from 90.3% to 85.3% (Figure 4.5g, Figure 4.5h, and Figure 4.5i).

In BDS, the paddy fields, irrigated land, and vegetable fields are reduced at an average annual rate of 25%, 1%, and 1.5%, respectively, while the number of livestock is increased to ensure that the GDP growth rate of the primary industry remains unchanged. At this time, the agricultural water demand will decrease from 656 million $m^3$ to 527 million $m^3$, and the proportion of water demand for farmland irrigation will drop from 90.0% to 87.7%.

(4) Ecological environment subsystem

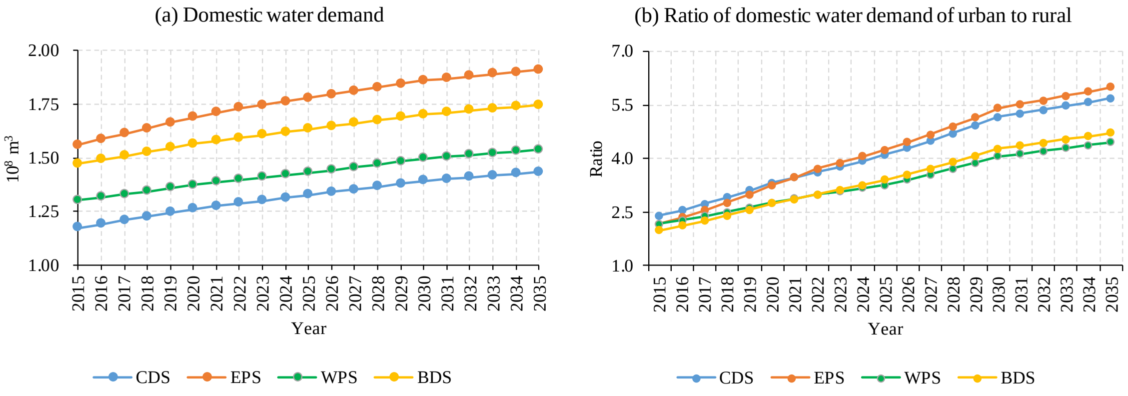
Since the per capita ecological environment water demand is set to 3.13 $m^3$ in the four scenarios, the ecological environment water demand increased from 14.7 million $m^3$ to 15.6 million $m^3$ with the increase of population in each scenario (Figure 4.5j).

The total amount of wastewater discharged is increasing in every scenario, from high to low are EPS (235 million $m^3$), BDS (190 million $m^3$), CDS (169 million $m^3$), and WPS (146 million m$^3$) in 2035 (Figure 4.5k). The wastewater mainly comes from urban domestic water and industry sectors, and the proportion of them will drop from 93%-94% to 83%-85% with the change of GDP.

(5) Total water demand

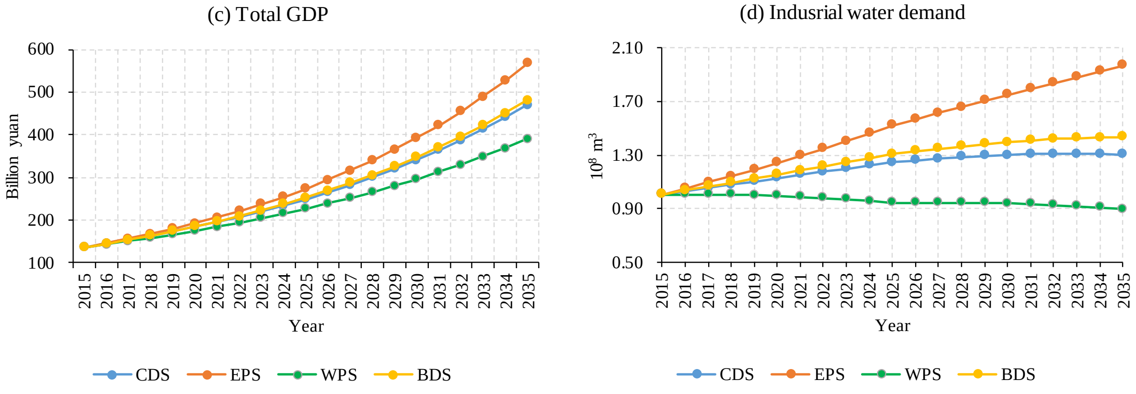
In CDS and EPS, the total water demand will increase from 954 million m$^3$ and 1,097 million m$^3$ to 1,057 million m$^3$ and 1,288 million m$^3$ (Figure 4.5l), and the proportion of agricultural water demand will drop to 67% and 63%, respectively.

In WPS and BDS, the total water demand will drop from 866 million m$^3$ and 936 million m$^3$ to 710 million m$^3$ and 924 million m$^3$, and the proportion of agricultural water demand will drop to 56% and 57% respectively.



(a) Domestic water demand

(b) Ratio of domestic water demand of urban to rural



(c) Total GDP

(d) Indusrial water demand

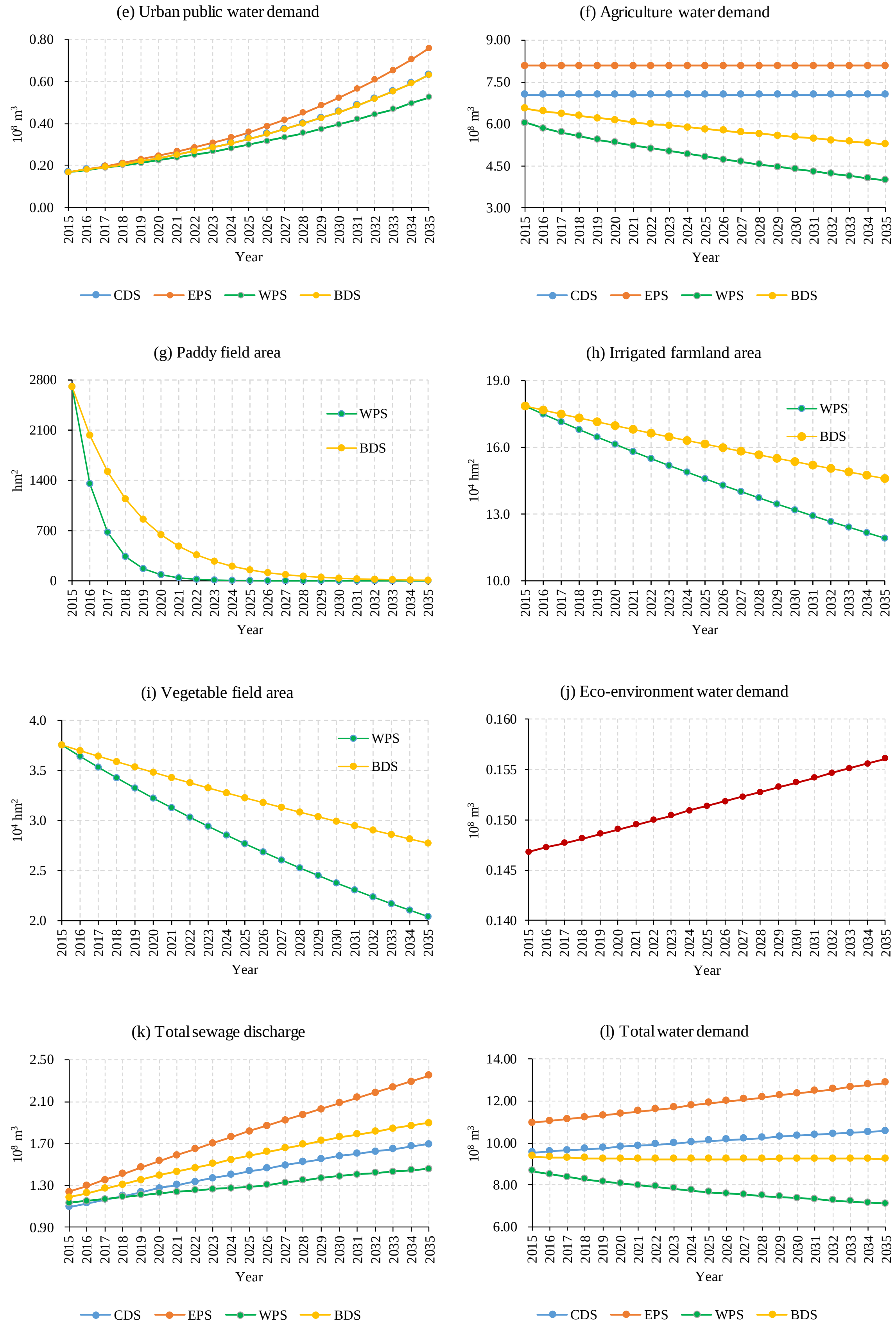
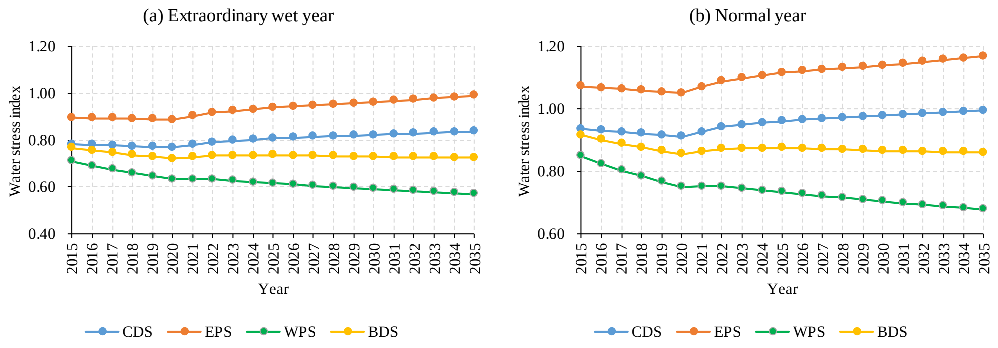


Figure 4.5 The simulation results of four development scenarios

#### 4.3.3.3 Water stress index

In the water supply subsystem, the amount of inbound water and outbound water from 2015 to 2035 are set according to the “Two-zone Planning” of Zhangjiakou City. The total water resources of the extraordinary wet year, normal year, and extraordinary dry year are the maximum value of 17.01, the average value of 14.51, and the lowest value of 11.42 from 2008 to 2016, respectively. Besides, due to the over-exploitation of water resources in Zhangjiakou City, from the perspective of sustainable development, the environmental flow coefficients of the extraordinary wet year, the normal year, and the extraordinary dry year are set to 0.2, 0.25, and 0.3, respectively, which are slightly higher than the proportion of unused water in Zhangjiakou City for many years.

As shown in Figure 4.6, in general, the water stress indexes in the four scenarios from high to low are EPS, CDS, BDS, and WPS. In the extraordinary wet year, the water stress indexes of the four development scenarios are between 0.5 and 1, indicating that the water resources are in surplus. In the normal year, the water stress indexes of CDS and EPS will rise continually, and it is going to exceed 1 in CDS and is always greater than 1 in EPS. The water stress indexes in WPS and BDS are between 0.6 and 1.0 and will decline continually. In the extraordinary dry year, the water stress indexes of CDS, EPS, and BDS are always greater than 1, while it is less than 1 after 2019 in WPS.



(a) Extraordinary wet year

(b) Normal year

(c) Extraordinary dry year

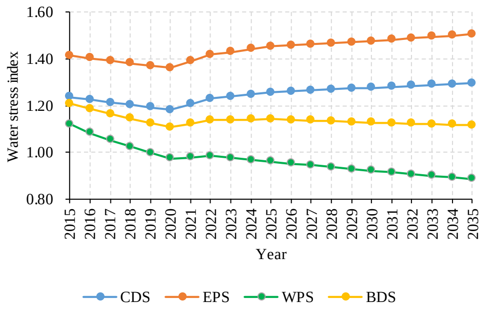


Figure 4.6 Water stress index of four development scenarios

## 4.4 Discussion

### 4.4.1 Comparison with the “Two-Zone Planning”

The industrial growth rates of Zhangjiakou City in this study are set between 3.6%-5.6%, slightly lower than 6% in the “Two-Zone Planning”. Because it has been declining in recent years, from 5.9% in 2014 to 2% in 2017, which is very difficult to keep an average annual growth rate of 6% until 2035. Nevertheless, considering that the current GDP of Zhangjiakou City is lagging behind in eleven cities in Hebei Province and facing the requirements of economic growth, we still set the industrial growth rate higher than 2017.

In 2015, the industrial water quota of Zhangjiakou City was 22.8 m$^3$, while the national average level was 58.3 m$^3$, which means that Zhangjiakou City’s industrial water efficiency has been at the leading level in the country, even exceeding some developed countries. Therefore, the average annual rate of water consumption per ten thousand yuan industrial GDP in this study is set around 3%, which is lower than that of the “Two-zone Planning” (6%). In fact, in terms of industrial water conservation, the current focus should be on how to adjust the industrial layout and structure to achieve a matching of the water resources distribution and industrial water demands.

The irrigated land is planned to reduce 64,667 ha (36.2%) by 2022 in the “Two-zone Planning”. The area of irrigated land, according to the sensitivity analysis, is indeed the biggest factor affecting the demand for water resources. However, the reduction rate of irrigated land should not be so fast because it is a very important factor to guarantee food security and residents’ income. Therefore, in this study, we make a modest adjustment of the reduction rate of irrigated land. The area of irrigated land will be reduced by 59,333 ha and 32,667 ha by 2035 in WPS and BDS, respectively.

In terms of water resources efficiency, the total GDP in the “Two-zone Planning” will increase from 136.35 billion yuan in 2015 to 407.50 billion yuan in 2035, resulting in a decrease in water consumption per ten thousand yuan GDP from 68.79 m$^3$ in 2015 to 21.66 m$^3$ in 2035. At the same time, the proportion of unused water resources will also drop from 41% in 2015 to 56% in 2035. Although it will indeed save water resources, will it cause a waste of water supply capacity? As shown in Figure 8, the water demand per ten thousand yuan GDP in the four scenarios varied from 63 m$^3$ to 80 m$^3$ in 2015, and the difference will become smaller and smaller over time, reaching from 18 m$^3$ to 23 m$^3$ in 2035. This means no matter which scenario is chosen, the water demand per ten thousand yuan GDP will eventually fall to about 20 m$^3$ in

2035 as the economy grows. If lower water demand is achieved only by slowing economic growth, the water resources efficiency will not be improved, and it may also result in the waste of water supply capacity. Therefore, Zhangjiakou City should choose a coordinated development model to balance economic development and water conservation.

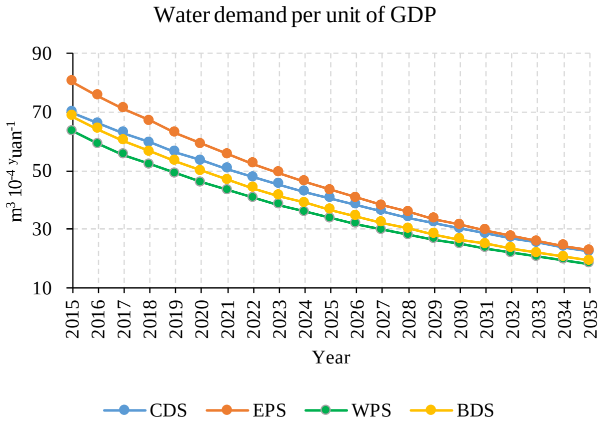


Figure 4.7 Water demand per unit of GDP

### 4.4.2 Policy suggestions for sustainable water use

In general, Zhangjiakou City should take the water resources carrying capacity as the primary consideration for regional economic development and ecological security of Beijing city. It is vital to assess the current status of water resources carrying capacity on the county scale from the perspectives of total water use, water use efficiency, and water pollution, so as to promote the structural adjustment and optimization of water use. In the meantime, the management concept should shift from the water supply side to the water demand side, from extensive water use to intensive water use.

Reduction of agricultural water use. According to the sensitivity analysis, the agricultural water-related indicators are most sensitive to the total water demand in Zhangjiakou City. That is to say, the agricultural sector has the largest water-saving potential. Therefore, there is a need to reduce the area of irrigated farmland. In this process, the correlation between the crop structure, food production, and agricultural income, as well as other factors must be considered to achieve maximum benefits. In addition, it is also essential to strictly control the planting area of high-water-consumption crops, vigorously promote water-saving renovation, and develop high-efficiency water-saving irrigation such as large-scale sprinkler irrigation, micro-irrigation, and high-standard pipe irrigation.

Targeted control of industrial water use. On the one hand, it is crucial to strictly limit the entry of high-water-consuming industries and enterprises, and focus on the promotion of water-saving technologies in high-water-consuming industries such as thermal power, building materials, and food, to ensure the continuous decrease of the total industrial water consumption. On the other hand, comprehensive strategies should be adopted in future water management, such as industrial transformation and upgrading, optimization of industrial layout, upgrading of water-saving technology, and strengthen long-term water consumption planning and quota management.

Urban public and ecological water conservation. First, the water-saving technological transformation of key water use sectors should be accelerated, such as schools, hospitals, hotels, restaurants, car washes, and ski resorts. Second, the government needs to promote the construction of recycled water utilization projects actively. For example, the water recycling systems should be set up in new communities and give priority to the use of recycled water and rainwater in urban greening, municipal environmental sanitation, and ecological landscapes. Besides, it is also important to optimize the layout of urban pipeline networks, replace severely aged water supply pipeline facilities, and reduce water leakage during water supply.

