博士論文

SECURITY ANALYSIS OF WATER RESOURCES BASED ON ECOLOGICAL FOOTPRINT AND SYSTEM DYNAMICS MODEL

エコロジカルフットプリント法及びシステム動的モデルに基いた水資源の安全性に関する研究

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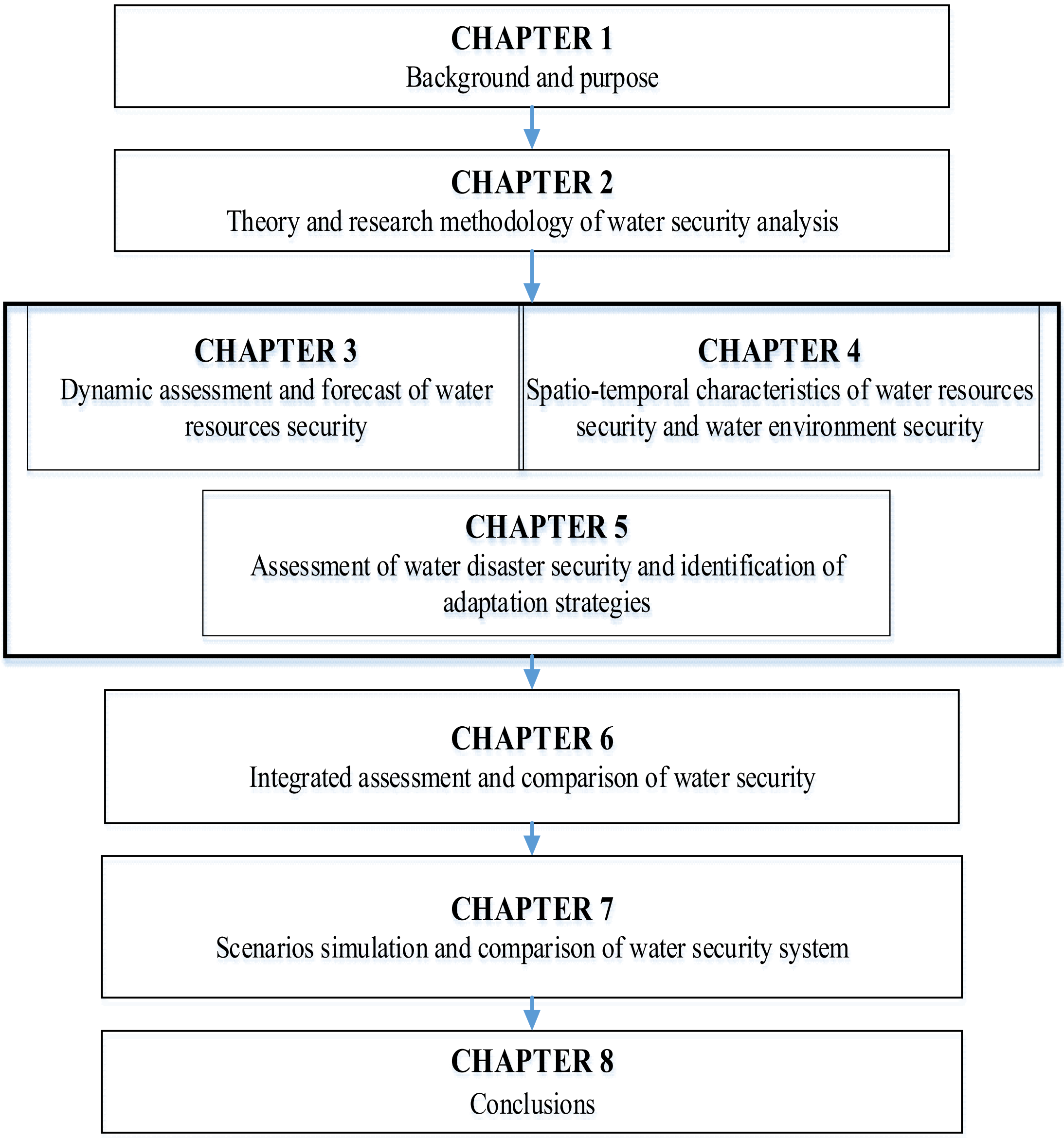

Security Analysis of Water Resources Based on Ecological Footprint and System Dynamics Model

ABSTRACT

Water security is widely recognized as an important and increasingly urgent challenge in policy and academic circles. Notwithstanding the palpable rise in water use, a comprehensive understanding of how water security is conceptualized and employed in different contexts around the world is limited. Moreover, the clear recognition that water security encompasses quantity, quality, water-related disasters and societal considerations, but discussions often focus on only one or two of these aspects. This practice masks critical ways in which water quality issues intersect with water quantity issues as well as social factors for many water security decisions. Therefore, in order to benefit achieving water security in the future, it is necessary to reorganize the initiate, connotation and extension, and the evolution of water security. Meanwhile, water security is expected to integrate water quantity, water quality, water disaster, and economic-societal factor.

This thesis focuses on simulation and evaluation of water security with the methodologies of ecological footprint and system dynamics and develops some feasible and scientific research tools for evaluating the issues of water scarcity, water pollution, and water damage and contributing to water management. Firstly, by studying the previous researches, water security is divided into three pillars i.e. water resources security, water environment security, and water disaster security. Then the three pillars are investigated respectively. For further research, we also do a comprehensive research by integrating the three pillars. Finally, a system dynamics model of water security is developed to analyze and predict the future trends in different scenarios.

IN CHAPTER 1, **BACKGROUND AND PURPOSE**, research background and significance of water security are summarized. In addition, the significance of different water management approaches to achieve water security is described and the related studies have been reviewed. Successively, motivation and goal of this study are proposed.

IN CHAPTER 2, **MOTIVATION AND METHODOLOGY**, firstly, the research method of ecological footprint (EF) is introduced for water resources security and water environment security. The fuzzy comprehensive evaluation (FCE) method for water disaster security is described. Then the set pair analysis (SPA) method is recommended to perform a comprehensive evaluation for water security. Finally, the theory of system dynamics (SD) applied in the simulation of water security system is also described.

IN CHAPTER 3, **DYNAMIC ASSESSMENT AND FORECAST OF WATER RESOURCES SECURITY**, water ecological footprint method has been applied to demonstrate how the sustainable utilization of water resources can be realized. According to the basic principle and calculation model of water ecological footprint, the water ecological footprint (WEF) and water ecological carrying capacity (WEC) in a period of 2004-2015 in Beijing, Shanghai, Tianjin, and Chongqing were analyzed. Then, the water ecological footprints per capita are predicted with the quadratic exponential smoothing in 2020 and 2025, respectively. Finally, we advise that the productive structure associated with the distribution of water resources in different cities should be manipulated towards improving the WEC, reducing the WEF and fix regional water imbalance for further promoting the sustainable development of the overall socio-economy.

IN CHAPTER 4, **SPATIO-TEMPORAL CHARACTERISTICS OF WATER RESOURCES SECURITY AND WATER ENVIRONMENT SECURITY**, ecological footprint method is applied to demonstrate the sustainable utilization of clean and safe water in Japan taking water quality in account. According to the basic principle and calculation method of water ecological footprint model (WEFM), the characteristics of water ecological footprint (WEF) in Japan are investigated not only in a temporal dimension, but also in a spatial dimension. Results show that the total WEF of Japan presented a decreasing trend from 1995 to 2014 both in water quantity and water quality accounts, the spatial distribution characteristic of WEF in Japan was that the higher the urbanization rate is, the larger the WEF. Therefore, the rational policies and measures associated to water resources should be implemented to ensure water sustainability in Japan.

IN CHAPTER 5, **ASSESSMENT OF WATER DISASTER SECURITY AND IDENTIFICATION OF ADAPTATION STRATEGIES**, the current situation of water disaster security of “sponge city” in China has been evaluated so as to lay the foundation for further study of sponge city construction and urban flood management. A comprehensive framework is developed to measure the resilience against flooding of city. The resilience against flooding is estimated from four interacting factors which are water balance, water stability, service function and organizational structure. The approach fuzzy comprehensive evaluation model (FCE) is adopted for the evaluation of its role to assess resilient performance. Taking the case of 30 pilot cities of China, namely the “sponge city”, the resilience of the four factors and the comprehensive resilience of sponge cities are analyzed. Recommendations for improving the urban resilient performance of different classes are made to help the decision-makers design and construct sponge city under local conditions.

IN CHAPTER 6, **INTEGRATED ASSESSMENT AND COMPARISON OF WATER SECURITY**, a water security system (WSS) can be described as a complex coupling system that integrates water resources, water environment, and water disaster systems into a whole. The WSS's operating mechanism is composed of water quantity balance, water quality balance and water resilience balance, and it interacts with and controls the system's evolution process. The chapter introduces a new approach, set pair analysis theory, to measure the state of a WSS, and an evaluation index system is established using the subsystems and operating mechanism of a WSS. The evaluation index system is separated into three levels (goal level, criteria level and index level) and divides the index standard into five grades. An evaluation model of the WSS based on set pair analysis theory is constructed and examples of WSS evaluation in Guizhou province of China and eight regions of Japan are presented. The connection degrees of the index in the three levels are calculated respectively, which classifies the WSS's condition. According to the evaluation grades of WSS, the water sustainable management in different regions is determined to be at a relatively adequate level that meets the requirements of sustainable development.