## 4.5 Conclusions

In this study, a complex system dynamics model (ZSD) reflecting the relationships between the water resources subsystem and other subsystems in Zhangjiakou City, such as population, economy, and environment subsystem, is established by using Vensim PLE, a system dynamics software. Then the ZSD model is employed to simulate water demand (2015-2035) in four designed alternative development scenarios. The main conclusions are as follows:

According to the sensitivity analysis, the variables related to irrigation farmland are the main driving factors of water demand, especially the area and the average water consumption of irrigated land. Therefore, reducing the area of irrigated farmland and improving the efficiency of agricultural irrigation water will be the main direction of water-saving in Zhangjiakou City. However, it is vital to consider various factors to decide to what degree to reduce the area of irrigation farmland, such as agricultural output value and farmers' income.

The total water demand will rise continually in CDS and EPS, and the proportion of agricultural water demand will drop to 67% and 63%, respectively. Meanwhile, it will decline continually in WPS and BDS, and the proportion of agricultural water demand will drop to 56% and 57%, respectively.

In the extraordinary wet year, the water stress indexes of the four scenarios are between 0.5 and 1.0, which means that water resources are sufficient. In the normal year, the water stress indexes will rise continually in CDS and EPS, and it is always greater than 1.0 in EPS, while the water stress indexes will decline continually in WPS and the BDS, changing between 0.6 and 1.0. In the extraordinary dry year, the water stress indexes are only less than 1.0 in WPS after 2019.

Regardless of which development model is chosen, the water demand per ten thousand yuan GDP will eventually fall to around 20 $m^3$ in 2035. Therefore, reducing water demand only by slowing down economic growth cannot improve the efficiency of water use, and even result in inefficiency of water supply capacity. Zhangjiakou City should adopt a dynamic and efficient water-saving model that not only sustains regional socio-economic development but also protects ecological security in the whole Beijing-Tianjin-Hebei region.

# Appendix

**Table S1.** Variables and equations in the ZSD model.

| Variables | Units | Equations |
|---|---|---|
| ***Population subsystem*** | | |
| Total population | $10^4$ persons | INTEG (Population growth, 469) |
| Population growth | $10^4$ persons | Total population * Population natural growth rate |
| Rural population | $10^4$ persons | Total population * (1-Urbanization rate) |
| Urban population | $10^4$ persons | Total population* Urbanization rate |
| Urbanization rate | % | See Table 3 |
| Population nature growth rate | ‰ | 3.07 |
| Per capita water quota of urban residents | L/person/day | See Table 3 |
| Per capita water quota of rural residents | L/person/day | See Table 3 |
| Urban domestic water demand | $10^8$ $m^3$ | (Urban population*10000*Per capita water quota of urban residents*365/1000)/100000000 |
| Rural domestic water demand | $10^8$ $m^3$ | (Rural population*10000*Per capita water quota of rural residents*365/1000)/100000000 |
| Domestic water demand | $10^8$ $m^3$ | Urban domestic water demand + Rural domestic water demand |
| ***Economic subsystem*** | | |
| Industrial GDP | $10^8$ yuan | INTEG (Industrial GDP increment, 442) |
| Industrial GDP increment | $10^8$ yuan | Industrial GDP*Industrial growth rate |
| Industrial growth rate | % | See Table 3 |
| Per unit of industrial GDP water use | $m^3$ | See Table 3 |
| Industrial water demand | $10^8$ $m^3$ | (Industrial GDP*10000*Per unit of industrial GDP water use)/100000000 |
| Construction industry GDP | $10^8$ yuan | INTEG (Construction industry GDP, 105) |
| Construction industry GDP increment | $10^8$ yuan | Construction industry GDP*Construction industry growth rate |
| Construction industry growth rate | % | See Table 3 |
| Per unit of construction industry GDP water use | $m^3$ | With Lookup ( Time, ( [ ( 2015, 1) - ( 2035, 3 ) ], ( 2015, 2.3 ), ( 2035, 2 ) ) |
| Construction industry water demand | $10^8$ $m^3$ | (Construction industry GDP*10000*Per unit of construction industry GDP water use)/100000000 |
| Secondary industry GDP | $10^8$ yuan | Industrial GDP + Construction industry GDP |
| Secondary industry water demand | $10^8$ $m^3$ | Industrial water demand + Construction industry water demand |
| Tertiary industry GDP | $10^8$ yuan | INTEG (Tertiary industry GDP increment, 574) |
| Tertiary industry GDP increment | $10^8$ yuan | Tertiary industry GDP*Tertiary industry growth rate |
| Tertiary industry growth rate | % | See Table 3 |
| Per unit of tertiary industry GDP water use | $m^3$ | With Lookup ( Time, ( [ ( 2015, 1) - ( 2035, 3 ) ], ( 2015, 2.5 ), ( 2035, 2.2 ) ) |
| Tertiary industry water demand | $10^8$ $m^3$ | (Tertiary industry GDP*10000*Per unit of tertiary industry GDP water use)/100000000 |
| Urban public water demand | $10^8$ $m^3$ | Construction industry water demand + Tertiary industry water demand |
| Agricultural GDP | $10^8$ yuan | INTEG (Agricultural GDP increment, 244) |
| Agricultural GDP increment | $10^8$ yuan | Agricultural GDP*Agricultural growth rate |
| Agricultural growth rate | % | See Table 3 |
| Total GDP | $10^8$ yuan | Agricultural GDP + Secondary industry GDP + Tertiary industry GDP |
| Per capita GDP | yuan | Total GDP/Total population |
| Per unit of GDP water use | $m^3*10^{-4}*yuan^{-1}$ | Total water demand/Total population |
| ***Agricultural subsystem*** | | |
| Paddy field area | ha | INTAG (Paddy field reduction, 2707) |
| Paddy field reduction | ha | Paddy field area*Paddy field reduction rate |
| Paddy field reduction rate | % | See Table 3 |
| Irrigated land area | ha | INTAG(Irrigated land reduction, 178473) |
| Irrigated land reduction | ha | Irrigated land area*Irrigated land reduction rate |
| Irrigated land reduction rate | % | See Table 3 |
| Vegetable field area | ha | INTAG (Vegetable field reduction, 37533) |
| Vegetable field reduction | ha | Vegetable field area*Vegetable field reduction rate |
| Vegetable field reduction rate | % | See Table 3 |

| | | |
|---|---|---|
| Paddy field water quota | $m^3/ha$ | 5535 |
| Irrigated land water quota | $m^3/ha$ | See Table 3 |
| Vegetable field water quota | $m^3/ha$ | See Table 3 |
| Paddy field water demand | $10^8$ $m^3$ | Paddy field area*Paddy field water quota/100000000 |
| Irrigated land water demand | $10^8$ $m^3$ | Irrigated land area*Irrigated land water quota/100000000 |
| Vegetable field water demand | $10^8$ $m^3$ | Vegetable field area*Vegetable field water quota/100000000 |
| Total irrigation water demand | $10^8$ $m^3$ | Paddy field water demand + Irrigated land water demand + Vegetable field water demand |
| Pasture irrigation area | ha | 300 |
| Pasture water quota | $m^3/ha$ | 1785 |
| Pasture water demand | $10^8$ $m^3$ | Pasture irrigation area*10000*Pasture water quota/100000000 |
| Irrigation area of forest and fruit land | ha | 14520 |
| Forest and fruit land water quota | $m^3/ha$ | 1860 |
| Forest and fruit land water demand | $10^8$ $m^3$ | Irrigation area of Forest and fruit land *10000*Forest and fruit land water quota/1000000000 |
| Number of large livestock | $10^4$ head | See Table 3 |
| Large livestock water quota | L/head/day | 40 |
| Large livestock water demand | $10^8$ $m^3$ | (Number of large livestock*10000*Large livestock water quota per day*365/1000)/100000000 |
| Number of small livestock | $10^4$ head | See Table 3 |
| Small livestock water quota | L/head/day | 5 |
| Small livestock water demand | $10^8$ $m^3$ | (Number of small livestock*10000*Small livestock water quota per day*365/1000)/100000000 |
| Livestock water demand | $10^8$ $m^3$ | Large livestock water demand + Small livestock water demand |
| Fish pond area | ha | 80 |
| Fish pond water quota | $m^3/ha$ | 30,000 |
| Fish pond water demand | $10^8$ $m^3$ | Fish pond area*10000*Fish pond area/100000000 |
| Agricultural water demand | $10^8$ $m^3$ | Total irrigation water demand + Forest and fruit land water demand +Pasture water demand + Livestock water demand + Fish pond water demand |
| ***Water resources subsystem*** | | |
| Local water resources | $10^8$ $m^3$ | Extremely wet year (17.01)/Average climatic year (14.51)/Extremely wet year (11.42) |
| Inbound water resources | $10^8$ $m^3$ | time |
| Total water resources | $10^8$ $m^3$ | Local water resources + Inbound water resources |
| Outbound water resources | $10^8$ $m^3$ | time |
| Environmental flow coefficient | % | Extremely wet year (0.20)/Average climatic year (0.25)/Extremely wet year (0.30) |
| Environmental flow | $10^8$ $m^3$ | Total water resources*Environmental flow coefficient |
| Total available water supply | $10^8$ $m^3$ | Total water resources-Outbound water resources-Environmental flow +Wastewater reuse |
| Total water demand | $10^8$ $m^3$ | Agricultural water demand + Industrial water demand + Urban public water demand +Domestic water demand + Eco-environmental water demand |
| Eco-environmental water demand | $10^8$ $m^3$ | Per capita eco-environmental water demand*Total population*10000/100000000 |
| Per capita eco-environmental water demand | $m^3$ | 3.13 |
| Water stress index | – | Total water demand/Total available water supply |
| Urban domestic wastewater coefficient | – | 0.61 |
| Urban domestic wastewater | $10^8$ $m^3$ | Urban domestic water demand*Urban domestic wastewater coefficient |
| Tertiary industry wastewater coefficient | – | 0.45 |
| Tertiary industry wastewater | $10^8$ $m^3$ | Tertiary industry water demand*Tertiary industry wastewater coefficient |
| Construction industry wastewater coefficient | – | 0.46 |
| Construction industry wastewater | $10^8$ $m^3$ | Construction industry water demand*Construction industry wastewater coefficient |
| Industrial wastewater coefficient | – | 0.51 |

|  |  |  |
|---|---|---|
| Industrial wastewater | $10^8\,m^3$ | Tertiary industry water demand*Industrial wastewater coefficient |
| Total wastewater | $10^8\,m^3$ | Urban domestic wastewater +Tertiary industry wastewater +Construction industry wastewater + Industrial wastewater |
| Wastewater treatment rate | % | With Lookup (Time, ( [ ( 2015, 0 ) - ( 2035, 100 ) ], ( 2015, 91.3 ), ( 2020, 97 ), ( 2022, 100), ( 2035, 100) ) |
| Total wastewater treatment | $10^8\,m^3$ | Total wastewater*Wastewater treatment rate |
| Wastewater reuse rate | % | With Lookup (Time, ( [ ( 2015, 0) - ( 2035, 0.7 ) ], ( 2015, 0.25 ), ( 2020, 0.3), (2022, 0.35), (2025, 0.4), (2030, 0.55), (2035, 0.6) ) |
| Wastewater reuse | $10^8\,m^3$ | Total wastewater treatment*Wastewater reuse rate |

Note: “-” stands for dimensionless.

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# 5. Spatiotemporal supply-demand characteristics and economic benefits of crops water footprint

## 5.1 Problem and objectives

### 5.1.1 Research problem

There is a wealth of research that has focused extensively on the water footprint of a variety of crops, but three shortcomings are remained to illuminate. First, the blue water footprint received considerable attention, and many indicators were introduced to analyze it deeply (Cao et al., 2017; Cao et al., 2018; Cao et al., 2014; Hoekstra and Zhuo, 2017; Zhuo et al., 2016a; Zhuo et al., 2016b), while few indicators were used to analyze the characteristics of the green water footprint in detail, despite green water is the major contributor to crops water footprint (Chu et al., 2017; Wei et al., 2016). Secondly, most of the studies did not consider or mention whether the irrigation farmland is fully irrigated or not, resulting in the calculated water footprint higher than the actual water footprint, especially in arid areas. Although a few studies have taken this into account, using actual irrigation water as the blue water footprint, however, further using it as the blue water footprint requirement (BWFr) to measure the extent of blue water scarcity is unreasonable. It is obvious that the actual irrigation water consumption cannot represent the water requirement of crop growth, due to water shortage and the imperfect infrastructures during the period of crop growth. Thirdly, so far one of the most common indicators for measuring crop water footprint is the virtual water content per unit of yield (also known as water footprint per unit of yield, VWY) (Zeng et al., 2012), which is used to depict the water footprint production efficiency from food yields perspective. However, besides food yields, the economic benefits also play a very critical role for the government and farmers to decide whether to plant one crop or not (Ren et al., 2018). Therefore, it is vital to calculate virtual water content per unit of output value (VWV), which can represent the water footprint economic benefits. VWY and VWV can reflect the productivity of water footprint from different perspectives, and their relationship is also worthy of discussion.

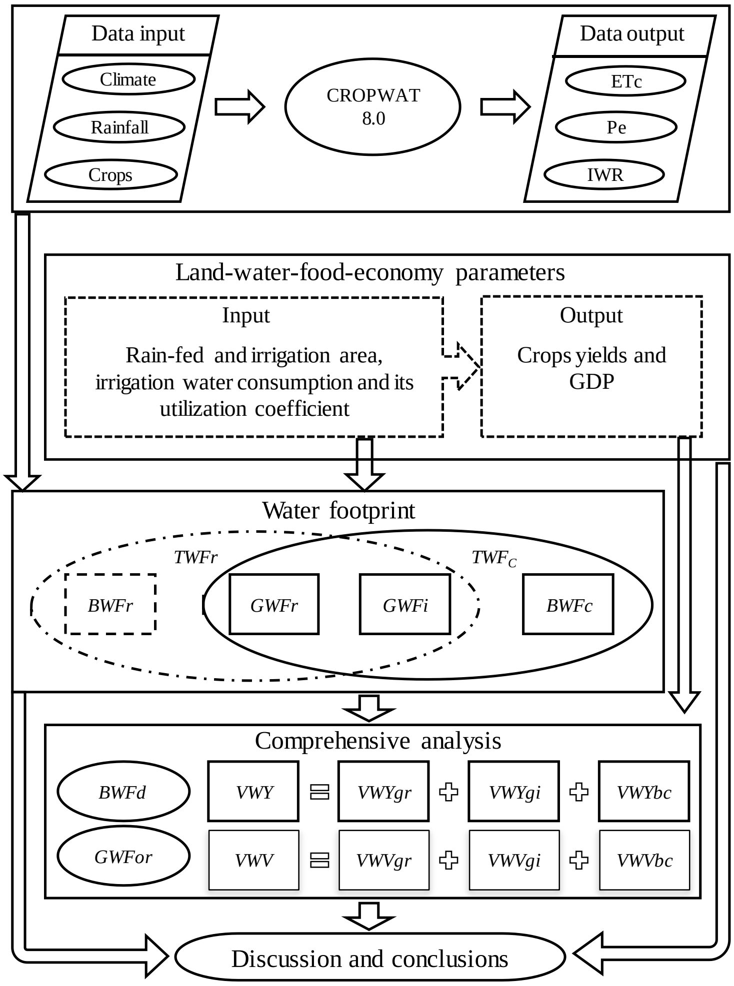
### 5.1.2 Research objectives

Zhangjiakou city, a semi-arid region with less than 400 $m^3$ water per capita, which is lower than the internationally recognized extreme water shortage standard (500 $m^3$), is located in the upstream of Beijing in northern China. The issue of water scarcity not only seriously restricts the local social and economic development but also poses a great threat to drinking water safety in the capital city of Beijing due to their close geographical relationship. The main research objectives of this study are as follows: (1) to estimate the water footprint requirement for the main crops with the help of CropWat 8.0, and identify its characteristics of spatial distribution and dynamic changing trends in Zhangjiakou City for 2005, 2010, and 2015. (2) to analyze the green water, blue water, and water footprint economic benefits using the three new indicators, i.e., green water footprint occupancy rate (GWFor), blue water footprint deficit (BWFd), and virtual water consumption per output value (VWV). (3) to enrich crop water footprint indicators and provide an alternative way for agricultural water conservation in Zhangjiakou city from the perspective of water footprint.

## 5.2 Methods and data sources

### 5.2.1 Methods

CropWat 8.0, developed by the Land and Water Development Division of the UN Food and Agriculture Organization (FAO), can be employed to calculate the water requirement of crop growth in every stage. Therefore, it was the first step to calculate the crop water footprint requirement in this study (Figure 5.1).



ETc: crop evapotranspiration; Pe: effective precipitation； IWR: irrigation water requirement; GDP: gross domestic product; TWFr: total water footprint requirement; TWFc: total water footprint consumption; BWFr: blue water footprint requirement; GWFr: rain-fed farmland green water footprint; GWFi: irrigation farmland green water footprint; BWFc: blue water footprint consumption; BWFd: blue water footprint deficit; GWFor: green water footprint occupancy rate; VWY: water footprint per unit of yield; VWYgr: rain-fed farmland green water footprint per unit of yield; VWYgi: irrigation farmland green water footprint per unit of yield; VWYbc: blue water footprint per unit of yield; VWV: water footprint per unit of GDP; VWVgr: rain-fed farmland green water footprint per unit of GDP; VWVgi: irrigation farmland green water footprint per unit of GDP; VWVbc: blue water footprint per unit of GDP.