IN CHAPTER 7, **SCENARIOS SIMULATION AND COMPARISON OF WATER SECURITY SYSTEM**, according to theory and methodology of system dynamics, this chapter discusses the water security system programming of economy - water resource - water environment - water disaster - population, and develops a system dynamics (SD) model by which several typical scenarios are proposed for comparative analysis. The optimal measurement is suggested in excellent coincidence with sustainable development of water resources, water environment, and water disaster system. Firstly, water security system is characteristic of complexity, nonlinearity and time – variation, thus, SD model is applicable to serve as an analysis tool due to its merits. Moreover, the historic test and analysis on sensitivity degree indicate that the SD model is reliable to elucidate the causal feedback relationship and dynamic behavior of water security system to a certain extent. Secondly, different various scenarios generate significant differences in the developing tendencies of water resources, water environment, and water disaster. Consequently, different modes have respective priorities and obvious developing drawbacks. Thirdly, under the considerations of current situation of water security system in different regions, as well as regular discipline on urbanization, a coordinated combination of optimal mode is believed to realize sustainable development of water security system. Finally, the chapter takes Guizhou province of China and eight regions of Japan as cases studies to carry out simulation for different type's development scenarios of water security in the future.

IN CHAPTER 8, CONCLUSIONS, the conclusions of whole thesis is deduced and the future work about optimization of water security system has been discussed.

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Chapter 1

BACKGROUND AND PURPOSE

CHAPTER 1: BACKGROUND AND PURPOSE

1.1 Introduction

Water is complex because it is linked to almost everything in the world. But complexity should not hinder understanding: Water is a precondition for human existence and for the sustainability of the planet. Water covers 70% of our planet, and it is easy to think that it will always be plentiful. However, 97% of water is saltwater and a little less than 3% of freshwater is hard to access. Only a mere 0.014% of all water on Earth is both fresh and easily accessible. Freshwater—the stuff we drink, bathes in, irrigates our farm fields with—is incredibly rare. Worse still, many of the water systems that keep ecosystems thriving and feed a growing human population have become stressed. Rivers, lakes and aquifers are drying up or becoming too polluted to use. More than half the world’s wetlands have disappeared. Agriculture consumes more water than any other source and wastes much of that through inefficiencies. Climate change is altering patterns of weather and water around the world, causing shortages and droughts in some areas and floods in others. These shifts severely impact lives and livelihoods. Decreased water supplies mean more human suffering and increased risk of instability, violent conflict and migration. Often the regions affected most deeply by environmental changes are already impoverished, and lack the resources necessary for sound water management. At the current consumption rate, this situation will only get worse. By 2025, two-thirds of the world’s population may face water shortages. And ecosystems around the world will suffer even more.

Water security is therefore concerned with water scarcity, water pollution, and both chronic pressures and extreme events. Water security has attracted widespread attention in both academic and policy circles [1, 2]. The most common threat to water security is water scarcity. Water scarcity already affects every continent. Water use has been growing globally at more than twice the rate of population increase in the last century, and an increasing number of regions are reaching the limit at which water services can be sustainably delivered, especially in arid regions. There can be several causes to water scarcity including low rainfall, climate change, high population density, and overall location of a water source. Another category of threats to water security is environmental threats. These include contaminates such as biohazards (biological substances that can harm humans), climate change and natural disasters. Contaminants can enter a water source naturally through flooding. Contaminants can also be a problem if a population switches their water supply from surface water to groundwater. Natural disasters such as hurricanes, earthquakes, and wildfires can damage man-made structures such as dams and fill waterways with debris. Other threats to water security include terrorism and radiation due to a nuclear accident. Therefore, it is critical to aggregate measure of quantitative, qualitative, regulatory and market based risks to local availability of adequate water supply, as well as risk of flooding.

1.2 Research background and significance

1.2.1 Proposal and evolution of water security

Water security, as a macroscopic and holistic concept, was first put forward during the 2nd World Water Forum in 2000 [3]. In the beginning, the concept and framework had been discussed by experts with different professional backgrounds from different perspectives. In a broad sense, it covers natural ecosystems and all human activities related to water. It is commonly embedded in social demographic system, economic system, and ecological system [2]. Simultaneously, it is not only linked to food security [4] and energy security [5], but also to human sociology [6], psycho social [7], political security [8], etc. In the broad concept of WS, it includes both certain objectives and some means of implementation. There is no clear boundary between goals and means. In a narrow sense, it is aimed at a specific water issue, such as water supply security including improving water supply infrastructure [9] and expanding water supply sources [10], drinking water security [11, 12], water use efficiency in agriculture [13], and water biodiversity [14]. There is no uniform WS concept standard because different professions have different understandings of WS. The changing interpretations reflect the changing insights and focuses of WS. The aim of WS is changed from a single goal of relevant policy and interventions to the multiple and cohesive macro goals, and then again from the multiple goals is transferred to the specific single goal. However, this cycle is not a simple repetition, but a spiral development. With the emergence of new water-related problems, the concept of WS is always changing. Fortunately, the term WS has been continuously enriched and improved. In this context, experts and policy-makers are always in a state of confusion. Therefore, it is necessary to reorganize the initiate, connotation and extension, and the evolution of WS and. It is benefit to clear the exact meaning of the terms for the future development of WS. Regardless of how the description of WS changes, it is achieved as a goal. Table 1-1 shows the representative WS definitions. However, we can find something in common, both in the broad and narrow sense. 1. WS is a dynamic state, not a static result. 2. WS is a goal, not the aggregation of various means. 3. Various water-related security issues are caused due to water balance being broken.

Table1-1 Definitions of water security

	Organizations/scholars	**Definition**
Broad sense (Extension)	**World Water Council [15]**	Ensuring that freshwater, coastal and related ecosystems are protected and improved; that sustainable development and political stability are promoted, that every person has access to enough safe water at an affordable cost to lead a healthy and productive life, and that the vulnerable are protected from the risks of water-related hazards
	Global Water Partnership [16]	Water security, at any level from the household to the global, means that every person has access to enough safe water at affordable cost to lead a clean, healthy and productive life, while ensuring that the natural environment is protected and enhanced
	United Nations Water [17]	Capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development
	Romero-Lankao, P., and Gnatz, D. M. [18]	Urban water security as the capacity of urban water actors to maintain a sustainable availability of adequate quantities and quality of water, to foster resilient urban communities and ecosystems in the face of uncertain global change
	Jepson, et al. [19]	Securing the ability to engage with and benefit from the sustained hydro-social processes that support water flows, water quality, and water services in support of human capabilities and wellbeing
Narrow sense (Connotation)	**The Food and Agricultural Organization [20]**	The ability to provide adequate and reliable water supplies for populations living in the world's drier areas to meet agricultural production needs
	United States Environmental Protection Agency [21]	Water security as prevention and protection against contamination and terrorism
	United Nations Educational, Scientific and Cultural Organization [22]	Water resources security comprises the sustainable use and protection of water systems, protection against water related hazards such as floods and droughts, sustainable development of water resources and safeguarding access to water functions and services for humans and the environment
	Al-Saidi, M. [23]	Water security as institutional harmony and peaceful cooperation

In the sense of water resources security, it mainly resolves water scarcity problem. Water scarcity is one of the greatest challenges of the twenty-first century. The balance of water resource supply-demand relationship is the most important key of water scarcity [26]. As water scarcity is defined as an imbalance of supply and demand, it impacts those areas where a lack of infrastructure or capacity prevents sufficient access to water as well as the regions that have a physical scarcity of water. First of all, in terms of water supply side, water sources mainly come from that are called traditional water sources including surface water, underground water, and glacial snow-melt water. However, with the impact of climate change and human activities, water supply has become more challenging. In order to adapt this change, there has been an increased reliance on no-traditional water sources such as desalinated water, rain water, reclaimed water, etc. It is a tough task to protect water source areas to secure water supply [27]. In terms of water demand side, in general, it includes three major sectors i.e. agricultural, industrial, and household sectors. Agriculture, encompassing crops, livestock, fisheries, aquaculture and forestry, is both a cause and a victim of water scarcity. It accounts for an estimated 70 percent of global water withdrawals (Fig.1-1), while competition with other sectors for water is increasing and water resources are impacted by climate change, in terms of both quantity and quality. More frequent and severe water extremes, including droughts and floods, impact agricultural production, while rising temperatures translate into increased water demand in agriculture sectors. Water scarcity includes physical water scarcity and economic water scarcity. Physical water scarcity is caused by inadequate available water, while economic water scarcity results from lacking proper method to access sufficient available water. Therefore, the former ensures water resources security by means of inter-basin water division and virtual water trade, and the later realizes water resources security through increasing investment in water infrastructure or technology to draw water. According to the United Nations Development Programme [28], around one fifth of the world's population currently is affected by physical water scarcity and one quarter is affected by economic water scarcity. Water withdrawals grew at almost twice the rate of population increase in the twentieth century (from Fig.1-2), and a 50 percent surge in food demand is expected by 2050. It is clear that there is an urgent need to address water scarcity. Whether it belongs to physical water scarcity or economic water scarcity, it is essential to balance water supply and demand sides, to change the idea and way of using water. To implement the essence of water resources security is increasing water income and reducing water expenditure. Thence, the countermeasures for water scarcity, oriented for water quantity balance, include ensuring water supply capacity and improving water conservation capacity.

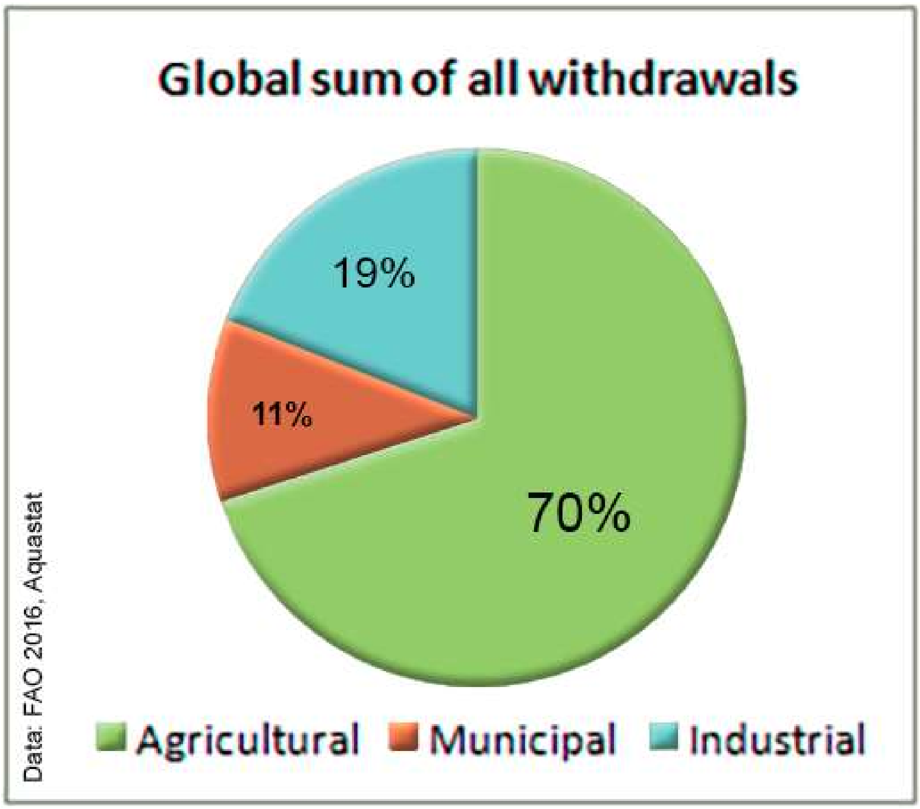

Fig.1-1 Global use of freshwater

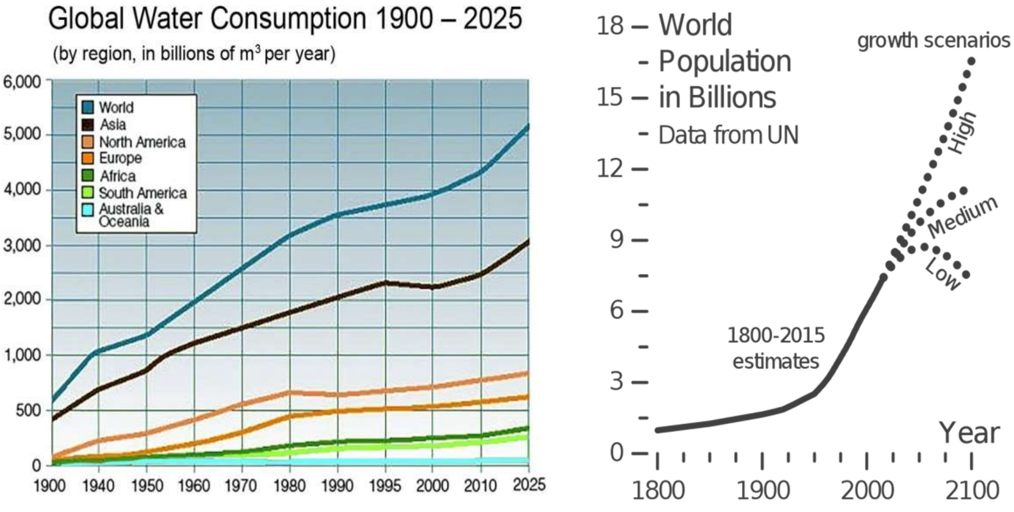

Fig.1-2 Global water consumption and population (Global water consumption from Sampa)

In the sense of water environment security, it is caused by water quality imbalance. In contrast to water resources security, water environment security mainly focuses on water pollution issue. According to the environmental campaign organization WWF, “Pollution from toxic chemicals threatens life on this planet. Every ocean and every continent, from the tropics to the once-pristine polar regions, is contaminated". Most human activities that use water produce wastewater. As the overall demand for water grows, the quantity of wastewater produced and its overall pollution load are continuously increasing worldwide. Over 80% of the world's wastewater – and over 95% in some least developed countries – is released to the environment without treatment. Water pollution includes surface water pollution, groundwater pollution, and marine pollution. Surface water pollution includes pollution of rivers, lakes and other surface water bodies. Water pollution is caused by contaminants resulting from human activities. The specific contaminants can cause alteration of acidity and temperature, eutrophication, and pathogens in water physical, chemical, and biological properties respectively. Runoff from agricultural land carries manure, pesticides and fertilizers (nutrients) into our waterbodies. In urban areas, water quality is affected by runoff from industry, housing, roads and storm water. Urban runoff may include heavy metals and other pollutants, as well as litter. Many harmful substances, including engine oil, garden chemicals and detergents will enter water courses if disposed of incorrectly. Nitrate and phosphate are important nutrients found naturally in water. However, human activities have dramatically increased the amount of nutrients in the environment, impacting water quality and causing huge changes to freshwater ecosystems. These activities include using fertilizers and changing land use, causing easier runoff and increased pollution. Before the global increase of industry at the turn of the 18th century, the only sources of nitrogen in fresh water were bacteria, volcanoes and lightning strikes. However, we can see from Fig.1-3, the use of nitrogen fertilizers has increased by 600 percent in the last 50 years. In order to make it more acceptable for different user (drinking, irrigation, industrial water supply, river flow maintenance, water recreation or many other uses), the contaminants and undesirable components in water need to be removed or their concentration should be reduced. Therefore, water treatment countermeasures, oriented for water quality balance, are any processes that improve the quality of water commonly including physical treatment, chemical treatment, and biological treatment.

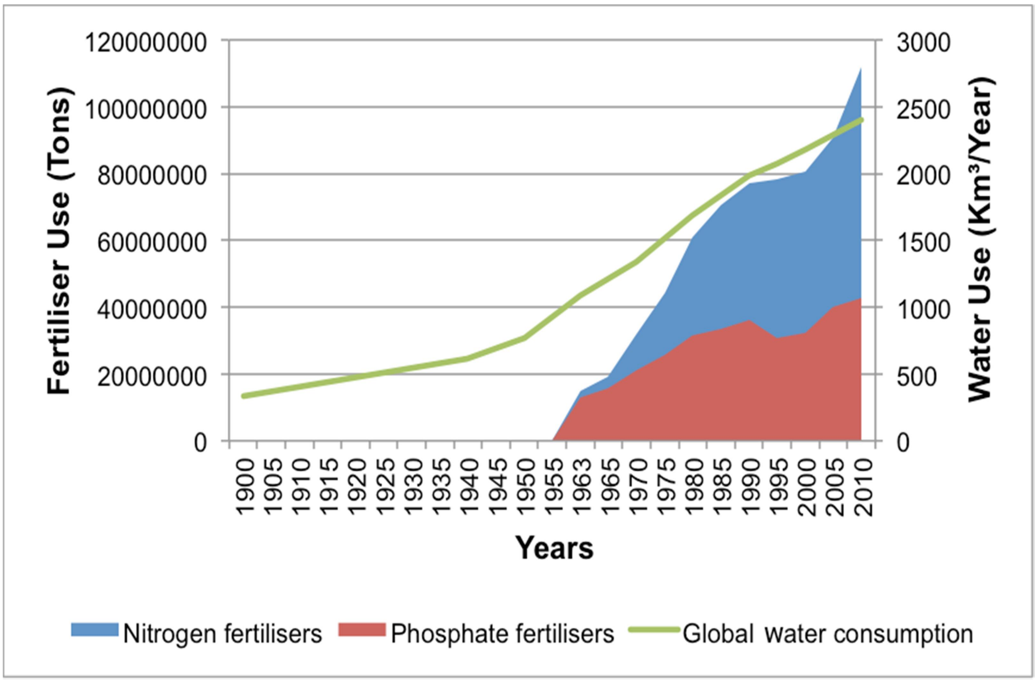

Fig.1-3 World-wide fertilizer use and water consumption

(Source:freshwaterwatch.thewaterhub.org/content/water-pollution)

In the sense of water disaster security, it occurs due to water resilience imbalance. The research object of water disasters is the disaster mechanism and process of too much and too little water (i.e. flood and drought), other water-related events (such as dam breakout), and other adverse effects on the economy, society and ecological environment. In the thesis, we mainly focus on flood disaster. Flood is a natural phenomenon in which the water volume of rivers and lakes increases rapidly due to natural factors such as heavy rain, sharp ice melting, and storm surges, or the water level rises rapidly. Its damage includes economic losses, water sources pollution, epidemics, environmental damage, etc. Flood has occupied 50% of total water related natural disaster and rest of the causes is landslide, famine, water related epidemic, drought etc. Seasonal monsoon rainfall often cause flood in south-Asia. Unplanned flood protection, land use, pollution also cause flood. Flood often carries a huge amount of sediments which ultimately settles in river bed and lessens the conveyance capacity of the river which causes flood. Main damage of flooding includes loss of life, damage of infrastructure and contamination of potable water. Fig. 1-4 shows increasing trend of flood occurrence from last century. So, water disasters countermeasures, such as flood planning [29, 30] and collective decision making [31], are any processes that improve the resilience of water infrastructures and adaptive ability.