Figure 5.1 Logic relationship of main variables and technical roadmap

#### 5.2.1.1 Water footprint

(1) Green water footprint

The amount of crop evaporation was calculated by CropWat 8.0 every 10 days, and the amount of green water evaporation every 10 days is equal to the minimum between the effective precipitation and the crop evapotranspiration. Effective precipitations were calculated using USDA SCS (United States Department of Agriculture Soil Conservation Service) method by default in CropWat 8.0, which are different among counties. The total green water footprint (GWFt) is equal to the sum of the irrigation farmland green water footprint (GWFi) and the rain-fed farmland green water footprint (GWFr).

$$ET_g = \sum min(ET_c, P_e) \tag{5-1}$$

$$GWF_i = 10A_i \times ET_g \tag{5-2}$$

$$GWF_r = 10A_r \times ET_g \tag{5-3}$$

$$GWFt = GWF_i + GWF_r \tag{5-4}$$

where $ET_g$ (mm) is the 10-day total green water evaporation; $ET_c$ (mm) and $P_e$ (mm) are the 10-day crop water evaporation and effective precipitation, respectively; $A_i$ (ha) and $A_r$ (ha) are the crop planting area of irrigation and rain-fed farmland, respectively; 10 is the coefficient from mm to $m^3$/ha.

(2) Blue water footprint

Currently, there are two main methods for calculating the BWF of irrigation farmland. The first one is to multiply the amount of blue water evaporation requirement calculated by CropWat 8.0 by the irrigated area, since crops are often cannot fully irrigated, especially in arid areas, so actually, it is the blue water footprint requirement (BWFr). The second one is to use the actual irrigation water consumption as the blue water footprint, but the irrigation water is not all consumed by crops, due to inevitable factors such as evaporation and infiltration, causing waste of water resources during the irrigation process. In other words, it is not the real blue water footprint consumption (BWFc) of crops. Based on this, BWFr and BWFc will be calculated, analyzed, and discussed separately in this study.

$$ET_b = \sum max(0,\ ET_c - P_e) \tag{5-5}$$

$$BWF_r = 10A_r \times ET_b \tag{5-6}$$

where $ET_b$ (mm) is the total blue water evaporation;

$$BWF_c = W_i \times \eta \tag{5-7}$$

Where $W_i$ is the actual irrigation water consumption, and η is the effective utilization coefficient of irrigation water.

(3) Total water footprint

Correspondingly, the total water footprint includes the total water footprint requirement (TWFr) and the total water footprint consumption (TWFc).

$$TWF_r = BWF_r + GWF_i + GWF_r \tag{5-8}$$

$$TWF_c = BWF_c + GWF_i + GWF_r \tag{5-9}$$

#### 5.2.1.2 GWF occupancy rate and BWF deficit

(1) GWF occupancy rate

From the perspective of ecological hydrology, Sun et al. (2010) proposed the green water occupation index, which considered that the total amount of green water is equal to the total amount of precipitation minus the amount of blue water (the total amount of water resources) in the whole region. However, the green water that can be used by crops is only part of the precipitation that falls on the planting area. Therefore, this study proposed a formula for calculating the green water footprint occupancy rate based on the planting area.

$$GWFor = \frac{\sum GWF}{10P\sum A} \times 100\% \tag{5-10}$$

Where GWFor is GWF occupancy rate, P (mm) is precipitation, ∑GWF and ∑A are the sum of the green water footprint and planting area of crops, respectively.

(2) Blue water footprint deficit

At present, studies on the blue water footprint only calculate the requirement or consumption of blue water, which cannot reflect the extent of blue water scarcity. Therefore, drawing on the concept of ecological footprint deficit, we propose the blue water footprint deficit ($BWF_d$). It will reflect the blue water shortage when the irrigation farmland is fully irrigated.

$$BWF_d = \frac{(BWF_r - BWF_c)}{\eta} \tag{5-11}$$

When $BWF_d$ is less than zero, it represents a blue water footprint surplus. The larger the $BWF_d$, the bigger the blue water shortage.

5.2.1.3 Virtual water content

(1) Virtual water content per unit of yield

The virtual water content per unit of yield is also called water footprint per unit of yield (VWY). It consists of three parts: the blue water footprint per unit of yield (VWYbc), the irrigation farmland green water footprint per unit of yield (VWYgi), and the rain-fed farmland green water footprint per unit of yield (VWYgr).

$$VWY_{bc} = \frac{BWF_c}{Y} \tag{5-12}$$

$$VWY_{gi} = \frac{GWF_i}{Y} \tag{5-13}$$

$$VWY_{gr} = \frac{GWF_r}{Y} \tag{5-14}$$

$$VWY = VWY_{bc} + VWY_{gi} + VWY_{gr} \tag{5-15}$$

where Y is the crop yield.

(2) Virtual water consumption per output value

For comparing the characteristics of the virtual water consumption per output value at the same price, it is necessary to eliminate the impact of price changes on the gross domestic product (GDP) of crops.

a. GDP comparable calculation

Based on 2005, the total GDP of crops in 2010 and 2015 were revised. By calculation, when 2005=1, 2010 and 2015 were 1.56 and 2.04 respectively.

$$GDP_{2010} = GDP_{2005} \times 1.56 \tag{5-16}$$

$$GDP_{2015} = GDP_{2005} \times 2.04 \tag{5-17}$$

where $GDP_{2005}$ is the actual GDP of crops in 2005.

b. Virtual water consumption per unit of GDP

The virtual water consumption per unit of GDP (VWV), equals to the water footprint divided by GDP, and also consists of three parts, will reflect the economic benefits of the water footprint.

$$VWV_{bc} = \frac{BWF_c}{GDP} \tag{5-18}$$

$$VWV_{gi} = \frac{GWF_i}{GDP} \tag{5-19}$$

$$VWV_{gr} = \frac{GWF_r}{GDP} \tag{5-20}$$

$$VWV = VWV_{bc} + VWV_{gi} + VWV_{gr} \tag{5-21}$$

where VWVbc is the blue water footprint per unit of GDP, VWVgi is the irrigation farmland green water footprint per unit of GDP, and VWVgr is the rain-fed farmland green water footprint per unit of GDP.

### 5.2.2 Data sources

The meteorological parameters required for the Cropwat 8.0 model include relative humidity, wind speed, and sunshine hours were obtained from *Zhangjiakou City Economic Yearbooks* (2006, 2011, 2016), which originally collected from 14 local weather stations. The maximum and minimum temperatures of every county were obtained from this weather website (http://www.tianqi.com/qiwen/city_zhangjiakou/). The parameters of crops, such as sowing and harvesting date, root depth, crop coefficient, growth period, crop height, were modified in accordance with the actual situation of Zhangjiakou city based on CropWat 8.0 default values and the FAO Irrigation and drainage paper 56 "*Crop evapotranspiration – Guidelines for computing crop water requirements*" (Allan et al., 1998).

The data, e.g., the planting area of crops in irrigation farmland and rain-fed farmland, yields, and the regional Gross Domestic Product, were all obtained from *the Zhangjiakou Economic Yearbooks* (2006, 2011, 2016). The data of actual water consumption of irrigation and utilization efficiency were obtained from the *Zhangjiakou City Water Resources Bulletin* (2006, 2011, 2016) and related government reports.

## 5.3 Results

### 5.3.1 Distribution of water footprint requirement

As shown in Figure 5.2, in 2005-2015, the total water footprint requirement of crops in Zhangjiakou City increased from 1.671 billion m$^3$ to 1.852 billion m$^3$, with an average annual growth rate of 1.03%. The water footprint requirement of irrigation farmland increased by 0.232 billion m$^3$, of which the blue water footprint requirement (BWFr) increased from 0.526 billion m$^3$ to 0.661 billion m$^3$, and the green water footprint requirement (GWFi) increased from 0.290 billion m$^3$ to 0.387 billion m$^3$. The water footprint requirement of rain-fed farmland (GWFr) decreased from 0.854 billion m$^3$ to 0.803 billion m$^3$. As a result, the water footprint requirement of irrigation farmland increased from 49% to 57%, and the water footprint of rain-fed farmland decreased from 51% to 43%.

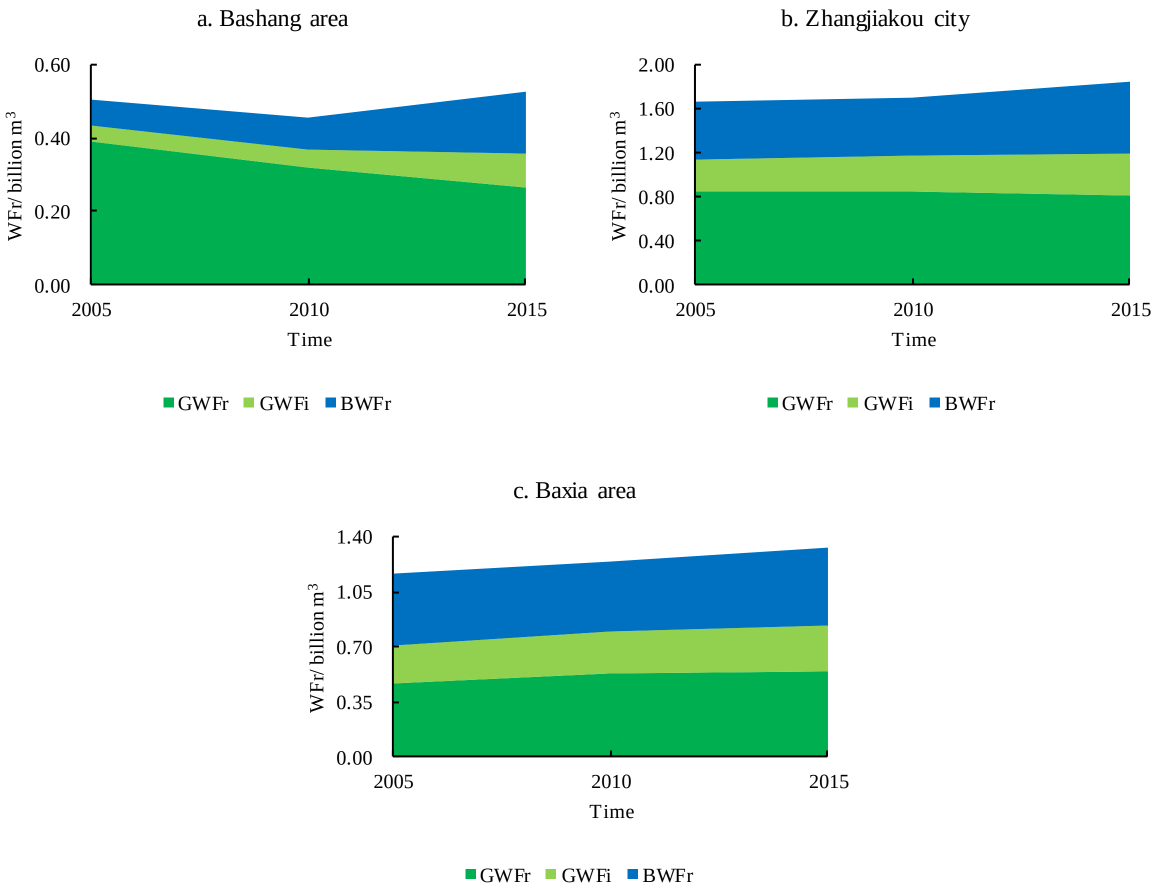


Figure 5.2 Total water footprint requirement of crops in 2005-2015

#### 5.3.1.1 Spatial patterns of water footprint requirement

In general, the relationships between water footprint requirement and altitude were negatively correlated (Figure 5.3). That is, the water footprint requirement of higher altitude counties was lower than that of lower altitude counties, and the gap between them was expanding. During the study period, the average water footprint requirement per country in the Bashang area increased from 0.101 billion $m^3$ to 0.105 billion $m^3$ (Figure 5.2a), while it increased from 0.130 billion $m^3$ to 0.147 billion $m^3$ in the Baxia area (Figure 5.2c). Among them, the water footprint requirement of Chongli County, Shangyi County, Wanquan County, and Chicheng County decreased, and other counties increased. In 2015, the county with the highest water footprint requirement was Zhuolu County (0.205 billion $m^3$), with a contribution rate of 11%; the county with the lowest water footprint requirement was Chongli County (0.041 billion $m^3$), with a contribution rate of 2%.

In terms of the source of water footprint, the contribution rate of water footprint requirement from rain-fed farmland positively correlated with altitude. That is, in general, the higher the altitude, the greater the proportion of water footprint requirement from rain-fed farmland in this area; the proportion of water footprint requirement from irrigation farmland is exactly the opposite. But this feature was gradually weakening (Figure 5.3). From 2005 to 2015, the proportion of WFr from rain-fed farmland decreased from 78% to 51% in the Bashang area, while it remained at 40%-43% in the Baxia area. In 2015, the three counties with the highest proportion of water footprint requirement from rain-fed farmland were Chicheng County (73%), Shangyi County (72%) and Wuyuan County (63%); the three counties with the highest proportion of water footprint requirement from irrigation farmland were Wanquan County (79%), municipal districts (77%) and Zhangbei County (71%).

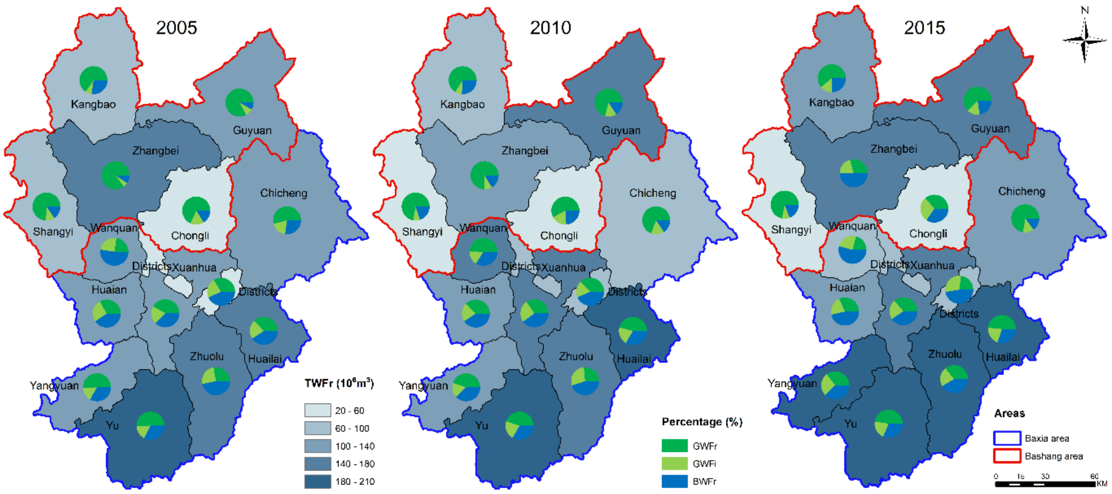


Figure 5.3 Spatial distribution of water footprint requirement of crops in 2005-2015

### 5.3.1.2 Water footprint requirement of different crops

During the study period, the water footprint requirement of beans and vegetables in Zhangjiakou city decreased from 0.133 billion m$^3$ and 0.134 billion m$^3$ to 0.079 billion m$^3$ and 0.095 billion m$^3$, respectively. It was increasing in other crops, but the difference in growth rates was significant. The water footprint requirement of potatoes had the largest increase of 47%, from 0.227 billion m$^3$ to 0.333 billion m$^3$, while the water footprint requirement of oil crops had the smallest increase of 8%, from 0.121 billion m$^3$ to 0.131 billion m$^3$.

Due to the large difference of the planted areas, the contribution rates of water footprint requirements were very different in crops, especially between the Bashang area and Baxia area (Figure 5.4 and Figure 5.5). In the Bashang area, the contribution rate of potatoes increased from 25% to 44%, while vegetables and beans decreased from 18% and 11% to 9% and 5%, respectively, and fruits was the smallest, only accounting for 1%-3%. In the Baxia area, the contribution rate of cereals was always the largest, accounting for 62%-66%, while vegetables was the smallest, accounting for 3%-4%.

Regarding the blue water footprint (BWFr), in the Bashang area, the contribution rate of vegetables dramatically decreased from 70% to 10%, and potatoes and cereals increased from 5% and 12% to 25% and 40%, respectively. In the Baxia area, the contribution rates of cereals had been the largest, accounting for 68%-73%, while other crops were stable.

Regarding the total green water footprint (GWFt), in the Bashang area, the contribution rate of cereals decreased from 34% to 29%, and potatoes increased from 28% to 42%. In the

Baxia area, the contribution rate of cereals had also been the largest as BWFt, maintaining at 58%-63%, followed by fruits, maintaining at around 20%.

According to the above analysis, the contribution rates of cereals BWFr and vegetables BWFr were higher than those of GWFt, which means that these two types of crops needed more blue water (irrigation water) than green water. The contribution rates of other crops BWFr were less than the contribution rate of GWFt, which means that these crops were more dependent on green water (rainwater) to growth.