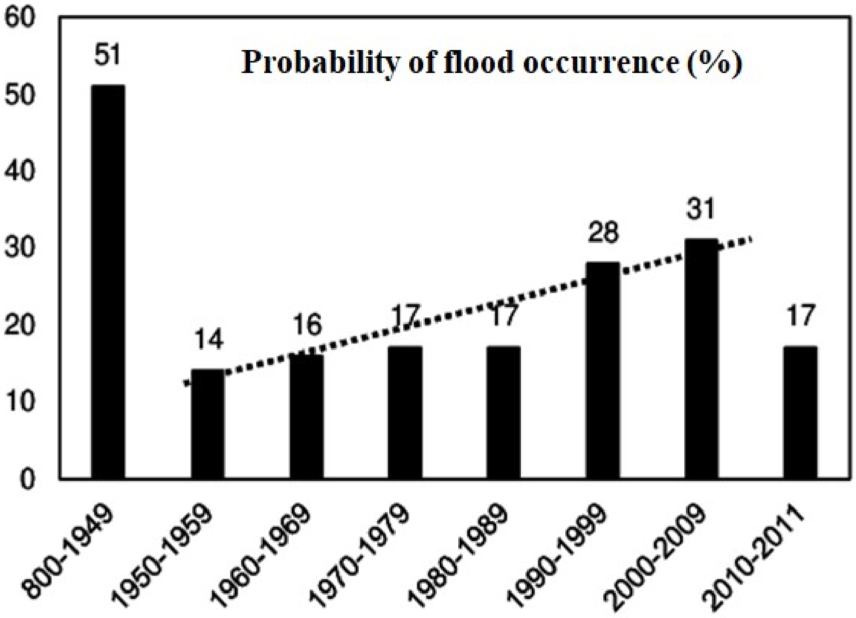

Fig.1-4 World-wide probability of flood occurrence (Source: Hossain, 2014) [97]

Therefore, based on the above descriptions we put forward the three pillars of WS: first, water resources security refers to solve freshwater scarcity issue, which continues to gain urgency in science and policy circles [24]; second, water environment security aims to protect water from degradation and pollution for guaranteeing public health, to maintain a good ecological status and sustainable functioning [25]; third, water disaster security focuses on eliminate the threats of water-related hazards and water emergency to solve water damage issue (See Fig. 1-5 for details). Water resources security, water environment security and water disasters security interact with each other. The emphasis of water resources security is on water quantity, while the water environment security is concerned with water quality. Water disasters (floods, droughts, or incidents of contamination) may sometimes be caused by “too much” or “too little” water quantity, and sometimes it may result from “too dirty” water quality, or it may be caused by both. In turn, water disasters will adversely affect water quantity and water quality, and interact with each other to form a chain of mutual causality. Only by ensuring the security of the three pillars can we truly achieve WS.

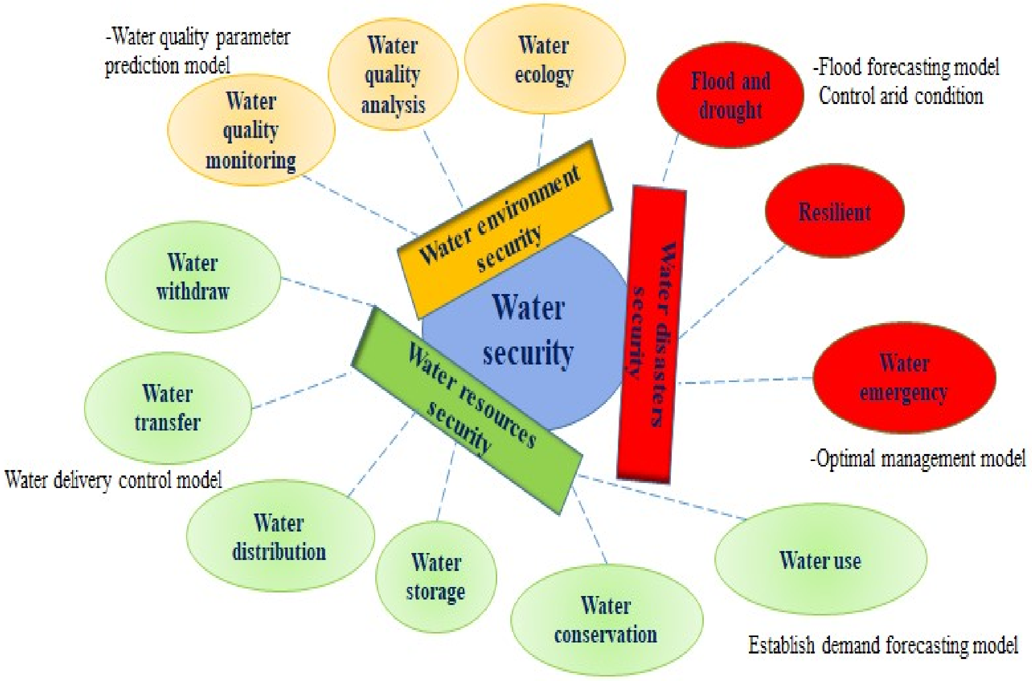

Fig.1-5 The contents of water security

In summary, in the thesis, WS is looked on as a dynamic goal and it has different meanings in different situations. With the emergence of new water-related issues, the concept of WS is constantly being replenished and enriched. How to solve these water insecurity issues, next we will introduce water management approaches.

1.2.2 Water management approaches for achieving water security

Almost all countries suffer different severity of water security issue. In the face of various water-related issues, experts have sought many solutions from different perspectives. These solutions reflect on the four focuses: shifting water management approach [32], establishing new legal and institutional frameworks [33], increasing adoption of market instruments [34], and developing new technology application. In the paper, we take the perspective of water management evolution on water security. Water management is the activity of planning, developing, distributing and managing the optimum use of water resources. Water management approach has been in a state of constant change since the term water security emergence. As the Fig.1-2 shows, traditional water management includes surface water management, water upstream management and water quantity management etc. These fragmented water management approaches are isolated and uncoordinated in the face of increased water stress due to population growth, increased economic activity, and water pollution. In the context, scholars initiated managing water in a “integrated” method in the 1980s and the integrated water management concept attracted much attention at the conferences on water and environmental issues in Dublin and Rio de Janeiro held during 1992 [23]. In the meantime, sustainable water management also was emphasized based on the sustainable development goals (SDGs). The most popular of integrated water management (IWM) was defined by the Global Water Partnership as “a process which promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems”. However, with the significant impact of climate change on water, new issues have been reflected in water sectors. For example, how to deal with the uncertain changes of water resources, how to improve the adaptability and flexibility of water management. Obviously the IWM approach is no longer applicable. A decade ago, the term adaptive water management became increasingly popular, inspired by the need to ‘adapt’ to climate change [35]. The definition of adaptive water management (AWM) was that the science–policy process to plan interactively for societal, ecosystem, and hydro-climatic uncertainties; initiate responsive action; and iteratively assess water security outcomes in societal and ecosystem resilience terms [36]. In order to response to the uncertain future of water resources immediately and more intelligent, it needs to collect a lot of data for interactive analysis. Hence, ICT technology was added to adaptive water management, and smart water management emerged as the times require. Smart water management (SWM) could be defined [37] as an intelligent water management model covering all aspects from water supply infrastructures to the production and distribution of water resources, digital data to manage water scientifically, ICT systems to process information in real-time and high-tech skills and equipment to use big data skillfully. In order to achieve each characteristic of water management in Fig.1-6, it is measured using specific indicators.

- ✧ Secure indicators

In terms of security characteristic, the security index is manifested in the support degree of water resources to the human socioeconomic development. It mainly includes the security of water availability, the security of water quality, the security of water risks, and the security of water sources diversity. The indicator corresponding to water availability is water poverty index [38] or water stress index [39]. The indicators used to interpret water quality, water risks, and water diversity are raw water quality index, flooding and public health risk index, and diversity of water sources index, respectively [40].

- ✧ Stable indicators

In terms of stability characteristic, the stability of water system refers to that the water supply side and the water demand side of the water system is in a dynamic balance process. And the water resource system has a strong ability to remain within desired states in the face of given changing conditions. It is similar with the concept of resilience [41]. Therefore, enhance the resilience of the water system, that is, to enhance the stability. Although both qualitative and quantitative resilience assessment methods have been proposed, most literatures still use qualitative methods. At present, there is no standard resilience assessment approach or metric [42].

✧ Sustainable indicators

In terms of sustainability characteristic, the sustainability index is manifested in the sustainable utilization degree of water resources by the human socioeconomic development. Water sustainability means the sustainable use of water resources to ensure the sustainable development of human society, economy and living environment. To date, there is no dedicated index system for the assessment of the sustainability of water management. We adopted the assessment system of the sustainability which is a composite index including four categories (social, economic, environmental and institutional), represented by a total of 16 indicators that are calculated using a total of 35 variables [35].

✧ Adaptable indicators

In terms of adaptability characteristic, it refers to reducing the uncertainty of water caused by climate change and the vulnerability of water-related disasters. Adaptive utilization of water resources is a kind of water management mode that adapts to environmental changes and guarantees the benign circulation of water system. Concerning adaptability, it is quantified by the indicator of adaptive capacity [43, 44]. Adaptive capacities is defined that capacities that facilitate learning, adapting to changes, and transforming management [45], including resources, (i.e., economic, technology, information and skills, infrastructure) institutions, and equity.

✧ Intelligent indicators

In terms of intelligence characteristic, the target is to create an integrated, intelligent water system that helps us to use water wisely. Information communication technology will help us to better understand, improve and manage our water. The intelligence mainly shows in four aspects: 1. effectively measure what water is available; 2. automatically monitor when and where the water needed; 3. computer analysis to determine how much water each sector needs; 4. interpret and make intelligent decisions from the information collected.

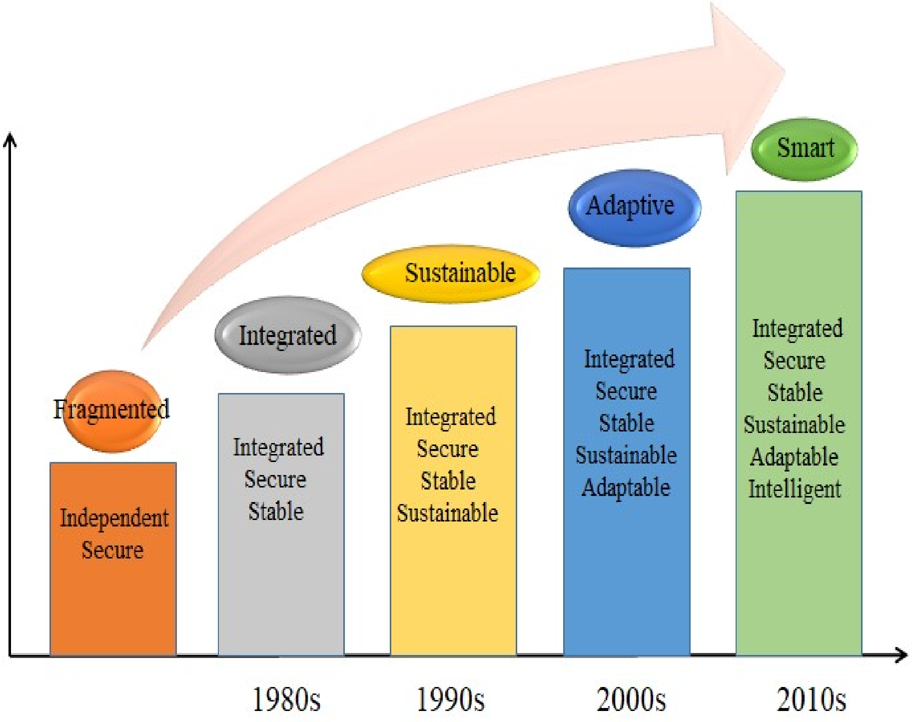

Fig.1-6 Evolution of water management approaches

1.2.3 Opportunities and challenges of water security

With the development of new technology, cloud computing, Internets of Things (IOT), and Supervisory Control and Data Acquisition (SCADA) technologies have been applied in the smart water management in order to achieve water security. It is an excellent opportunity for managers to allocate water resources in real-time monitoring and management. According to previous studies concerning smart water grid [46, 47], the relevant layers depicted in Fig.1-7 can be mainly divided into: the perception physical layer, the transmission control system, the collection processing layer, the manage display layer, and the fusion analysis layer. In addition, the technologies applied in the layers can be classified by function as follows: ① monitoring, collecting, and stored data technologies for the perception physical layer, ② data transfer technologies of mobile WIFI in the transmission control layer, ③ clouds computing and GIS (Geography Information System) technologies in collection processing layer, ④ IOT (Internets of Things) technology in management layer, and ⑤ SCADA (Supervisory Control And Data Acquisition) and analysis technologies to enable the effective operation of the center control layer.

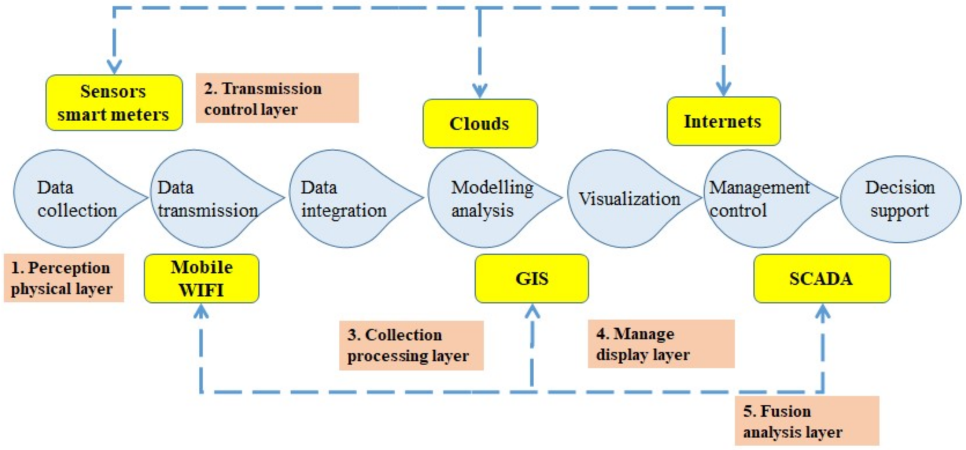

Fig.1-7 The layers and technologies of smart water grid

Of course, there are also various challenges in the water management approaches for achieving water security. In the implementation of IWM, it mainly includes the lack of relevant data exchange, specific information, and planning coordination between departments and regions. Among the most significant two obstacles are lack of considering local realities and the decision on adopting specific or holistic solution. Regarding the local realities, the IWM approach did not consider the local political institution and cultural background. Just as the Allan [48] pointed out, developing countries in the global south rely on the implementation of water policy in face of water management issues, while developed countries in the global north depend more on the upgrading and development of technology. Additionally, water management issues and priorities are also different in different countries. With regard to the decision on adopting specific or holistic solution, the benevolent see benevolence and the wise see wisdom. Regarding the holistic solution of water management, the relevant authors have studied and explored how to “integrate” different water issues under this framework. Unfortunately, professionals have not reached an agreement on what is IWM. What kind of water issues should be integrated, the instruments of water management and the objectives to be achieved all depend on the stakeholders and institutions concerned, and their interests. What’s more, they considered that “integrated” means bring not any benefits and improvement, but also high cost and mask for other agendas [49]. At the same time, they also believed the role and effectiveness of IWM are not obvious in solving specific problems. Therefore, they argued the IWM approach can be replaced by other specific solution, while it is no need to focus on holistic solution.

Concerning the AWM approach, scholars [50] have proposed that it is very difficult to achieve adaptive water management, because adaptive management requires integrated learning of social and ecosystems. The integrated learning requires a specialized database to provide a large amount of basic data. Moreover, even if the requirements for integrated learning are fulfilled, the transition from recognizing to action is also a difficult process. Other major problems encountered are monitoring technology and high costs [51]. AWM requires long-term monitoring of water-related data so that it can make a rapid and accurate respond to the uncertain change of water resources. Although the monitoring problem was solved by the initiated SWM approach later, funding is still a problem. Therefore, few successful cases of AWM projects are implemented or exists too short to evaluate the effectiveness [52].

In terms of SWM, there are four main problems facing SWM development and smart water grid construction. First, the government has not fully engaged the public in smart water management project. The public lack awareness about this technology and water conservation. Moreover, the public believe that the smart water devices cause health problems and physical ailments because the smart water meter utilizes radio frequency. Second, the most important problem is the need for sufficient funding and investment to implement smart water management technology. In addition, upgrading and maintaining existing infrastructure including improving water sources system, water storage and treatment facility, and water distribution and transmission infrastructure also needs high costs. For instance, according to the survey of Environmental Protection Agency of United States, it will costs 384 billion dollars to improve the current drinking water infrastructure through 2030 [53]. Third, there is an economic disincentives problem. It requires longer payback periods for the investment in applying the technology of SWM approach to improve water efficiency, which is a huge challenge for smaller water utilities. Additionally, although it is beneficial to the whole society to realize SWM, it is only an additional cost and burden from the perspective of the water utility company. Fourth, the extent to which disasters can affect the smart water grid is uncertain in SWM approach. The smart water grid is vulnerable in facing the natural events [54]. The incidents including flood and drought, forest fires etc., affect water quantity and quality at the sources.

1.2.4 Research significance

For many countries, water scarcity represents the most pressing challenge to socio-economic and human development at large. Furthermore, increasing human pressure threatens the ability to provide adequate water resources and functioning of ecosystem services in the arid and semi-arid regions and is particularly vulnerable to climate variability and changes.

Declining water quality has become a worldwide concern as human populations grow and economic activities expand. Poor water quality makes water unfit for use, has multiple health and environmental consequences, and further reduces water availability. Water pollution is becoming one of the greatest threats to freshwater availability. Water security aims to make a significant contribution to understanding and managing water quantity and quality worldwide, and especially in the developing world.

The number of fatalities and economic damage caused by water-related disasters, such as floods and droughts, landslides and land subsidence, is dramatically increasing worldwide, mainly as a result of more people living in areas vulnerable to water-related disasters. Land-use changes, urbanization, migration patterns, energy issues and food production are derived from population change and economic development, with climate change and variability likely to exacerbate the risk with more uncertainties. The great challenge for the hydrological community is to identify the impacts of such global changes on water resources and to appropriate and timely propose and implement adaptation measures in a continuously changing environment. We also need to ensure that policy makers have access to the best available knowledge when making decisions to develop and put in place relevant policies to address such challenges.

Given population growth, deteriorating water quality, the growing impact of floods and droughts and the other hydrological effects of global change, water security is a growing concern. It touches upon all aspects of life and requires a holistic approach, which actively integrates social, cultural and economic perspectives, scientific and technical solutions and attention to societal dynamics. It needs to strength the science-policy interface to reach water security at local, national, regional, and global levels.