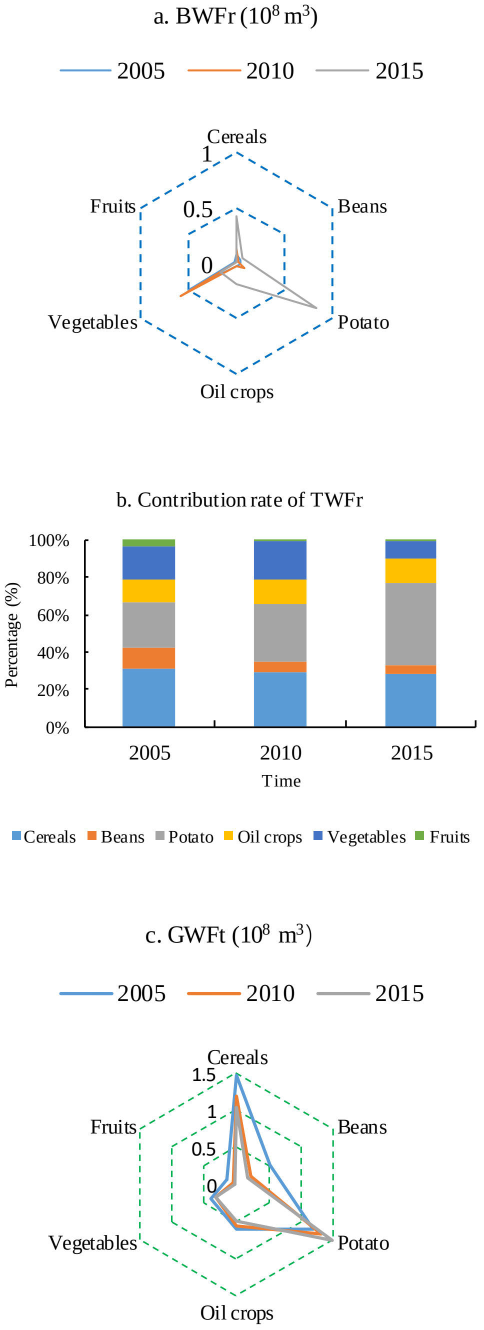
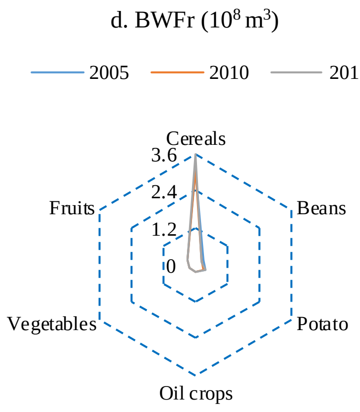
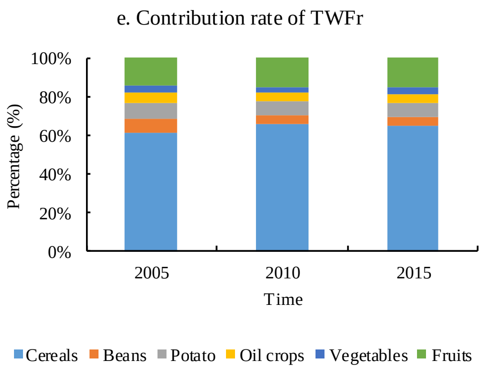


Figure 5.4 Total water footprint requirement and contribution rate in the Bashang area





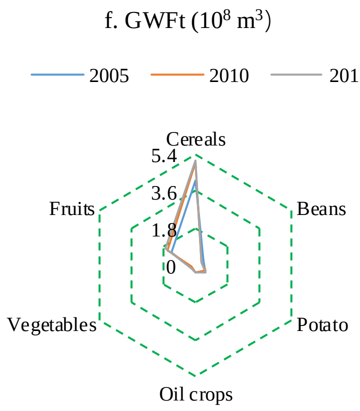


Figure 5.5 Total water footprint requirement and contribution rate in the Baxia area

### 5.3.2 Supply-demand relationships of the water footprint

#### 5.3.2.1 Green water footprint occupancy

In 2005-2015, the Green water footprint occupancy rate in Zhangjiakou city was 48%-60% (Figure 5.6). Among them, it was 43%-49% in the counties of the Bashang area, with an average of 44%, while it was 51%-59% in the counties of the Baxia area, with an average of 54%. Therefore, in general, the green water footprint occupancy in the Bashang area was lower than that in the Baxia area. In terms of months, as shown in Figure 5.7, it was zero from January to

March and from November to December, since the growth periods of main crops were between April and October. The green water footprint occupancy rate was the highest from May to August, with a multi-year average of 58%-83%; and it was 20%, 15%, and less than 1% in April, September, and October, respectively. In addition, due to differences in climate and the planting area of crops, the green water footprint occupancy rate in the Bashang area from May to June was higher than in the Baxia area, and vice versa in other months.

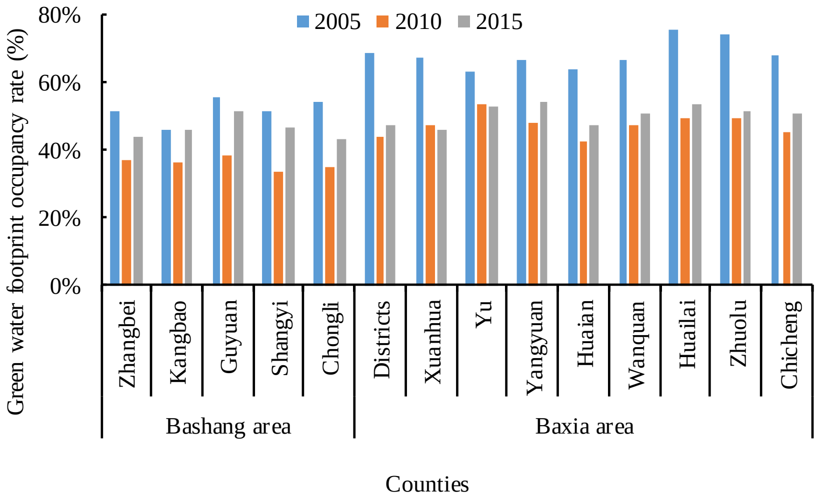


Figure 5.6 Green water footprint occupancy rate in counties

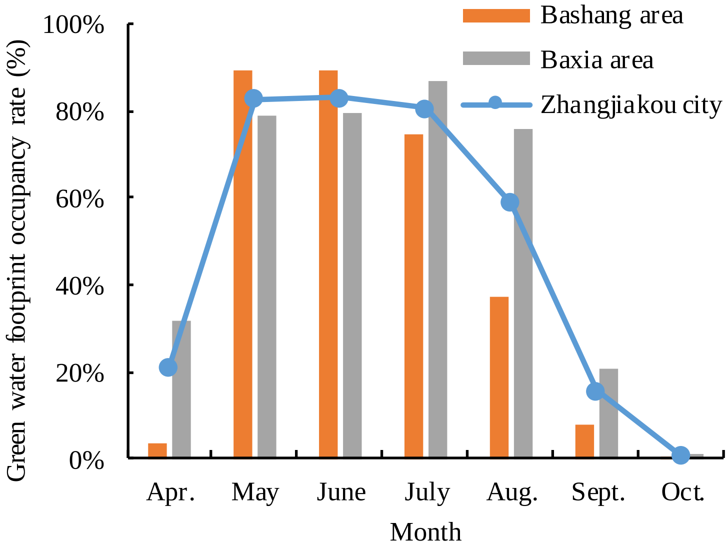


Figure 5.7 Green water footprint occupancy rate in months

#### 5.3.2.2 Blue water footprint deficit

The blue water footprint deficit of Zhangjiakou city decreased from 0.544 billion $m^3$ in 2005 to 0.480 billion $m^3$ in 2010 due to the improvement of irrigation water efficiency. With the rapid expansion of the irrigated area, however, the improvement of water use efficiency was not enough to offset the increase of water demand due to irrigation farmland expanding after 2010, resulting the blue water footprint deficit increased to 0.612 billion m$^3$ in 2015 and the situation of blue water shortage has become more severe.

At the level of counties (Figure 5.8), the blue water footprint deficits of counties in the Bashang area were generally lower than that of counties in the Baxia area. Some counties in the Bashang area were even in the state of blue water surplus before 2015, while the counties of the Baxia area had always been in the state of blue water deficit. It was the largest in Yangyuan County (located in Baxia area), which increased from 0.088 billion m$^3$ to 0.116 billion m$^3$. It was the smallest in Shangyi County (located in the Bashang area), which decreased from 0.08 billion m$^3$ to 0.04 billion m$^3$.

In terms of crops (Figure 5.9), the blue water footprint of cereals, beans, and fruits decreased, while it increased in potatoes, oil crops, and vegetables. Among them, cereals were the largest, with an average annual blue water deficit of 0.363 billion m$^3$, while vegetables were the smallest, even in the state of blue water surplus in 2005 and 2010, with 0.06 billion m$^3$ in 2015.

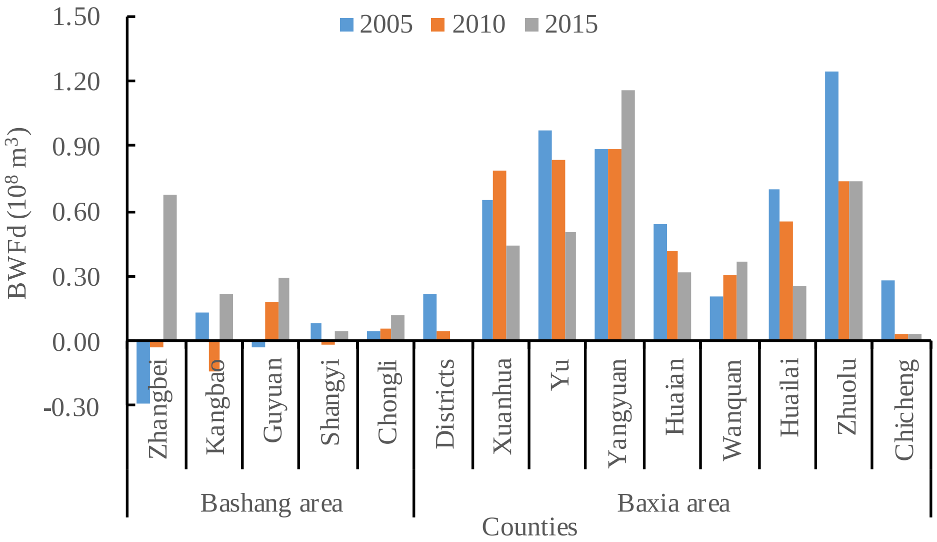


Figure 5.8 Blue water footprint deficit in counties

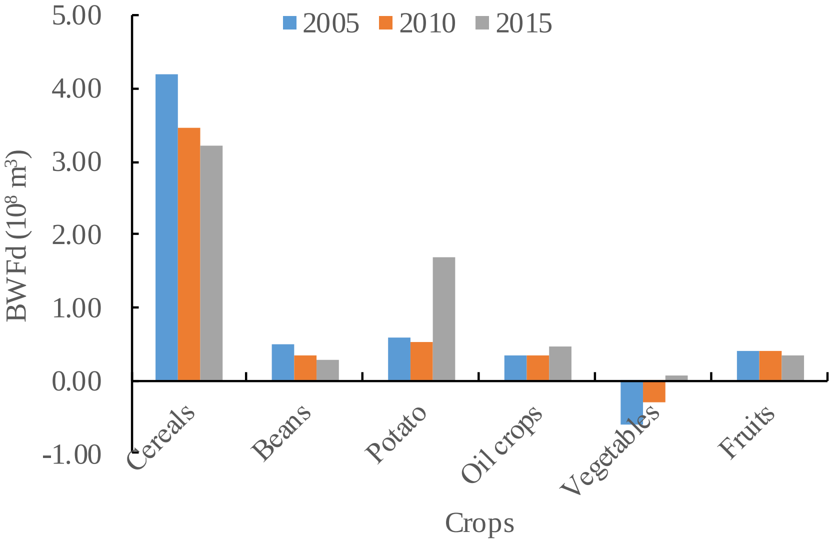


Figure 5.9 Blue water footprint deficit of crops

### 5.3.3 Water footprint productivity

#### 5.3.3.1 Virtual water content per unit of yield

As shown in Figure 5.10, the virtual water content per unit of yield (VWY) decreased from 0.331 $m^3$/kg in 2005 to 0.195 $m^3$/kg in 2015 in Zhangjiakou city, of which green water comes from rain-fed farmland (VWYgr) decreased from 0.199 $m^3$/kg to 0.103 $m^3$/kg, green water comes from irrigation farmland (VWYgi) decreased from 0.068 $m^3$/kg to 0.050 $m^3$/kg, and blue water (VWYbc) decreased from 0.065 $m^3$/kg to 0.043 $m^3$/kg. As a result, the proportion of green water decreased from 80% to 78%, and the proportion of blue water increased from 20% to 22%. In the Bashang area, the virtual water content decreased from 0.205 $m^3$/kg to 0.091 $m^3$/kg, of which the proportion of VWYgr decreased from 77% to 64%, the proportion of VWYgi increased from 8% to 21%, and the proportion of VWYbc remained at around 15%. In the Baxia area, the virtual water content decreased from 0.505 $m^3$/kg to 0.393 $m^3$/kg, of which the proportion of VWYgr decreased from 51% to 43%, the proportion of VWYgi decreased from 27% to 24%, and the proportion of VWYbc increased from 22% to 34%. The virtual water contents of Yangyuan County and Kangbao County were the highest (0.89 $m^3$/kg) and lowest (0.06 $m^3$/kg) in 2015, respectively.

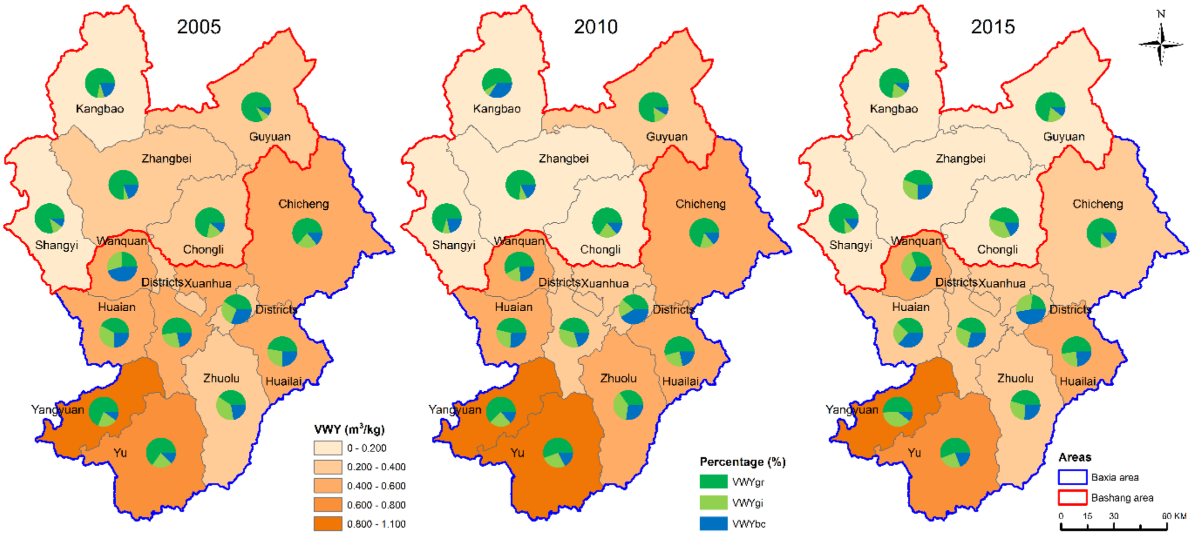


Figure 5.10 Spatial distribution and structure of virtual water content per unit of yield

In terms of corps, as shown in Figure 5.11, during the study period, the multi-year average of virtual water contents from high to low were beans (2.40 $m^3$/kg), oil (2.38 $m^3$/kg), cereals (0.82 $m^3$/kg), potatoes (0.78 $m^3$/kg), fruits (0.46 $m^3$/kg), and vegetables (0.04 $m^3$/kg). Regarding changing trends, the virtual water content of all crops decreased, among them, the potatoes decreased from 1.36 $m^3$/kg to 0.78 $m^3$/kg, with the largest decrease of 91%, while the cereals decreased from 0.892 $m^3$/kg to 0.807 $m^3$/kg, with the smallest decrease of 10%. In terms of blue water content, the VWYbc of vegetables and fruits decreased, while VWYbc of other crops increased. The proportion of VWYbc in vegetables had been the largest, although it decreased from 58% to 38%; the proportion of VWYbc in fruits had been the smallest, it also decreased from 7% to 5%. In addition, the average VWYbc of each crop in the Bashang area was lower than that in the Baxia area. Apart from vegetables, the proportion of VWYbc in the Bashang area was only 7%, while it was 26% in the Baxia area.

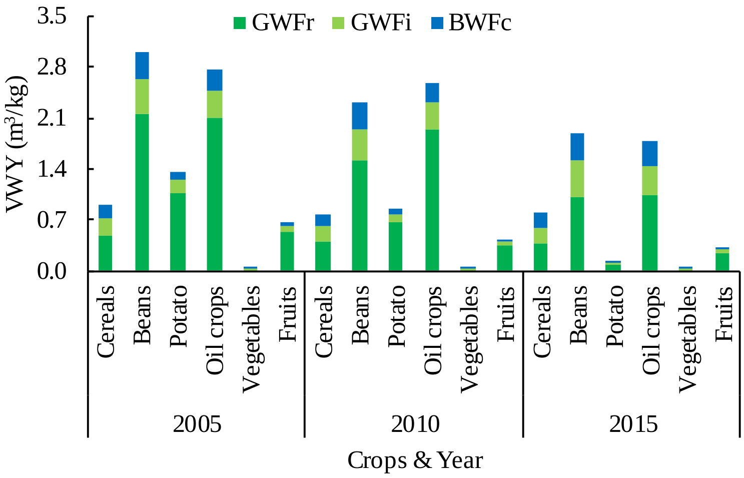


Figure 5.11 Virtual water content per unit of yield in different crops

#### 5.3.3.2 Water footprint consumption per output value

The water footprint consumption per output value (VWV) of Zhangjiakou city dropped from 3,380 $m^3/10^4$ yuan in 2005 to 2,183 $m^3/10^4$ yuan in 2010 and then increased to 2,344 $m^3/10^4$ yuan in 2015, which was different from the virtual water content per unit of yield (continuous decline). The contribution rate of green water decreased from 80% to 78%, and the contribution of blue water increased from 20% to 22%, which was the same as the virtual water content per unit of yield. The VWV decreased from 2,811 $m^3/10^4$ yuan to 1,394 $m^3/10^4$ yuan in the Bashang area, with a decrease of 50%, while it decreased from 3,811 $m^3/10^4$ yuan to 3,164 $m^3/10^4$ yuan in the Baxia area, with a decrease of only 17%. Chongli County had the largest decline of 65%, decreased from 3062 $m^3/10^4$ yuan to 2,004 $m^3/10^4$ yuan; Municipal districts had the smallest decline, decreased from 2,197 $m^3/10^4$ Yuan to 2,155 $m^3/10^4$ Yuan, and only dropped 2%. However, not every county's VWV declined. The VWV of Wanquan County and Yangyuan County increased from 4,148 $m^3/10^4$ yuan and 6,350 $m^3/10^4$ yuan to 4306 $m^3/10^4$ yuan and 8382 $m^3/10^4$ yuan, respectively.

In terms of spatial differences in contribution rate (Figure 5.12), in the Bashang area, the proportion of VWVgr decreased from 77% to 64%, the proportion of VWVgi increased from 8% to 21%, and the proportion of VWVbc remained stable at around 15%. In the Baxia area, the proportion of VWVgr decreased from 51% to 49%, the proportion of VWVgi remained stable at around 27%, and the proportion of VWVbc increased from 22% to 24%. Therefore, in general, the total green water content was relatively stable, but the proportion of GWFr and GWFi had changed greatly, showing that GWFr decreased and GWFi increased.

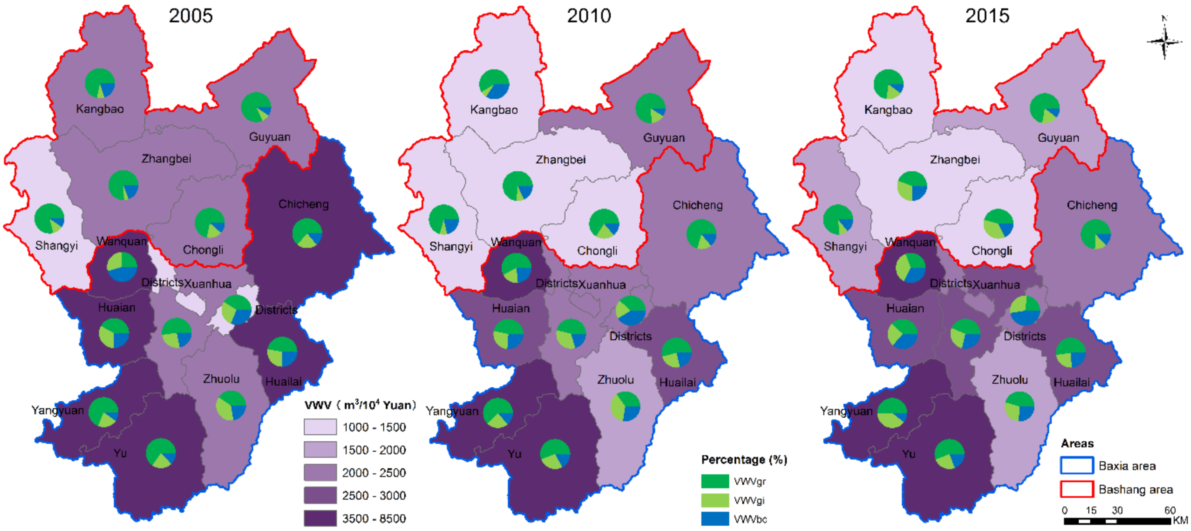


Figure 5.12 Spatial distribution and structure of virtual water content per unit of GDP

As shown in Figure 5.13, in 2005-2015, the VWV of cereals, beans, and oil crops decreased first and then increased, while the VWV of potatoes, vegetables, and fruits decreased continuously. Multi-year average values of VWV from high to low were beans (8,697 $m^3/10^4$ yuan), oil crops (8,391 $m^3/10^4$ yuan), cereals (5,590 $m^3/10^4$ yuan), potatoes (3,062 $m^3/10^4$ yuan), fruits (2,356 $m^3/10^4$ yuan) and vegetables (540 $m^3/10^4$ yuan). In addition, in 2005, only the VWV of potatoes in the Bashang area was lower than that in the Baxia area, while in addition to potatoes, there were beans, oil crops, and vegetables in 2015. In terms of blue water and green water proportion, the proportion of blue water was the highest (53%) in vegetables, while it was the lowest (6%) in fruits.

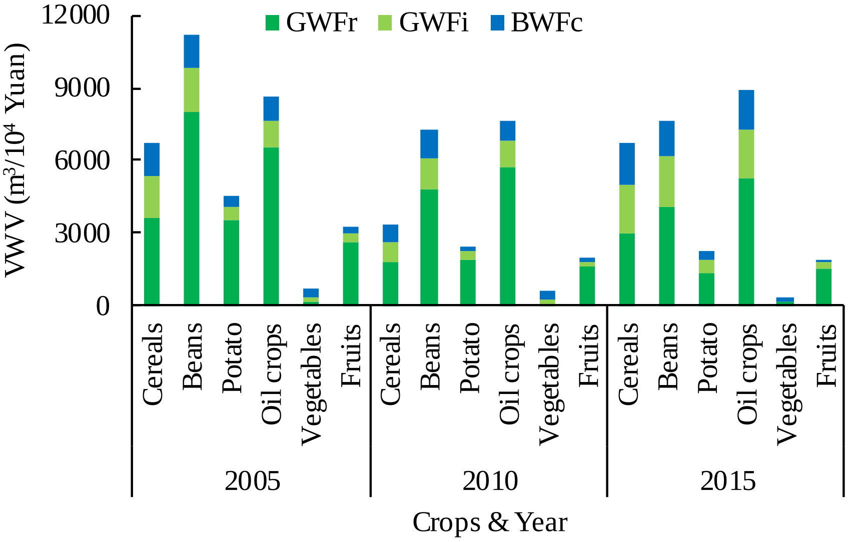


Figure 5.13 Virtual water content per unit of GDP in different crops

## 5.4 Discussion

### 5.4.1 Differences between water footprint requirement and consumption

The CropWat 8.0 is developed for estimating the amount of water evaporation (water requirement) of crops at each growth stage under local climatic conditions, e.g., soil temperature and sunshine hours, and for guiding agricultural irrigation. However, due to water shortage and imperfect water supply infrastructures, crops cannot always be fully irrigated, especially in arid and semi-arid regions like Zhangjiakou. Therefore, in this study, to distinguish it from the actual consumption of crop water footprint, we propose the concept of water footprint requirement. Since the difference between the two comes from whether the crops are fully irrigated, this study further proposes the concept of blue water footprint deficit (BWFd).

In Zhangjiakou City, the main crops planting area increased from 544,527 ha in 2005 to 565,010 ha in 2015, of which the irrigation area increased from 141,560 ha to 182,933 ha. There is no doubt that this process would inevitably lead to an increase of water requirement for crops, which is confirmed by our results that it increased from 1.671 billion $m^3$ to 1.852 billion $m^3$. In addition, 20 890 ha of rain-fed farmland was converted to irrigation farmland over the study period, resulting in blue water footprint deficit increased from 0.544 billion $m^3$ to 0.612 billion $m^3$. Therefore, controlling the expansion of farmland, or even returning farmland to forests, is the primary task of Zhangjiakou City to reduce the water demand of crops. At the same time, it is necessary to restrict the conversion of dry land into paddy fields and irrigated land. In terms of spatial differences, the irrigation area increased from 30,202 ha to 55,320 ha in the Bashang area, while it increased from 111,359 ha to 127,612 ha in the Baxia area. That is, the irrigation area in the Baxia area was always much larger than that in the Bashang area, so the $BWF_d$ of counties in the Baxia area was higher than that in the Bashang area. That is, the Baxia area is the key area for agricultural water saving in Zhangjiakou City. It is vital to vigorously increase the irrigation water utilization rate by increasing investment in irrigation facilities, improving management level, and changing irrigation methods. Meanwhile, it is also necessary to slow down the growth rate of irrigated farmland in the Bashang area.

### 5.4.2 The contribution rate of blue water and green water

In Zhangjiakou City, although the virtual water content per unit of yield (VWY) decreased from 0.331 $m^3$/kg in 2005 to 0.195 $m^3$/kg in 2015, the contribution rate of blue water and green water has always remained about 20% and 80%, respectively. This is because, from 2005 to 2015, the irrigation area of Zhangjiakou City was only 26% -32%, that is, most crops were still growing in rain-fed farmland, and only consumed green water. Therefore, the contribution rate of green water footprint of crops was always much higher than that of blue water footprint, and how to make full use of green water resources is of vital importance to the sustainable development of agriculture.

In Zhangjiakou City, green water occupancy rates were only 48%-60% and showed a significant spatial and temporal difference during the study period. Because the precipitation from May to September accounts for 80% of the annual total precipitation, and the temperature in these months is also the most suitable time for crop growth, so the green water occupancy rates were higher than other months. In addition, due to the higher altitude and the lower accumulated temperature, the green water occupancy rate was higher than 70% from May to July in the Bashang area, while from May to August in the Baxia area. Therefore, the possibility of improving the utilization of green water from May to July is limited, because evaporation and part of precipitation will inevitably form runoff. However, it might be suitable for some crops to grow in August and September, especially in the Bashang area, because the average temperature in these two months is 20 and 15 degrees, respectively. The green water occupancy rate is introduced in this study will provide a novel way of thinking for the research of the green water utilization.

### 5.4.3 Food productivity and economic benefits of water footprint

Virtual water content per unit of yield (VWY) and water footprint consumption per output value (VWV) can be considered as food productivity and economic productivity of water footprint, respectively. The VWY has been analyzed in almost all existing studies, but the VWV was largely neglected. There are three possible reasons. Firstly, the development of the water footprint concept derived from virtual water, and the virtual water was proposed to explore the characteristics of the flow of water embedded in products in international trade. Secondly, the analysis of the water footprint from the perspective of food would be easy to make comparisons between countries and regions. Thirdly, with the explosive growth of the global population, food security issues are receiving more and more attention, and the accessibility of freshwater is the biggest challenge for food production.

However, the economic benefits of crop water footprint should get more attention because higher food productivity does not necessarily mean higher economic benefits. Economic benefits are always changing due to unstable crop prices, the cost of labor, and other production factors. Based on the results, the relationship between VWY and VWV in Zhangjiakou city can be summarized into three types: (a) Mutual match among crops, which means when the VWY of one crop is lower (higher), the VWV is also lower (higher), such as fruits and oils. (b) Mismatch among crops. In 2005, the VWY of potatoes was higher than cereals, but the VWV of potatoes was lower than that of cereals. Therefore, whether to plant potatoes or vegetables depends on the priority of food production and economic benefits. (c) Mismatch among regions, that is, the VWY and VWV of the same crop did not match in different regions. In 2005, VWY of vegetables in the Bashang area (0.045 $m^3$/kg) was lower than that in the Baxia area (0.054 $m^3$/kg), while VWV of vegetables in the Bashang area (792 $m^3/10^4$ yuan) was higher than that in Baxia area (591 $m^3/10^4$ yuan). That means, for vegetables, water footprint food production efficiency in the Bashang area was higher than that in the Baxia area, but the water footprint economic benefits were reversed. Therefore, it is clear that significantly different policies could be made from two perspectives (VWY or VWV).

### 5.5 Conclusions

In this study, with the help of CropWat 8.0, the water footprint and its spatiotemporal characteristics and variations of the main crops in Zhangjiakou city for 2005, 2010, and 2015 were estimated. Furthermore, an in-depth analysis of blue water, green water, and food productivity and economic benefits of water footprint was further analyzed by introducing three new indicators, i.e., green water footprint occupancy rate, blue water footprint deficit, and virtual water consumption per GDP. It is expected to make a contribution to sustainable water management for Zhangjiakou city ad broaden crop water footprint research. The main results are as follows:

(1) The results of this study agree with previous studies in terms of the importance of green water in crop production. The total water footprint requirement of Zhangjiakou city increased from 1.671 billion $m^3$ in 2005 to 1.852 billion $m^3$ in 2015, of which the ratio of green water to blue water was around two, which means green water plays a greater role than blue water. Besides, the total water footprint requirement in the counties of the mountainous Bashang area is lower than those of the Baxia area, and the gap between them was further expanding.

(2) Cereals, as the main staple food, had the largest water footprint requirement in Zhangjiakou city, accounting for 52%-55%. Meanwhile, the water footprint requirement of potatoes increased the fastest, with an increase of 47%, which is a result of large-scale planting in recent years. The crop with the highest proportion of blue water was vegetables, but it declined from 55% to 40% gradually, while the crop with the highest proportion of green water was fruits, accounting for 83%-85%.

(3) By introducing the green water footprint occupancy rate, we found there were significant differences between the Bashang area and the Baxia area in terms of green water use. The green water footprint occupancy rate in counties of the Bashang area was 43%-49%, with an average of 44%, while it was 51%-59% in counties of the Baxia area, with an average of 54%. The highest utilization rates of green water in a year was from May to August, which were 58%-83%. In terms of blue water footprint deficit, it dropped from 0.544 billion $m^3$ in 2005 to 0.480 billion $m^3$ in 2010 and then increased to 0.612 billion $m^3$ in 2015. In general, it was lower in the Bashang area than in the Baxia area.

(4) From 2005 to 2015, the virtual water content per unit of yield dropped from 0.331 $m^3$/kg to 0.195 $m^3$/kg continuously, while the virtual water consumption per output value dropped from 3,380 $m^3/10^4$ yuan to 2,183 $m^3/10^4$ yuan and then rose to 2,344 $m^3/10^4$ yuan. In other words, the changing trends of water footprint food productivity and water footprint economic benefits were not always the same. The relationships between them in Zhangjiakou city were mainly in three forms: mutual match among crops, mismatch among crops, and mismatch among counties. Therefore, it is vital to consider them simultaneously when developing policies from the perspective of water footprint.

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# 6. Agricultural water footprint and socioeconomic matching evaluation from the perspective of ecological zones

## 6.1 Problem and objectives

### 6.1.1 Research problem

In the past two decades, research on agricultural water footprint has experienced changes from global and national scales (Bulsink et al., 2010; Chapagain et al., 2006; Hoekstra and Hung, 2002; Huang et al., 2019; Mekonnen and Hoekstra, 2018) to regional and watershed scales (Chu et al., 2017; Zeng et al., 2012; Zhuo et al., 2014). Most studies focused too much on virtual water transfer, that is, reducing the consumption of local water resources by importing agricultural products (Zhang et al., 2017). However, in the context of food security also facing severe challenges globally, it is impossible for all regions to solve water scarcity through food imports. Especially in areas where agricultural production plays a great role in economic growth, and rural residents' income is heavily dependent on agriculture (Su et al., 2020). The optimization of water resources management should be closely integrated with the resources and environmental conditions of regional natural ecosystems and implement targeted strategies that are suitable for regional characteristics, this is why the ecological function zoning theory is constantly being accepted worldwide (Chen et al., 2016; Faheem et al., 2019; Ibidhi and Ben Salem, 2018).

The ecological function zoning is a way to divide a region into areas with different ecological characteristics according to the pattern of the ecological system, ecological environment sensitivity, and the spatial differentiation of ecosystem service functions (Zhai et al., 2016). Its purpose is to identify the types and functions of different ecosystems in the region and the driving factors that cause such differences, which is a prerequisite for the formulation of specific development plans and ecological environmental protection measures suitable for each type of ecological zone (Chen et al., 2016). However, few studies have considered local ecological function planning when analyzing agricultural water footprint and its spatial distribution characteristics, especially in combination with socioeconomic factors, which is a key to achieving sustainable development of regional social ecosystems (Ibidhi and Ben Salem, 2018; Langarudi et al., 2019). Therefore, the research purpose of this study is to take Zhangjiakou City as an example to make up for this gap.

### 6.1.2 Research objectives

Zhangjiakou City, located in Hebei Province, northwestern China, is a vital water resource and ecological function area in the Beijing-Tianjin-Hebei region. With the development of Beijing-Tianjin-Hebei integration, the deterioration of the ecological environment and the decline of water conservation functions in the region have become increasingly significant, especially the shortage of water resources, which has seriously restricted the sustainable development of the socioeconomic system. Based on natural resources and geographic characteristics, all of the counties (districts) are classified into six ecological zones in Zhangjiakou City (Figure 6.1). The objectives of this study are: (1) to estimate and evaluate the agricultural water footprint of each county (district) in Zhangjiakou City in 2005 and 2015; (2) to analyze the distribution and matching characteristics of agricultural water footprint and socioeconomic factors (planting area, population, and agricultural GDP) in each county (district) using mathematical models, i.e., Gini coefficient and imbalance index firstly; (3) to propose suitable measures and policies for sustainable agricultural development in counties (districts) based on the ecological zone to which they belong.