1.3 Review of Previous Study

1.3.1 Study on water resources

Water scarcity is increasingly becoming the biggest bottleneck for urban future development. In this sense, how to coordinate the sustainability between social-economy and water resources is very significant [55]. In order to achieve sustainable utilization of water resources and meet regional demand for water use, some commonly used methods, such as analytical hierarchy process [56], data envelopment analysis [57], are applied to comprehensively evaluate the water resources. In another way, some researchers were inspired by the concept of ecological footprint [58, 59]. This method measures the sustainable development of the region by estimating the difference value of ecological carrying capacity and the amount of required productive space (ecological footprint) for sustaining the human consumption of natural resources and assimilating human waste. For example, Wiedmann et al. [60] allocated the ecological footprint according to input and output analysis; Jia et al. [61] combined ecological footprint with ARIMA model; Miao et al. [62] performed a grade classification of environmental quality based on ecological footprint; Liu et al. [63] calculated the ecological footprint of campus based on life cycle assessment. The application of ecological footprint model is also very extensive depending on different scales. Verhofstadt et al. [64] applied it to individual consumption assessments. It can also be used in tourist activities [65], even households studies [66]. Commonly, it was applied to city's ecological footprint assessments [67], regional ecological footprint studies [68], and the research of ecological footprint in a country [69, 70]. Additionally, it can be embedded in hybrid multi-scale analysis [71].

1.3.2 Study on water environment

Since the beginning of 19th century, the rapid growth of human populations in urban areas, resulting from the industrial revolution, led to large quantities of domestic sewage discharge into the water environment, which [72] resulted in the outbreak of waterborne diseases such as cholera. This led to an understanding of threats associated with polluted water [73] and, for the first time, the realization of the importance of WES. Later, during the 20th century, water issues such as organic pollution and eutrophication, also threatened the health of human communities [72, 74, 75]. People perceived the water environment passively through pollution issues but began to develop a fundamental recognition of the need for WES, particularly in terms of quality, and how this related to the basic demands of industrial production and public living. At the same time, the rapid development of water treatment technology in the 20th century resulted in an amelioration of water pollution and improved water quality. The outbreak of "Itai-Itai Disease" and "Minamata Disease," however, broke the illusion as it became clear that apparently-clean water was not equivalent to environment security [75, 76]. A new aspect was added to people's perspective of water environment security: a secure water environment should not only meet the basic demand for production and life, but also protect the public from health risks in the long and short-term. Since the beginning of 21st century, great progress has been made in water pollution control and water quality has improved in many countries. The emphasis of water management in some developed countries switched to aquatic ecological restoration and protection [77]. The third aspect attached to WES is the need to ensure good water quality to protect aquatic life and the environment, so as to attain a high ecological status and sustainable functioning

1.3.3 Study on water disaster

Li Senyan and Zhu Xiaoyan [78] establish a flood disaster quantitative analysis model by using matter element extension method, indicators of floods disaster response, and analytic hierarchy process method. Tian Yugang and Tan Donghua [79] express flood risk as results of the average annual disaster losses and terrain hazard together, put forward to the threshold method based on the data field and flood risk level of , and apply it in a flood risk assessment of the Dongting Lake. Shi Yong and Xu Shiyuan [80] analyze variation of Shanghai suburb of agricultural flood vulnerability based on the CCR envelopment analysis input-output model. The results show that the method is reliable scientifically. Yu Xiaoling [81] analyzes the current situation of the central and local governments in water disaster, build game model to study the decision-making behavior of the investment share, and finally put forward to countermeasures of water disaster fund. Liu Juan [82] estimates the flood and drought hazard rate of provinces and regions by the hazard rate of flood and drought affected, the standard variance of rate and the hazard rate, water conservancy investment annual growth rate. He draws the conclusion: in recent years, increasing investment in water conservancy, but the water investment is used for the defenses of the flood of investment, neglecting the management of drought.

1.3.4 Study on water security system

Challenges faced by more and more countries in their struggle for economic and social development are increasingly related to water. Water shortages, quality deterioration and flood impacts are among the problems which require greater attention and action. This situation recalls the need for a holistic approach to management, recognizing all the characteristics of water security system and its interaction with society and ecosystems. The scholars also recognize that water security is required for many different purposes, functions and services; integrated management, therefore, has to involve water security in a holistic system consideration. The water security system is a large, complex and nonlinear system [83-85]. When water shortage occurs, not only the social system but also the original environmental and aquatic ecological equilibrium are affected [86, 87]. Any individual water-related activity or issue may have profound effects on the relevant processes and factors within a water system [88-91]. Systematic thinking for any variations in water-related activities is thus desired [92]. Simonovic et al. [93] used STELLA II to establish a goal-oriented model to analyze the potential advantages of water resources planning in the Nile River Valley in Egypt. Assaf [94] established a groundwater resource management model based on economic principles to explore water resource management policies for different water requirements in the Middle East and North Africa. Sánchez-Román et al. [95] built a SD simulation model based on the STELLA platform to simulate and evaluate the water carrying capacity of 3 basins in Brazil. Wang et al. [96] developed an integrated approach of SD, orthogonal experimental design and inexact optimization to support water resources management under uncertainty and applied it in water-stressed areas.

1.4 Purpose of this study

The world population has increased by a factor of about three during the 20th century whereas water withdrawals have increased by a factor of about seven. It is estimated that currently one third of the world's population live in countries that experience medium to high water stress. This ratio is expected to grow to two thirds by 2025. Pollution of water is inherently connected with human activities. In addition to serving the basic requirement of biotic life and industrial processes, water also acts as a sink and transport mechanism for domestic, agricultural and industrial waste causing pollution. Deteriorating water quality caused by pollution influences water usability downstream, threatens human health and the functioning of aquatic ecosystems so reducing effective availability and increasing competition for water of adequate quality. The above problems are aggravated by shortcomings in the management of water. Sectoral approaches to water resources management have dominated and are still prevailing; this leads to the fragmented and uncoordinated development and management of the resource. Moreover, water management is usually left to top-down institutions, the legitimacy and effectiveness of which have increasingly been questioned. Thus, the overall problem is caused both by inefficient governance and increased competition for the finite resource. A combination of social equity, economic development and water resources programmers is essential for people living in extreme water condition to overexploit water resources, which often results in positive impacts on water resources.

The term water security shows an overwhelming superiority in both policy and academic circles. Firstly, the thesis reviews the multiple interpretations of water security. Specifically, we emphasize that water security, as one of the human sustainable development goal, consists of three pillars: water resources security focusing on water scarcity issue; water environment security focusing on water pollution issue, and water disasters security focusing on water damage issue. Secondly, it assesses and contrasts the three pillars of water security, which are as the basic elements to achieve water security. A prevailing element, i.e. water resources security, seeks to promote the coordinated development and management of water demand and water supply. A second, water environment security is found to address water pollution. A third, water disaster security is developed to address the harmony between man and water. Thirdly, the study mainly discusses the integrated situation of water security and policy formulation from integrated water management perspective. Finally, this thesis presents the optimal simulation model of water security system based on system dynamics. Although water security system is a complicated and huge system, our focuses can provide a map for water policy makers and stockholder companies to guide the future development of water management and realizing water security. The flow chart of this thesis is described in Fig.1-8.

- Background and purpose

In chapter one, research background and significance of water security is investigated. In addition, the importance of plan and evaluation of water security is analysis and the previous study about this research is reviewed. Finally, Purpose of this study is proposed.

- Methodology and approach

In chapter two, firstly, the concept and application of ecological footprint model for water scarcity and water pollution issues is introduced. Then method of fuzzy comprehensive evaluation for water disaster issue is depicted. In addition, theory, development history and application methods for system dynamics model are described. Finally, the merit and demerit of ecological footprint and system dynamics is discussed and the future improved work is put forward.

- Assessment of water security's three pillars

In chapter three, water resources security (WRS) in a period of 2004-2015 in Beijing, Shanghai, Tianjin, and Chongqing is investigated, WRS is constructed based on resources from both supply and demand sides, strategies focus on improving water ecological carrying capacity and reducing water ecological footprint. Analysis results of water ecological footprint in economic sectors reveal the water consumption intensity in different cities and water balance analysis uncovers the situation of water resources sustainable utilization.

In chapter four, assessment of water resources security (WRS) and water environment security (WES) is conducted from the spatio-temporal perspectives in Japan respectively. It is investigated water security from not only water quantity but water quality in this section. In addition, water sustainability indicators are applied to evaluate the water sustainable utilization.

In chapter five, water disaster security (WDS) is assessed by taking 30 pilot cities of China. Firstly, introduces the comprehensive evaluation framework of WDS. Then fuzzy comprehensive evaluation model and cluster model are used to assess and classify the objects. The results obtained include that: (1) the resilient performances of the four factors in sponge city were elaborated and the ranking was divided into five levels; (2) the comprehensive resilience result, which was mainly influenced by the organizational structure factor and the ecological water indicator, was determined by weighted average principle; (3) in order to help develop more effective policies to improve China's flood disaster management, the 30 sponge cities were classified into 3 classes based on the comprehensive resilience results and cluster analysis.

- Integrated assessment of water security

In chapter six, integrated water security is measured from the three dimensions water resources security, water environment security and water disaster security in this section. The set pair analysis method is applied to aggregate the three pillars of water security. First of all, the current situation of water resources security, water environment security, and water disaster security is presented respectively. Afterwards, the current situation of integrated water security is discussed.

- Scenarios simulation of water security system

In chapter seven, water resources subsystem, water environment subsystem, water disaster subsystem, economic subsystem, and population subsystem are aggregated together in to a water security system. From system dynamics perspective, the performance of different scenarios based on parameters adjustment is simulated. The future behaviors change of subsystems in different scenarios can be obviously observed and comparable under different driving parameters. Subsequently, the influence of the variables of each subsystem on water security is analyzed. Finally, reasonable suggestion or relevant improved policy to different subsystems is proposed.

- Conclusion & outlook

In chapter eight, a conclusion of whole thesis is deduced and the future study about simulation and optimization of water security system has been discussed.