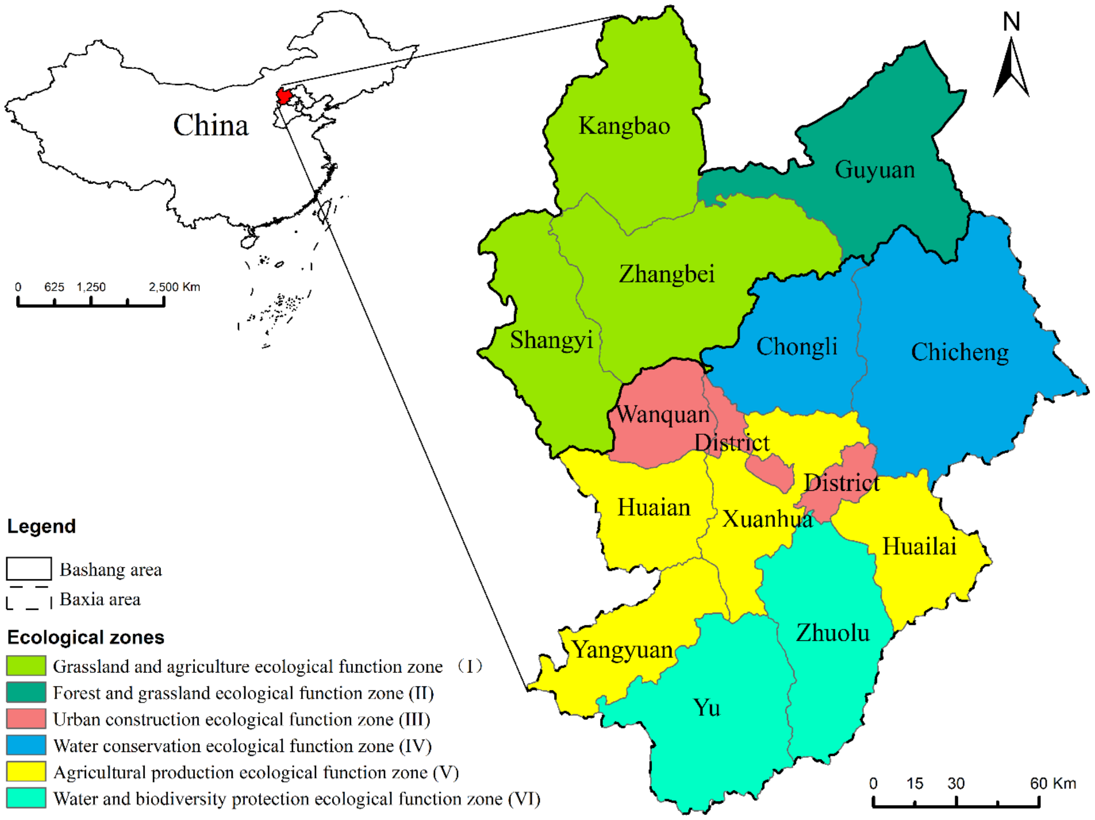

Figure 6.1 Geographical location and ecological function zoning map of Zhangjiakou

## 6.2 Methods and data sources

### 6.2.1 Methods

#### 6.2.1.1 Crop water footprint

Because the gray water footprint has no effect on crop growth, only blue and green water was taken into consideration for calculation. Water requirements for crop growth are mainly related to the meteorological environment, crop types, soil conditions, crop types, and harvest times, and are usually estimated using the CropWat 8.0 model recommended by the Food and Agriculture Organization (FAO) of the United Nations (Zeng et al., 2012). In CropWat 8.0, first of all, the required information of climate, rainfall, and crop growth need to be entered in the Climate, Rain and Crop modules, and then the evapotranspiration (ETc) of crop growth can be obtained in the CWR (Crop Water Requirements) module, with every ten days as a unit. In this study, when the effective rainfall is larger than ETc, it is assumed that the crop growth only consumes rainwater, i.e., green water; when the effective rainfall is less than ETc, it is assumed that all the effective rainfall is consumed.

(1) Blue water footprint

Zhangjiakou City is an arid region, and crops are generally under-irrigated, which means blue water consumption is less than the blue water demand. Therefore, the blue water footprint was calculated based on actual irrigation water use. Taking the loss of water resources during transportation and other processes into account, the blue water footprint (BWF) is calculated as follows:

$$BWF = W_i \times \eta \tag{6-1}$$

Where $W_i$ is the actual amount of irrigation water, and $\eta$ is the effective utilization coefficient.

(2) Green water footprint

$$ET_g = \sum min(ET_c, P_e) \tag{6-2}$$

$$GWF = 10A \times ET_g \tag{6-3}$$

where $ET_g$ (mm) is the green water evaporation, which is calculated every 10 days during the growth period; $ET_c$ (mm) and $P_e$ (mm) are the 10-day crop water evaporation and effective precipitation, respectively; $A$ represents the planting area of crop; factor 10 is the coefficient that converts water depth (mm) to water volume ($m^3hm^{-2}$).

### 6.2.1.2 Animal products water footprint

The water footprint of animal products includes two parts: the water consumption in the animal breeding stage and in the post-processing of animal products. It is related to many factors such as animal types, breeding methods, and breeding areas, and the calculation process is complicated. Here we refer to the results of Hoekstra (2003) (Table 6.1), and the water footprint of animal products is calculated as follows:

$$WF_{ani} = UWF \times Y \qquad (6\text{-}4)$$

Where $n$ is the type of animal products, $UWF$ is the virtual water content per kilogram of the animal products, and $Y$ is the weight of animal products.

Table 6.1 Water footprint calculation factor of animal products

| Crops | Beef | Equidae meat | Pork | Mutton | Poultry | Milks | Eggs | Fishes |
|---|---|---|---|---|---|---|---|---|
| $UWF$（$m^3$/ kg） | 12.56 | 5.67 | 2.21 | 5.2 | 3.65 | 3.55 | 1 | 3.11 |

### 6.2.1.3 Spatial heterogeneity analysis of water footprint and socioeconomic factors

(1) Gini coefficient

The Gini coefficient was proposed by the Italian economist Gini (1912) based on the concept of the Lorenz curve. According to the definition of the Gini coefficient, we introduce “the Gini coefficient of water footprint and socioeconomic factors” to identify the spatial difference between the regional agricultural water footprint and various socioeconomic factors. It is calculated as follows:

$$Gini = \sum_{i=1}^{n} X_i Y_i + 2\sum_{i=1}^{n} X_i (1 - V_i) - 1 \qquad (6\text{-}5)$$

Where $n$ represents the number of ecological zones; $X_i$ and $Y_i$ represent the percentage of socioeconomic factors (planting area, population, and agricultural GDP) and water footprint of ecological zone $i$ in Zhangjiakou City, respectively; $V_i$ represents the cumulative percentage of the water footprint.

(2) Water footprint and socioeconomic factors imbalance index

The Gini coefficient can only reflect the overall spatial matching degree of the water footprint and socioeconomic factors. Therefore, for figuring out the specific imbalance in each county of Zhangjiakou City, we introduce the water footprint and socioeconomic factors imbalance index, which is calculated as follows:

$$I_i = \frac{Y_i}{X_i} \qquad (6\text{-}6)$$

where $I_i$ represents the imbalance index of county i. When $I_i > 1$, it means that water footprint consumption of per unit planting area (per capita or per unit GDP) is higher than the average level of Zhangjiakou City; When $I_i < 1$, it means that per unit of planting (per capita or per unit of GDP) water footprint consumption is less than the average level of Zhangjiakou City. The closer $I_i$ is to 1, the higher the matching degree between the water footprint and the socioeconomic factors.

### 6.2.2 Data sources

According to the characteristics of terrain, landforms, and the type of land use, Zhangjiakou was classified into six ecological function zones in the city’s 13th Five-Year Plan (2016-2020) in 2015, which are represented by I, II, III, IV, V and VI for simplicity (Figure 6.1). As shown in Table 6.2, there were great spatial heterogeneities in these six ecological zones, regardless of irrigation rate, the percentage of agricultural water use or socioeconomic factors. Therefore, it is of great significance to analyze the spatial difference of the dynamic evolution of the agricultural water footprint from the perspective of the ecological zone.

Table 6.2 Socioeconomic characteristics of the six ecological zones of Zhangjiakou City in 2015

| Ecological zone | GDP (billion yuan) | Planting area (1,000 ha) | Irrigation rate | Population (1,000 person) | Agricultural water use （10,000 $m^3$） | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Irrigation | Animal | In total | Percentage in all sectors |
| I | 10.4 | 149.7 | 21% | 851 | 8,372 | 1,030 | 9,402 | 81% |
| II | 4.1 | 76.7 | 20% | 232 | 3,372 | 295 | 3,667 | 80% |
| III | 3.6 | 40.6 | 51% | 1,137 | 10,026 | 217 | 10,243 | 50% |
| IV | 4.6 | 62.1 | 4% | 426 | 3,533 | 326 | 3,859 | 58% |
| V | 10.3 | 220.4 | 41% | 1189 | 26,495 | 887 | 27,382 | 84% |
| VI | 7.4 | 126.8 | 32% | 855 | 15,081 | 404 | 15,486 | 87% |

CropWat 8.0 was used to calculate evaporation and effective rainfall during crop growth. The data required mainly includes meteorological and crop parameters. Meteorological data such as relative humidity, sunshine duration, wind velocity, and precipitation were obtained from *Zhangjiakou Economic Yearbooks* (The People's Government of Zhangjiakou City, 2006-2016), average maximum temperature and average minimum temperature were obtained from the weather website (http://www.tianqi.com/qiwen/city_zhangjiakou/). The parameters of crops, such as sowing and harvesting date, root depth, crop coefficient, growth period, crop height, were modified based on the data provided by FAO according to the actual situation in Zhangjiakou (Allan et al., 1998). In addition, socioeconomic factors, such as the crops planted area, the output of animal products, and GDP, were derived from the *Zhangjiakou Economic Yearbooks* (2006, 2011, 2016). The data of actual water consumption of irrigation and

utilization efficiency were derived from the *Zhangjiakou City Water Resources Bulletin* (Zhangjiakou Water Resource Bureau, 2006-2016) and other related government reports.

## 6.3 Results

### 6.3.1 General characteristics of the agricultural water footprint

The total agricultural water footprint of Zhangjiakou City increased from 3.61 billion $m^3$ in 2005 to 5.30 billion $m^3$ in 2015, an increase of 1.69 billion $m^3$, of which the crop water footprint increased from 1.42 billion $m^3$ to 1.52 billion $m^3$, an increase of only 98 million $m^3$, and the water footprint of animal products increased from 2.19 billion $m^3$ to 3.78 billion $m^3$, an increase of 1.59 billion $m^3$ (Figure 6.2). As a result, the contribution rate of crop water footprint dropped from 39% in 2005 to 29% in 2015. The main reason for the slow growth of the crop water footprint is that the planting area has increased by only 3.7% (from 0.553 million ha to 0.565 million ha) due to the limited cultivated area. However, with the transformation of residents' dietary structure during the process of urbanization and economic development, the animal husbandry industry has developed rapidly, and the output of animal products has increased by 102.2% (from 0.94 million tons to 1.90 million tons), resulting in a rapid increase of animal products water footprint.

In terms of spatial differences, the agricultural water footprint was always the largest in Zhangbei County (increased from 0.599 billion $m^3$ to 0.688 billion $m^3$) and the smallest in Chongli County (increased from 0.155 billion $m^3$ to 0.203 billion $m^3$) (Figure 6.2). The contribution rate of crops to the total agricultural water footprint declined in each county, while it increased from 40% to 47% in the area of districts. Regarding ecological zones, the agricultural water footprint was the largest in ecological zone V (1.73 billion $m^3$) and the smallest in ecological zone IV (0.405 billion $m^3$) in 2015, accounting for 48% and 11% of Zhangjiakou City, respectively. The contribution rate of crop water footprint was the highest (34%) in ecological zone IV and the lowest (21%) in ecological zone I in 2015.

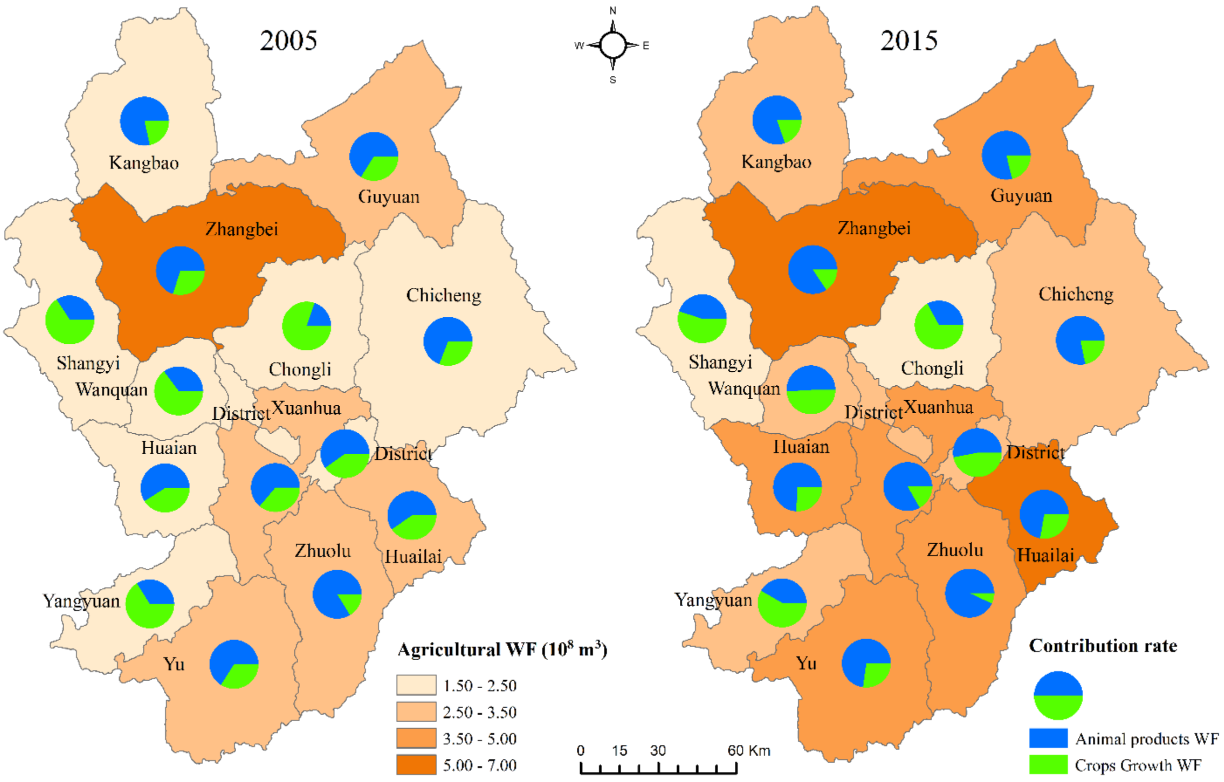

Figure 6.2 Agricultural water footprint in Zhangjiakou City

## 6.3.2 Spatiotemporal changes of the crop water footprint

### 6.3.2.1 Crop water footprint composition

From 2005 to 2015, the structure of the crop water footprint was in a relatively stable state. Among them, the water footprint of cereals was always the largest, slowly increasing from 0.699 billion $m^3$ to 0.829 billion $m^3$, and the contribution rate increased from 49% to 54%, which means cereals were the main contributor to crop water footprint in Zhangjiakou City. The water footprint of beans was the smallest, slowly decreasing from 0.112 billion $m^3$ to 0.064 billion $m^3$, and the contribution rate dropped from 8% to 4%.

In terms of spatial differences, from 2005 to 2015, the crop water footprint increased in ten counties (districts) and declined in the other four counties without showing obvious characteristics associated with the ecological zone (Figure 6.3). The largest region of crop water footprint thus has changed from Zhangbei County (0.180 billion $m^3$) in the ecological zone I to Huailai County (0.185 billion $m^3$) in the ecological zone V. Regarding ecological zones, the crop water footprint in ecological zone V was always the largest, and the contribution rate has increased from 30% to 36%. The crop water footprints in ecological zone II and V were the smallest, and the contribution rates were only 9% in 2015.

In terms of water footprint structure, the contribution rates of cereal in all counties of ecological zone III, V and VI were always higher than 50%, and they increased from 72%, 57%, and 58% to 80%, 66%, and 61% in these ecological zones, respectively (Figure 6.4); while the contribution rates of cereal in most counties of ecological zone I, II, and IV were always less than 50%, and they were getting smaller and smaller in these ecological zones, from 27%, 40%, and 48% decreased to 25%, 34%, and 46%, respectively. The decline of contribution rates of the cereal water footprint was mainly due to the continuous increase of the water footprint of potatoes.

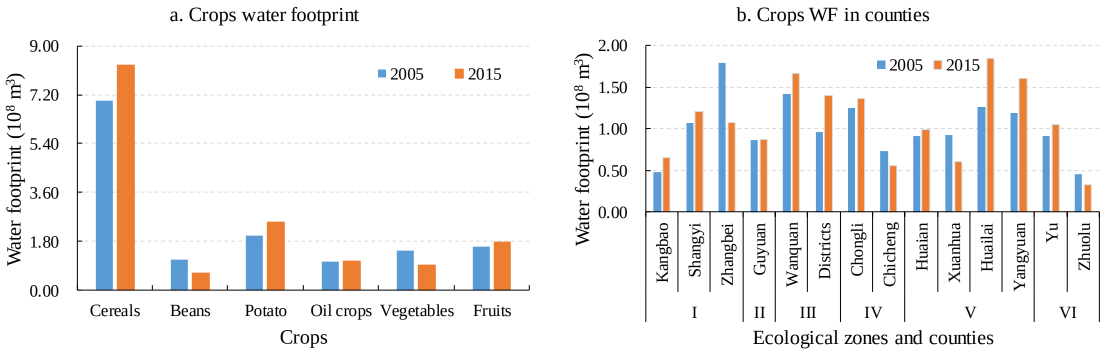

Figure 6.3 Crops water footprint in Zhangjiakou City

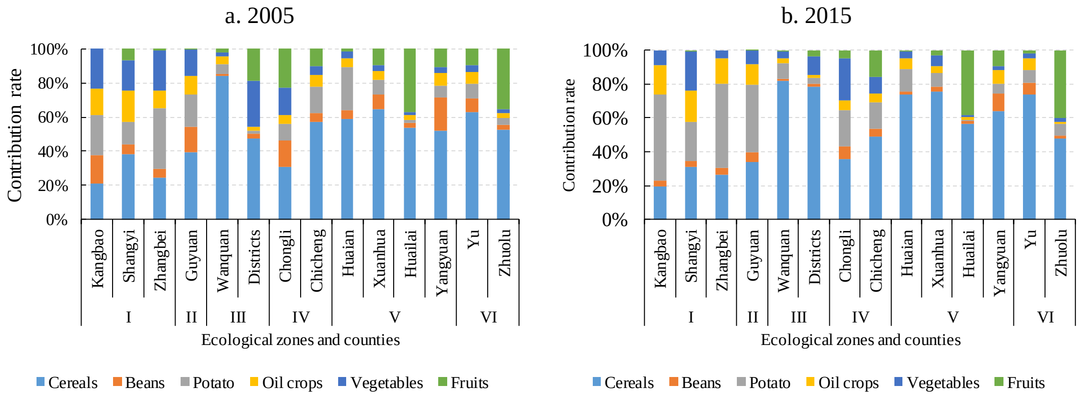

Figure 6.4 The contribution rate of crops water footprint in Zhangjiakou City

### 6.3.2.2 Blue and green water footprint

The irrigated area of the major crops increased from 0.141 million ha in 2005 to 0.183 million ha in 2015, which accounted for 26% and 32% of the total planting area, respectively. Therefore, as shown in Figure 6.5, the contribution rate of green water footprint was always about four times higher than the blue water footprint. In terms of spatial difference, the ecological zone V had the largest share of green water footprint, which increased from 29% to 35%, while the ecological zone III had the smallest share, which has been maintained at 6% to

7%. The ecological zone V had the largest share of blue water footprint, which increased from 32% to 39%, while the ecological zone II had the smallest share of blue water footprint, which was always below 5%. In 2015, the share of blue water consumption in the ecological zones III, V, and VI totaled 76%. This is because these three ecological zones were the main irrigation areas, and the proportion of irrigated farmland is higher than in other ecological zones.