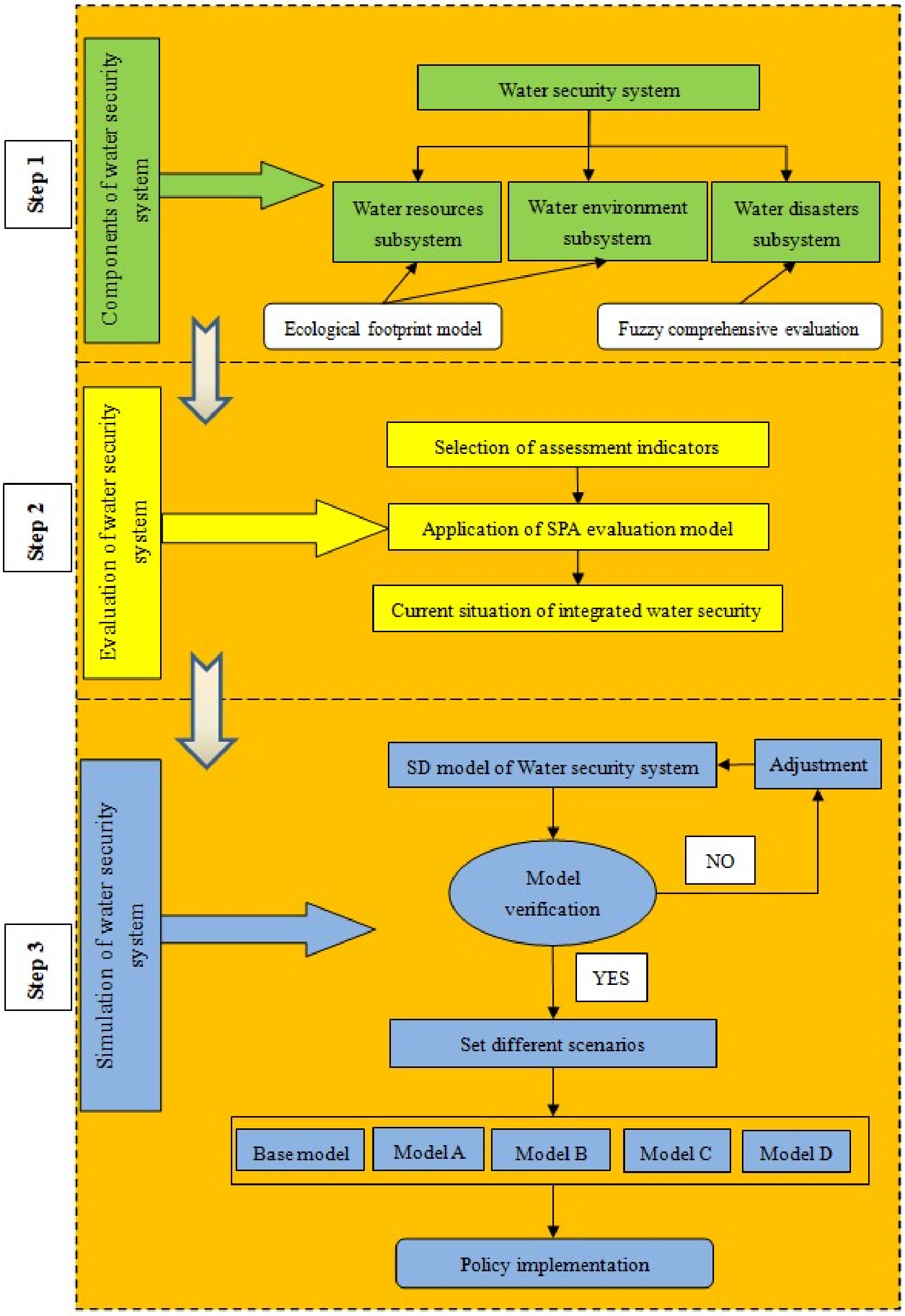

Fig.1-8 Research flow chart of the thesis

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Chapter 2

MOTIVATION AND METHODOLOGY

CHAPTER 2: MOTIVATION AND METHODOLOGY

2.1 Motivation

There are two ways to evaluate the consumption of water resources from the perspective of ecological footprint at home and abroad. One way is water footprint model which was originally proposed by Hoekstra [1]. The model converts water-related consumption into water quantity with the concept of virtue water. However, it is different from the ecological footprint model's measurement unit and cannot assess the sustainable use of water resources. It can only be used as an integral part of the family of footprints [2]. The other way is the water ecological footprint model (WEF) which was proposed by the Chinese scholar Fan [3]. The consumption of water resources is converted into the required water productive area that could be compared globally. As a step forward, the WEF model was extended by Chinese scholars Huang et al. [4] who pointed out the limitations of water function description in the ecological footprint model. For example, water as one of the six major types of production land in ecological footprint model was defined as the productive water surface. However, biological production is only one function of water area. In order to address the limitations of neglecting the role of water resources in social and economic development in the traditional model, the seventh land type—water resources was established. And then water resources accounts were established. The accounts contrast the water biologically productive area people use for their consumption to the water biologically productive area available i.e. water ecological carrying capacity (WEC) within a region or the world. In short, according to the comparison between the WEF and WEC, we know that whether the local water use is sustainable or not. When local water ecological carrying capacity can support the local water ecological footprint, we call it as the water ecological surplus (WES); otherwise, we call it as the water ecological deficit (WED). The WEF and the WEC can be compared at the individual, regional, national or global scale. Both the WEF and the WEC change every year with number of people, per person consumption, efficiency of water use, and water endowments. It is simple and convenient to assess the sustainable utilization of local water resources through the WEF and overcome the shortcomings of water footprint. The implementing meaning of water ecological footprint and the cases study of comparison is that: on one hand, the problem of water resource caused by the imbalance between supply and demand, WEC is a basic measurement of water resource security that plays an important role in recognizing and building water resource security system. The ecological footprint method can estimate human occupation of natural assets and the comprehensive carrying capacity of the study area. It can also be used to estimate the degree of human development and utilization of water resources as well as the capacity of water resources to carry the "natural and socio-economic environment" system, and measure whether, or not, the development and utilization of water resources are within the range of the ecosystem's carrying capacity, by using the specific biological and physical indicators. So, the paper adopted water ecological footprint indicator to have a try to combine water footprint and ecological footprint from both the water demand and water supply sides. On the other hand, as we all know, regionalism is one of the characteristics of geography. Water resources are one of the geographical elements. In different regions, it differs in the spatial and temporal distribution of water resources, in the structure of water supply and water use, and in the utilization efficiency of water resources. The reasons for the shortage of water resources are also varied. These differences are the basis of regional comparative studies and also the basis for the study of water ecological footprints among different cities. Because of the different characteristics of regionalism, the sources of water resources, water use structure, water quantity, and water quality have different natural and socio-economic conditions. Due to the regions facing different water-related problems, it leads to different development potentials and possibilities. So, the paper performed a comparative study of WEF indicators. Therefore, based on the two reasons, the WEF is applied to study the water resources security and water environment security. Simultaneously, comparing the WEF indicators in different cases to further understand the sustainable utilization of water resources and forecast the WEF so as to define the future trends of WEF of different cases.

Fuzzy comprehensive evaluation (FCE) method is a comprehensive evaluation method based on fuzzy mathematics. The comprehensive evaluation method transforms qualitative evaluation into quantitative evaluation according to the membership degree theory of fuzzy mathematics that is, using fuzzy mathematics to make an overall evaluation of things or objects subject to various factors. It has the characteristics of clear results and strong system, which can solve fuzzy and difficult to quantify problems, and is suitable for solving various non-deterministic problems.

System dynamics is an aspect of systems theory as a method to understand the dynamic behavior of complex systems. The basis of the method is the recognition that the structure of any system, the many circular, interlocking, sometimes time-delayed relationships among its components, is often just as important in determining its behavior as the individual components themselves. Examples are chaos theory and social dynamics. It is also claimed that because there are often properties-of-the-whole which cannot be found among the properties-of-the-elements, in some cases the behavior of the whole cannot be explained in terms of the behavior of the parts. The rapid development of society and economy, as well as the growing population, has drastically changed the social environment and water security. No in-depth research has investigated the interaction among water security, society, and the economy through the SD method. Meanwhile, a water security system includes the subsystems of water resource security, water environment security, and water disaster security. All the subsystems interact with and restrain each other. Furthermore, considering that most researches [5-7] have focused on the issue of a single subsystem or has ignored the water disaster security subsystem easily, this study integrates multiple factors.

2.2 Basic theory of water ecological footprint

2.2.1 Water ecological carrying capacity

An increase in global population can result in a decrease in bio capacity. This is usually due to the fact that the Earth’s resources have to be shared; therefore, there becomes little to supply the increasing demand of the increasing population. Resources will run out due to the increasing demands and as a result a collapse of an ecosystem can be the consequence of such actions. According to ecological footprint theory, the biological production capacity of water resources is used to measure the water ecological carrying capacity (WEC), that is, the corresponding biological survival area that the water resources can carry. Fig.2-1 shows the stepwise framework. The following are the formulas of WEC [8]:

$$WEC = N \bullet wec = \left(1 - 0.12\right) \bullet \psi_w \bullet r_w \bullet (Q / p_w) \tag{2.1}$$

Where, *WEC* (gha) is the water ecological carrying capacity; ψ_w is the yield factor of study area; r_w is the global balance factor of water resources; Q (m^3) is the regional total amount of water resource; p_w (m^3/hm^2) is the global water yield per unit area. It is a normal practice to allocate 12 % of the available supply land to protect the local biodiversity [9].