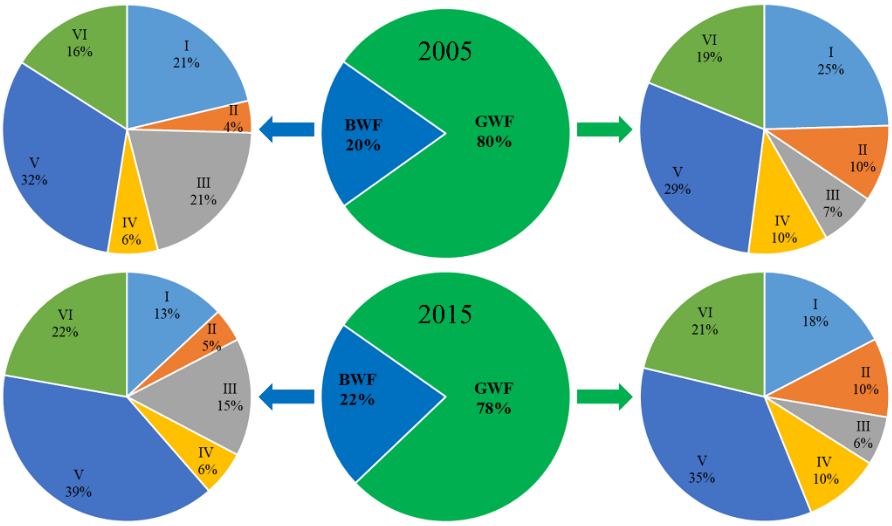

Figure 6.5 Share of crops blue and green water footprint in 2005 and 2015

### 6.3.3 Water footprint of animal products

As shown in Figure 6.6a, the water footprint of each type of animal products has been rising from 2005 to 2015. Milk products had the largest water footprint and the fastest growth rate, increasing from 0.535 billion $m^3$ to 1.26 billion $m^3$. Fish products had the smallest water footprint, increasing from 0.022 billion $m^3$ to 0.041 billion $m^3$.

It is obvious that the water footprint of animal products has increased in every county (district), but the growth rates were significantly different (Figure 6.6b). The water footprint of animal products was always the largest in Zhangbei County (increased from 0.420 billion $m^3$ to 0.581 billion $m^3$), while it was always the smallest in Chongli County (increased from 0.031 billion $m^3$ to 0.067 billion $m^3$). In general, the water footprint of animal products in counties of ecological zone I, V, and VI was higher than it in the other counties, and the total contribution rate of these three ecological zones has increased from 73% to 75%.

In addition, the structure of the water footprint of the eight major animal products varies significantly in each area (Figure 6.7). The total water footprint of beef, pork, and mutton in the ecological zone IV has been declining, but it was still higher than 64%, while it was less than 35% in the ecological zones II and III. The water footprint of equine was the largest in the ecological zone IV but only accounted for 6-7%. The proportions of the milk water footprint in the ecological zones I and II have been expanding, from 35% and 60% to 55% and 72%, respectively. The water footprints of poultry-related products, such as poultry meat and eggs, were very small in the ecological zones I and II, accounting for less than 7%. The proportions of fish water footprint were very small in all ecological zones.

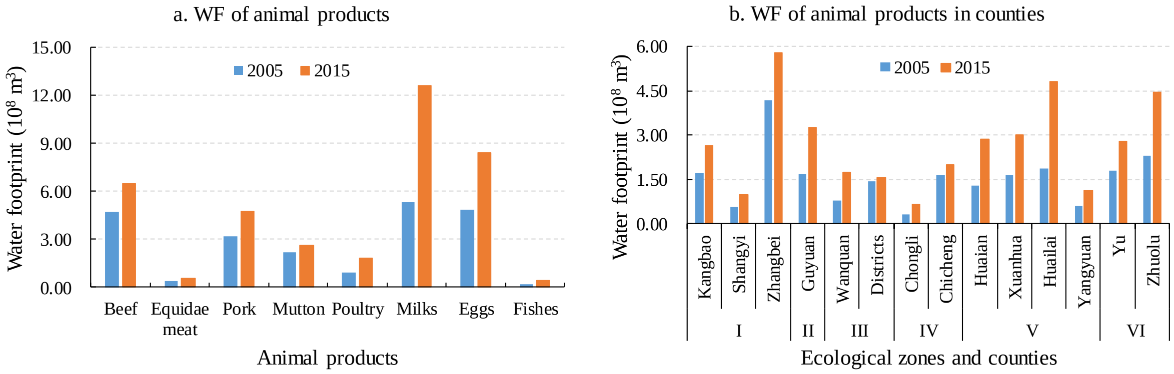

Figure 6.6 The water footprint of animal products in Zhangjiakou City

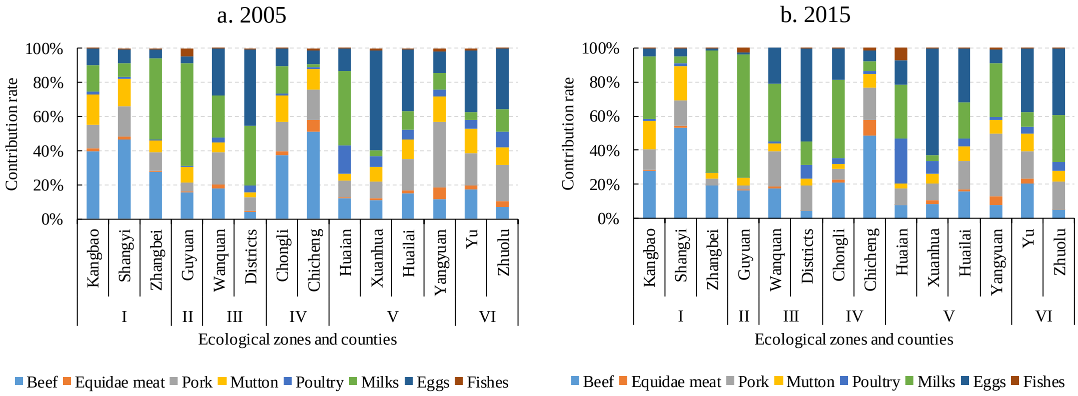

Figure 6.7 The contribution rate of animal products water footprint in Zhangjiakou City

### 6.3.4 The spatial relationship of water footprint and socioeconomic factors

#### 6.3.4.1 Gini Coefficient

(1) Crop water footprint and planting area

As shown in Figure 6.8a and Figure 6.8b, from 2005 to 2015, the Gini coefficient of crop water footprint and planting area increased from 0.12 to 0.14, indicating a “high balance” distribution pattern of the crop water footprint on the county scale. Regarding blue water and green water, the Gini coefficient of blue water footprint and planting area slightly increased from 0.33 to 0.34, indicating that the blue water footprint of crops was in a “relatively reasonable” spatial distribution pattern. Meanwhile, the Gini coefficient of green water footprint and planting area increased from 0.09 to 0.11, which means that the spatial distribution of green water footprint always remained in a “high balance” state. Therefore, in general, the spatial distribution of the green water footprint was more balanced than the blue water footprint during the research period.

(2) Agricultural water footprint and population.

As shown in Figure 6.8c and Figure 6.8d, the Gini coefficient of agricultural water footprint and population increased from 0.12 in 2005 to 0.16 in 2015, which means the spatial distribution of agricultural water footprint and the population was in a “high balance” state. The Gini coefficient of the crop water footprint and the population increased from 0.23 to 0.26, indicating that the spatial distribution of the crop water footprint and the population was in a “relative balance” state. The Gini coefficient of the water footprint of animal products and population increased from 0.30 to 0.32, which indicates that the distribution of water footprint of animal products and the population was always in a “relatively reasonable” state. In general, the spatial balance degree of agricultural water footprint and the population was moving towards a more unbalanced trend.

(3) Agricultural Water Footprint and GDP

As shown in Figure 6.8e and Figure 6.8f, the Gini coefficient of agricultural water footprint and agricultural GDP rose from 0.08 in 2005 to 0.15 in 2015, indicating that the spatial relationship between agricultural water footprint and agricultural GDP was always in a “high balance” state in county scale. In terms of crops, the Gini coefficient of crop water footprint and crops GDP increased from 0.15 to 0.27, indicating that the spatial distribution of crop water footprint and crops GDP dropped from a “high balance” state to a “relative balance” state. In terms of animal products, the Gini coefficient of the water footprint and GDP of animal products increased from 0.14 to 0.21, which indicates that the spatial relationship of them changed from “high balance” to “relative balance”. In general, the spatial matching degree of the water footprint and animal products GDP was higher than that of the water footprint and crops GDP.

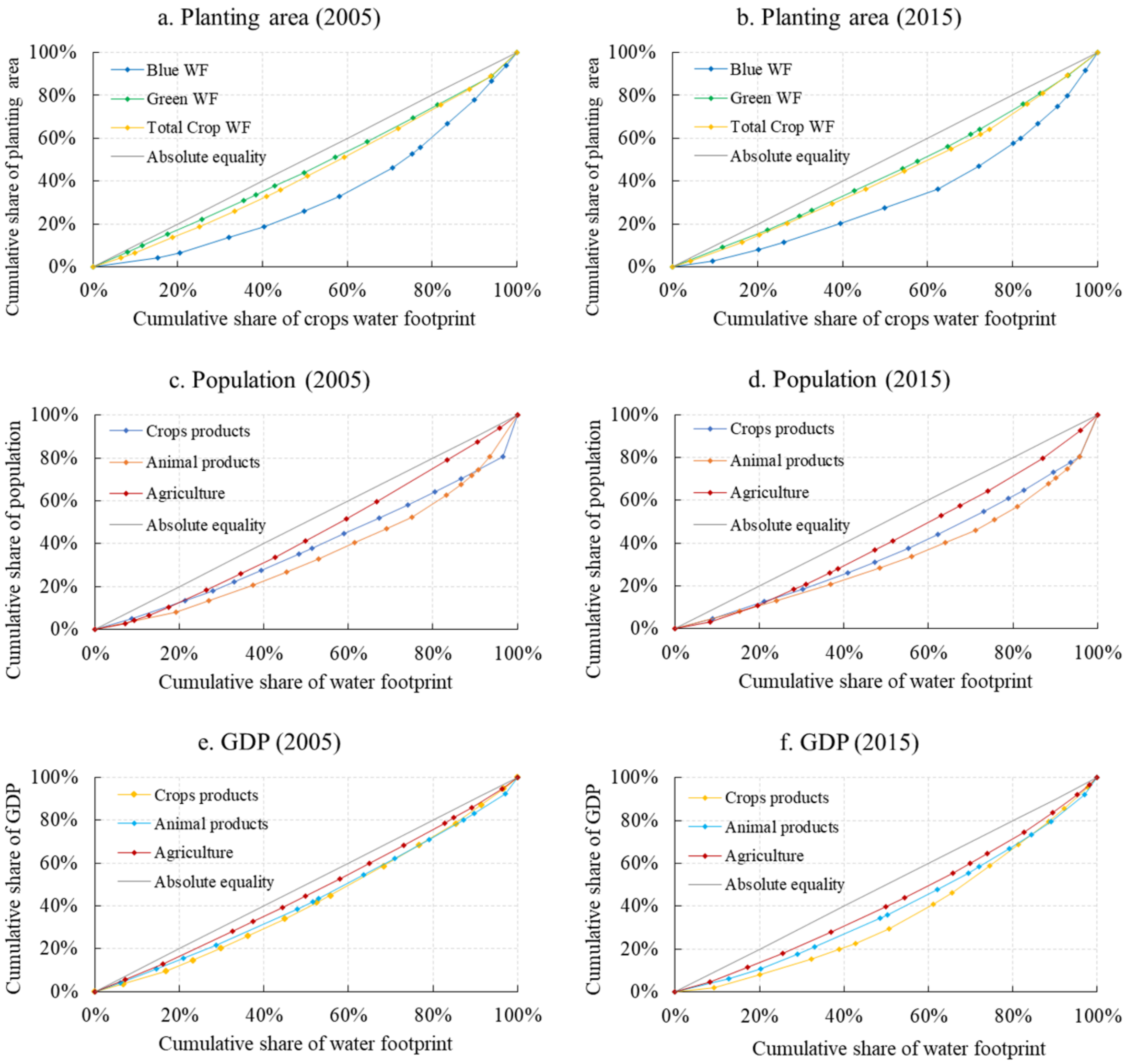

Figure 6.8 Lorentz curve of water footprint and socioeconomic factors in Zhangjiakou City

#### 6.3.4.2 Imbalance index

(1) Water footprint and planting area

As shown in Figure 6.9a, the imbalance indexes of the blue water footprint and planting area were always less than 1 in the counties of ecological zones I, II, and IV from 2005 to 2015, indicating the amount of blue water per unit area of cultivated land in these counties was lower than the average level. Meanwhile, the imbalance indexes of the blue water footprint and the planting area were always greater than 1 in most counties of ecological zones III, V, and VI, which means the amount of blue water per unit area of cultivated land in these counties was higher than the average level.

Regarding green water, as shown in Figure 6.9b, the imbalance index of green water footprint and planting area was less than 1 only in four counties (Kangbao, Shangyi, Zhangbei, and Yu) in 2005, while it was less than 1 in half of the counties in 2015. In general, the imbalance index of green water footprint and planting area was more concentrated near the absolute balance line, which also confirms that the spatial distribution of green water was more balanced.

(2) Agricultural water footprint and population

As shown in Figure 6.9c, it is obvious that the imbalance index of agricultural water footprint and population was far less than 1 in districts area, indicating that per-capita agricultural water footprint was far below the average level during the research period. This is due to the high population density in the city center. The imbalance index of agricultural water footprint and population decreased in all counties of ecological zones I, II, III, and IV, indicating that per-capita agricultural water footprint decreased in these counties; while it increased in most counties of ecological zones V and VI, indicating that per-capita agricultural water footprint increased in these counties.

(3) Agricultural water footprint and GDP

As shown in Figure 6.9d, the imbalance index of agricultural water footprint and agricultural GDP was more concentrated around the absolute balance line in 2005 than in 2015, indicating that the differences in the consumption of water footprint per unit of GDP were increasing among counties. The imbalance index of agricultural water footprint and agricultural GDP decreased in almost all counties (except Zhangbei) of ecological zones I, II, III, and IV, indicating that the consumption of water footprint per unit of GDP was decreasing in these counties; while it increased in all counties of ecological zones V and VI, indicating that the consumption of water footprint per unit of GDP was increasing in these counties.

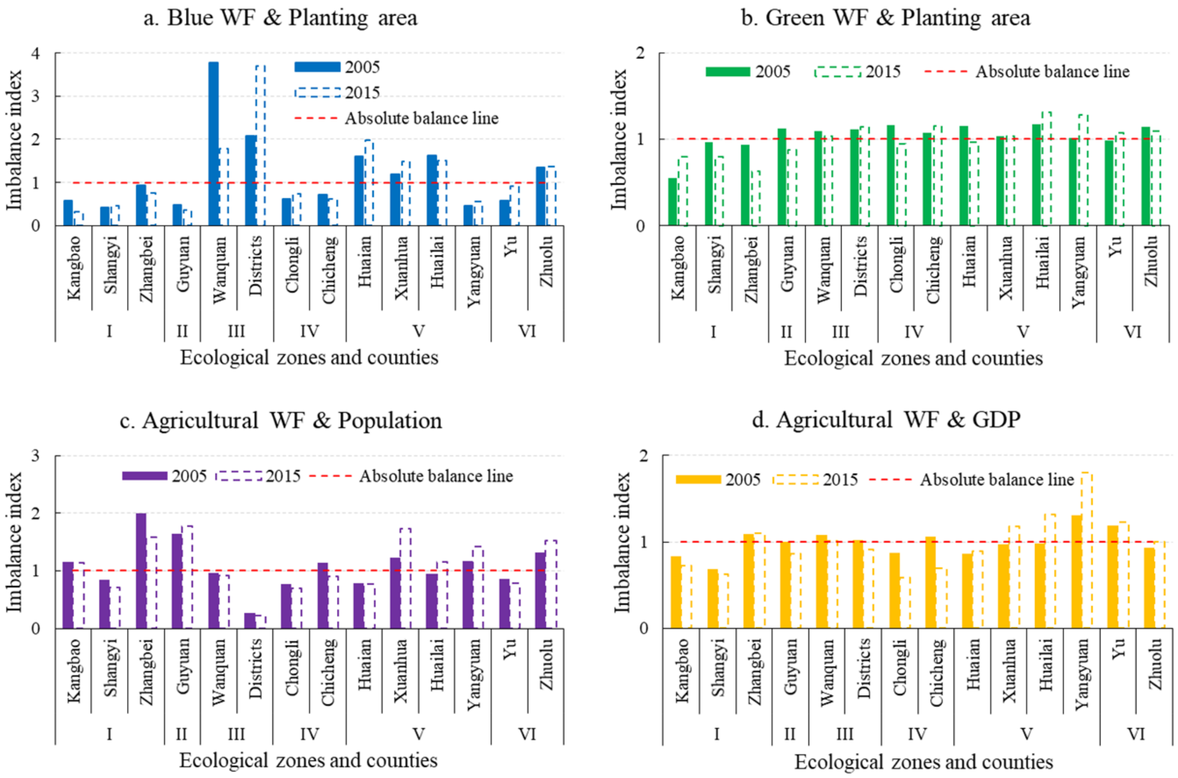

Figure 6.9 The imbalance index between water footprint and socioeconomic factors

## 6.4 Discussion

### 6.4.1 Recommendations for sustainable development

Cultivated land and grassland are the main types of land use in counties of ecological zone I, which account for 42% and 47% in total in Zhangjiakou City, respectively. From 2005 to 2015, the water footprint of crops decreased from 0.34 billion m$^3$ to 0.25 billion m$^3$. This is because the government has vigorously implemented conversation measures to return farmland to forests and grasslands to restore the ecological environment. The planting area has been reduced from 0.174 million ha to 0.150 million ha. Meanwhile, the area of irrigated land was reduced by planting drought-resistant potatoes instead of water-consuming vegetables, and the water-saving technology of dropper was actively promoted. However, the water footprint of animal products has increased from 0.650 billion m$^3$ to 0.946 billion m$^3$, especially dairy products have increased from 0.230 billion m$^3$ to 0.520 billion m$^3$. Therefore, in addition to continuing to optimize the planting structure, implement efficient water-saving irrigation measures, and control the water footprint of crops, the government needs to strictly prohibit overload grazing and develop modern animal husbandry from the perspective of water resources carrying capacity.

In Guyuan County, the ecological zone II, the crop water footprint increased from 0.125 billion $m^3$ to 0.136 billion $m^3$. Compared with ecological zone I, the government needs to strengthen the implementation of measures to return farmland to forests and grasslands to save water. In addition, due to the rapid increase in the milks water footprint, the water footprint of animal products in this area increased from 0.170 billion $m^3$ to 0.328 billion $m^3$. Therefore, the government should accelerate the adoption of measures such as prohibiting grazing, rotation grazing, and captives to strictly control overgrazing of grasslands and prevent grassland degradation. It should also limit the scale of animal husbandry development from the perspective of water conservation.

The ecological zone III is the political, economic, and cultural center of Zhangjiakou, with the largest population density and a high-level economic development. It is also the main area of high-quality cultivated land. The crop water footprint decreased from 0.141 billion $m^3$ to 0.126 billion $m^3$, of which the proportion of cereal water footprint increased from 72% to 80%, while the water footprint of animal products increased from 0.220 billion $m^3$ to 0.310 billion $m^3$. The government thus needs to use the technological advantages of this region to explore effective ways to increase the irrigation coefficient of crops, improve the agricultural ecological environment, establish green ecological agriculture, and improve the efficiency of water resource utilization.

In Chongli County and Chicheng County, the ecological zone IV, woodland and grassland are the main types of land use, accounting for 54% in total. There are three rivers, Heihe, Baihe, and Honghe, which are important water supply sources for Beijing. From 2005 to 2015, the crop water footprint remained around 0.137 billion $m^3$, and the water footprint of animal products increased from 0.196 billion $m^3$ to 0.268 billion $m^3$. In addition to the protection of natural ecosystems and enhancement of water conservation functions, the government needs to control the cultivated area of crops, optimize the production and management methods of animal husbandry, and strictly control the number of animals based on water resources carrying capacity.

The counties of ecological zone V are the main area for agricultural development, accounting for 25% of the total arable land in Zhangjiakou City. From 2005 to 2015, the water footprint of crops increased from 0.420 billion $m^3$ to 0.545 billion $m^3$, and the water footprint of animal products increased from 0.542 billion $m^3$ to 1.18 billion $m^3$, which made ecological zone V has the largest agricultural water footprint and the fastest growth rate among the six ecological zones. Therefore, these counties need to actively develop ecological agriculture, promote the development of water-saving and efficient agriculture, and build high-tech agriculture to save water around key industries such as vegetables, animal husbandry, and fruit processing.

Yu County and Zhuolu County are located in the south of Zhangjiakou City, the ecological services such as natural forest water conservation and soil and water conservation have weakened because of the impact of human activities. From 2005 to 2015, the crops water footprint increased from 0.261 billion $m^3$ to 0.327 billion $m^3$, and the animal products water footprint increased from 0.410 billion $m^3$ to 0.725 billion $m^3$. Therefore, these two counties need to continue to strengthen forest construction, prohibit land reclamation on slope land, and improve water conservation capacity. Meanwhile, the government should actively implement water-saving irrigation technologies to control the increase of the water consumption of the plantation industry and optimize the structure of animal husbandry based on the virtual water content of the feed.

### 6.4.2 Relationships of water footprint and socioeconomic factors

In terms of planting area, the crop water footprint and the planting area were always in a “high balance” state, indicating that the water consumption per unit of cultivated land in all counties was relatively close. The spatial distribution of green water and planting area always remained in a stable state of “high balance”, it only means that the green water consumption per unit area was quite close in all counties. It is still vital to optimize the structure of the planting industry to improve the use of precipitation. Meanwhile, the balance between the blue water footprint and the planting area declined slightly. This is mainly due to the reduction of irrigated land in the counties of Bashang area and the increase in the proportion of rainfed and dripper farmland, which has led to the reduction of irrigation water in the area. Through the analysis of the imbalance index, the crop water footprint per unit area in counties of ecological zone III was much higher than the average level of Zhangjiakou City, especially the blue water footprint. Therefore, it is necessary to use various water-saving measures and technologies to focus on improving the efficiency of the water footprint in these counties.

In terms of population, the agricultural water footprint and the Gini coefficient of the population remained stable and were always in a “high balance” state. According to the analysis of imbalance degree, the per capita agricultural water footprint was larger than the average level in most counties of ecological zones I, II, V and VI, while it was lower than the average level in counties of ecological zones III and IV. Therefore, it is necessary to actively reduce the agricultural water footprint in areas of ecological zones I, II, V, and VI from the perspective of population, especially in ecological zones I and II.

In terms of GDP, the Gini coefficient of water footprint and GDP of animal products was always smaller than the Gini coefficient of water footprint and GDP of crops, indicating that the distribution of water footprint of animal products was more balanced than crop water footprint in terms of GDP. This is mainly due to the difference in planting structure and price of crops, which led to a poor balance of the water footprint of the crops per unit of GDP in these counties. Through the analysis of imbalance degree, the agricultural water footprint per unit of GDP in most counties of ecological zones I, II, and IV was lower than the average level in Zhangjiakou, while the agricultural water footprint per unit of GDP in most counties of ecological zone VI was higher than the average level in 2015. Therefore, from the perspective of economic development, it is vital to give priority to optimizing the structure of planting and animal husbandry in counties of ecological zone VI to maximize the economic benefits of water footprint.

However, it needs to be emphasized that the adjustment of the agricultural structure in each county requires comprehensive consideration of multiple socioeconomic factors, which is similar to the research result of Fernández et al. (2020) that the market value and local environmental conditions should be considered at the same time in irrigation management. For example, the water footprint consumption per unit planting area in counties of ecological zone III was much higher than the average level, but the per capita water footprint and the per-unit GDP water footprint were far below the average level.

## 6.5 Conclusions

Zhangjiakou City is in a critical period of economic transformation and development. The shortage of water resources has become a serious factor restricting the sustainable development of society and the economy. The water footprint theory was employed to calculate and analyze the dynamic evolution of agricultural water use in the scale of ecological function zone in 2005 and 2015, and the spatiotemporal matching characteristics of agricultural water footprint and socioeconomic factors were analyzed using the Gini coefficient and the imbalance index. The main results are:

The agricultural water footprint of Zhangjiakou City increased from 3.61 billion $m^3$ to 5.30 billion $m^3$, an increase of 1.69 billion $m^3$, of which the water footprint of crops increased by only 0.098 billion m$^3$, while the water footprint of animal products increased by 1.59 billion m$^3$, indicating that animal products will have a more significant impact on the use of water resources.

The cereal water footprint has always been a major contributor to the crop water footprint, with an increasing contribution rate from 49% to 54%. Products of milk and eggs are the main drivers of the increase in the water footprint of animal products, with an increasing total contribution rate from 46% to 55%. The spatial differentiation of the agricultural water footprint is significant. In 2015, the contribution rate of the cereal water footprint was less than 50% in counties of high-altitude ecological zones I, II, and IV, while it was higher than 50% in counties of low-altitude ecological zones III, V, and VI. In general, the contribution rate of milk water footprint was higher in counties of high-altitude ecological zones I and II and IV than in counties of low-altitude ecological zones III, V, and VI.

The Gini coefficient and imbalance index of agricultural water footprint and socioeconomic factors indicate that the spatial distribution of agricultural water footprint and planting area, population, agricultural GDP was relatively balanced, but there were still some significant differences. For example, the water footprint consumption per unit planting area in counties of ecological zone III was much higher than the average level, but the per capita water footprint and the per-unit GDP water footprint were far below the average level, which indicates that adjustment of the agricultural structure in each county requires a comprehensive consideration of multiple socioeconomic factors.

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# 7. Conclusions and future work

## 7.1 Conclusions

Zhangjiakou City is in a critical period of economic transformation. The shortage of water resources has become a serious factor restricting the sustainable development of society and the economy. It is not only unlikely to solve the water shortage by transferring water from outside but also needs to deliver water to Beijing, which means the only way to solve the water dilemma is coordination and cooperation between upstream (Bashang) and downstream (Baxia) areas and different industrial sectors within the region. In this thesis, based on system dynamics and water footprint theory, the demand for water resources under different industrial layouts and agricultural planting patterns was investigated, which could provide a scientific basis for achieving coordinated and balanced development of the entire city.

Based on system dynamics, the agricultural water-related indicators are the most sensitive factors to the total water demand in Zhangjiakou City. That is to say, the agricultural sector has the largest water-saving potential. There is a need to reduce the area of irrigated farmland. However, in this process, the correlation between the crop structure, food production, and agricultural income, as well as other factors must be considered to achieve maximum benefits. The four development scenarios established through the integration of the “Two-zone Planning” provided specific and feasible alternatives for the sustainable development of Zhangjiakou City. But it is noted that no matter which scenario is chosen, as the economy grows, the water demand per 10,000 yuan of GDP will eventually drop to about 20 $m^3$ by 2035. This means that if only by slowing down economic growth to achieve lower water demand, not only the water use efficiency cannot be improved, but it may also lead to a waste of water supply capacity.

In view of the fact that agricultural production has responsible for the largest utilization of water resources in Zhangjiakou City. With the help of CropWat 8.0, the water footprint and its spatiotemporal characteristics and variations of the main crops for 2005, 2010, and 2015 were estimated. Furthermore, from the perspective of the ecological zone, the spatiotemporal matching characteristics of agricultural water footprint and socioeconomic factors were analyzed using the Gini coefficient and imbalance index. In Zhangjiakou City, although the virtual water content per unit of yield decreased from 0.331 $m^3$/kg in 2005 to 0.195 $m^3$/kg in 2015, the contribution rate of blue water and green water has always remained about 20% and 80%, respectively. Therefore, how to make full use of green water resources is of vital importance to the sustainable development of agriculture. The agricultural water footprint of

Zhangjiakou City increased from 3.61 billion m$^3$ to 5.30 billion m$^3$, an increase of 1.69 billion m$^3$, of which the water footprint of animal products increased by 1.59 billion m$^3$. Therefore, in addition to continuing to optimize the planting structure, implement efficient water-saving irrigation measures, and control the water footprint of crops, the government needs to strictly prohibit overload grazing and develop modern animal husbandry to reduce the water footprint of animal products, especially in counties of high-altitude ecological zones.

## 7.2 Limitations and future work

There are several limitations in this study, which are also the directions of future work. First, the relationship of agriculture GDP and the area of the irrigated farmland should be reflected in the system dynamics model (Chapter 4), but we failed to achieve it due to the lack of data. Because agriculture consists of crop farming, forestry, and animal husbandry, and there are both irrigation farmland and rain-fed farmland in crop farming, and the areas of various crops are changing every year. In Zhangjiakou City, however, there were only total yield and GDP data for each crop that can be used, without distinguishing between irrigation farmland and rain-fed farmland. It is thus very difficult to get the contribution rate of different types of irrigation farmland to the agriculture GDP and the inherent relationship between them. Second, due to the same reason, in Chapter 5, the comparative analysis of economic benefits and food production of crop water footprint from the perspective of irrigated crops and rain-fed crops cannot be achieved. It is necessary to improve this in future research when data are available, which can contribute to adjusting the structure of crops for water conservation. Third, with the decrease of the virtual water content of crops, the virtual water contained in animal feed should also be continuously decreasing. However, a constant virtual water coefficient was used in Chapter 6 to calculate the water footprint of animal products. Although it is common in the current water footprint research of animal products, it should be improved in future work.

## 7.3 Summarizing the results regarding the goals and the objectives

**Research goal 1:** *Provide scientific support for coordinating conflicts between regions and industrial sectors is a general scientific goal.*

In Chapter 4, based on the “Two-zone Planning” of Zhangjiakou City, a system dynamics model has been established, and then the water demand (2020 - 2035) of various sectors, i.e., agriculture, industry, urban public, residents, and the environment has been estimated under four development scenarios. By doing this, the research results have achieved the goal of providing policymakers with scientific support for resolving conflicts in the use of water resources between regions and sectors.

**Research goal 2:** *Provide scientific support for regional sustainable development is another general scientific goal.*

First, the results of Chapter 4 could help local government to mitigate the conflict of water use between different sectors. Second, in Chapter 5 and Chapter 6, the green water was introduced through water footprint theory to draw more attention to the utilization of rainwater resources in arid areas, and the spatiotemporal differences in water footprint economic benefits were also analyzed. In general, the results of these three chapters could provide scientific support for the sustainable development of the socio-economic system.

**Objective 1:** *Based on the "Two-zone Planning" of Zhangjiakou City, a system dynamics model will be established to simulate the water demand of various departments in Zhangjiakou City from 2020 to 2035 under different development scenarios.*

In Chapter 4, the system dynamic model of Zhangjiakou City has been successful established. The sensitive factors of total water use were identified based on this model, that is, the variables related to irrigation farmland are the main driving factors of water demand. Then the water demand (2020 - 2035) was estimated under four development scenarios, The results show that the total water demand will rise continually in CDS and EPS, and the proportion of agricultural water demand will drop to 67% and 63%, respectively. Meanwhile, it will decline continually in WPS and BDS, and the proportion of agricultural water demand will drop to 56% and 57%, respectively.

**Objective 2:** *According to water footprint theory, the water footprint requirement of the main crops in Zhangjiakou City will be estimated with the help of CropWat 8.0, and its characteristics of spatial distribution and dynamic changing trends for 2005, 2010, and 2015 will be identified. Besides, water footprint food productivity and water footprint economic benefits will be investigated.*

In Chapter 5, the water footprint requirement of the main crops in Zhangjiakou City was estimated with the help of CropWat 8.0. The water footprint requirement increased from 1.671 billion $m^3$ in 2005 to 1.852 billion $m^3$ in 2015, of which the ratio of green water to blue water was around two. The water footprint requirement in the counties of the high-latitude Bashang area was lower than that of the low-latitude Baxia area, and the gap between them was further expanding. The changing trends of water footprint food productivity and water footprint economic benefits were not always the same. Therefore, it is vital to consider them simultaneously when developing policies from the perspective of water footprint.

**Objective 3:** *For the first time, from the ecological zone perspective, the distribution and matching characteristics of agricultural water footprint and socioeconomic factors (planting area, population, and agricultural GDP) in each county (district) using mathematical models, i.e., Gini coefficient and imbalance index will be analyzed, and the suitable measures and policies for sustainable agricultural development for counties (districts) will be proposed accordingly.*

In Chapter 6, from the perspective of the ecological function zones, the agricultural water footprint of 2005 and 2015 has been estimated, and the spatiotemporal matching characteristics of agricultural water footprint and socioeconomic factors (planting area, population, and agricultural GDP) were investigated using the Gini coefficient and the imbalance index. The agricultural water footprint increased from 3.61 billion $m^3$ to 5.30 billion $m^3$, an increase of 1.69 billion $m^3$, of which the water footprint of animal products increased by 1.59 billion $m^3$. The spatial distribution of agricultural water footprint and planting area, population, agricultural GDP was relatively balanced, but there were still some significant differences. For example, the water footprint consumption per unit planting area in counties of ecological zone III was much higher than the average level, but the per capita water footprint and the per-unit GDP water footprint were far below the average level, which indicates that adjustment of the agricultural structure in each county requires a comprehensive consideration of multiple socioeconomic factors.