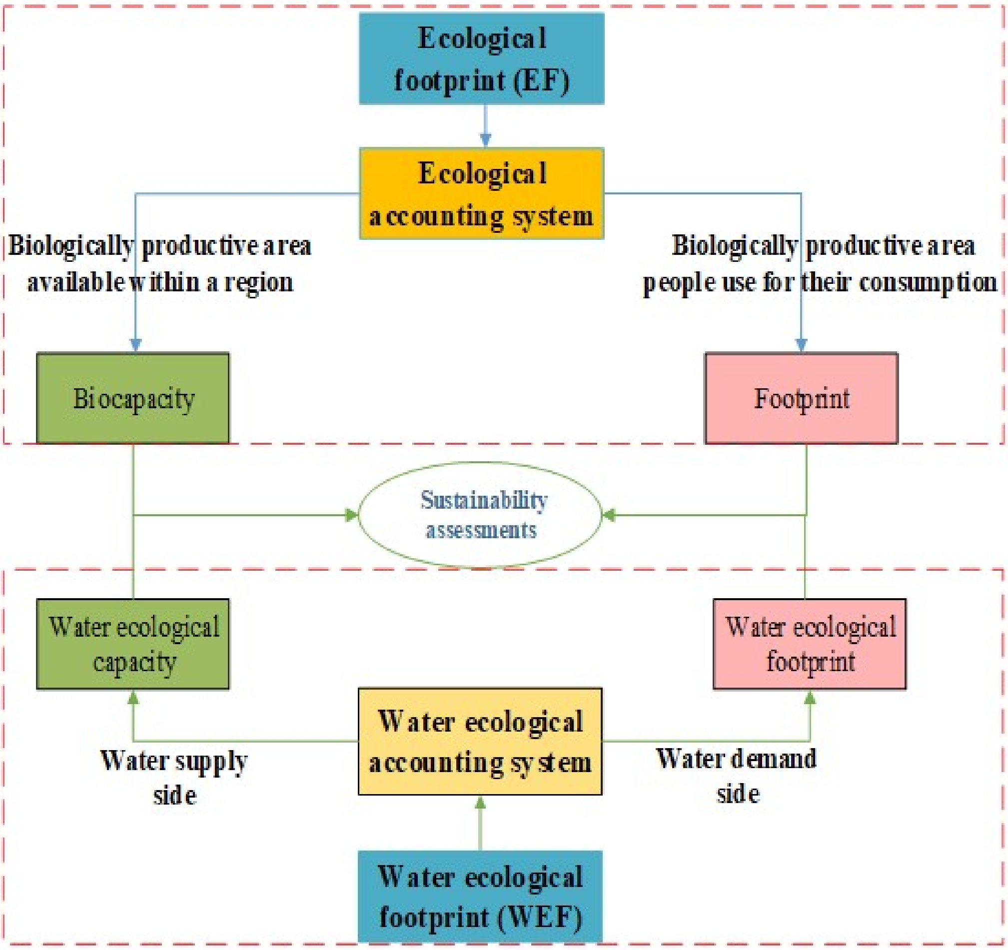


Fig.2-1. Water ecological footprint evaluation framework

2.2.2 Water ecological footprint

The water ecological footprint measures human demand on water resources, i.e., the quantity of water it takes to support people or an economy. It tracks this demand through a water ecological accounting system. The accounts contrast the water productive area people use for their consumption to the water productive area available within a region or the world. In short, it is a measure of human impact on water and reveals the dependence of the human economy on water capital.

The calculation model of ecological footprint of water resources is:

$$WEF = N \bullet wef = r_w \bullet (W / p_w) \tag{2.2}$$

Where, WEF (gha) is the total ecological footprint of water resources, wef (gha/cap) is the WEF per capita, and W (m^3) is the consumption of various types of water resource.

2.2.3 Water sustainability indicators

a. When the WEC is less than the WEF in a region, it goes into water ecological deficit (WED) and indicates that human pressure on water exceeds the water sustainability. On the contrary, when the WEC is more than the WEF in a region, it goes into water ecological surplus (WES), which means its regional water utilization is sustainable.

$$WES\,/\,WED = WEF\text{-}WEC \tag{2.3}$$

b. To further investigate the sustainable utilization of regional water resources, an indicator of water ecological press (WEPI) is introduced, which is the ratio of WEF to WEC. According to the classification standard of Chu-xiong [10], if WEPI < 0.5, the utilization of water resources in the region is in a secure state; if 0.5≤WEPI<0.8, it is a sub secure state; if 0.8≤WEPI≤1, it is a critical state; if WEPI >1, it is insecure.

$$WEPI = \frac{WEF}{WEC} \tag{2.4}$$

c. Water use efficiency index (WUEI) is a terminology that can be defined at the watershed, farm, field, individual plant or even at the scale of the leaf [11-13]. In most cases, water use efficiency refers to the ratio of water input to useful economic/product output [14]. The WEF of per ten thousand yuan Gross Domestic Product (GDP) refers to the ratio of regional WEF to regional GDP, which can be used to measure the water use efficiency in WEFM.

$$WUEI = \frac{WEF}{GDP} \tag{2.5}$$

2.3 Basic theory of fuzzy comprehensive evaluation

2.3.1 Fuzzy set

In mathematics, fuzzy sets (aka uncertain sets) are somewhat like sets whose elements have degrees of membership. Fuzzy sets were introduced independently by Lotfi A. Zadeh [15] and Dieter Klaua [16, 17] in 1965 as an extension of the classical notion of set. In classical set theory, the membership of elements in a set is assessed in binary terms according to a bivalent condition — an element either belongs or does not belong to the set. By contrast, fuzzy set theory permits the gradual assessment of the membership of elements in a set; this is described with the aid of a membership function valued in the real unit interval [0, 1]. Fuzzy sets generalize classical sets, since the indicator functions (aka characteristic functions) of classical sets are special cases of the membership functions of fuzzy sets, if the latter only take values 0 or 1[18]. In fuzzy set theory, classical bivalent sets are usually called crisp sets. The fuzzy set theory can be used in a wide range of domains in which information is incomplete or imprecise, such as bioinformatics [19].

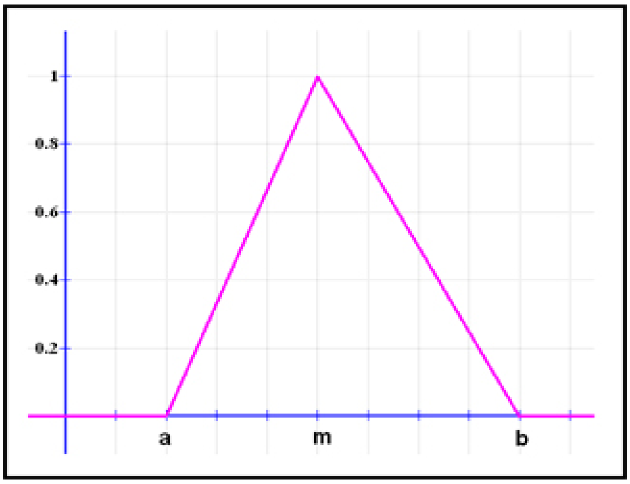
2.3.2 Membership functions

The membership function of a fuzzy set is a generalization of the indicator function in classical sets. In fuzzy logic, it represents the degree of truth as an extension of valuation. Degrees of truth are often confused with probabilities, although they are conceptually distinct, because fuzzy truth represents membership in vaguely defined sets, not likelihood of some event or condition.

For any set X, a membership function on X is any function from X to the real unit interval [0, 1]. Membership functions represent fuzzy subsets of X. The membership function which represents a fuzzy set A is usually denoted by μ_A. For an element x of X, the value $\mu_A(x)$ is called the membership degree of x in the fuzzy set A. The membership degree $\mu_A(x)$ quantifies the grade of membership of the element x to the fuzzy set A. The value 0 means that x is not a member of the fuzzy set; the value 1 means that x is fully a member of the fuzzy set. The values between 0 and 1 characterize fuzzy members, which belong to the fuzzy set only partially. Simple functions are used to build membership functions. Because we are defining fuzzy concepts, using more complex functions does not add more precision.

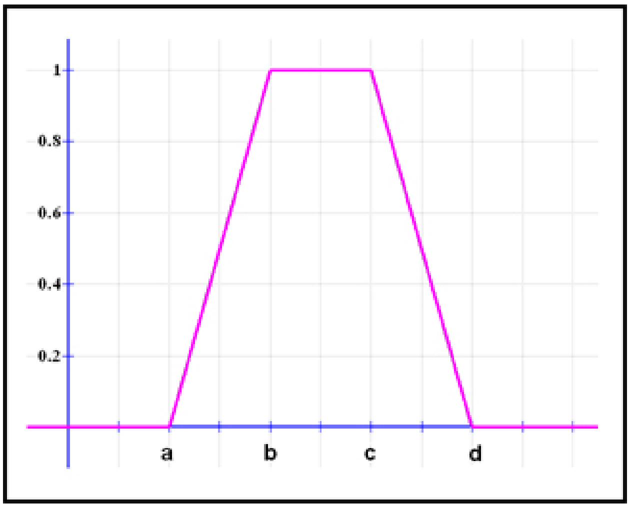
Triangular function: defined by a lower limit **a**, an upper limit **b**, and a value **m**, where **a < m < b**.

$$\mu_A(x) = \begin{cases} 0 & x \le a \\ \dfrac{x-a}{m-a}, & a \le x \le m \\ \dfrac{b-x}{b-m}, & m \le x \le b \\ 0 & x \ge b \end{cases} \tag{2.6}$$



Trapezoidal function: defined by a lower limit **a**, an upper limit **d**, a lower support limit **b**, and an upper support limit **c**, where **a < b < c < d.**

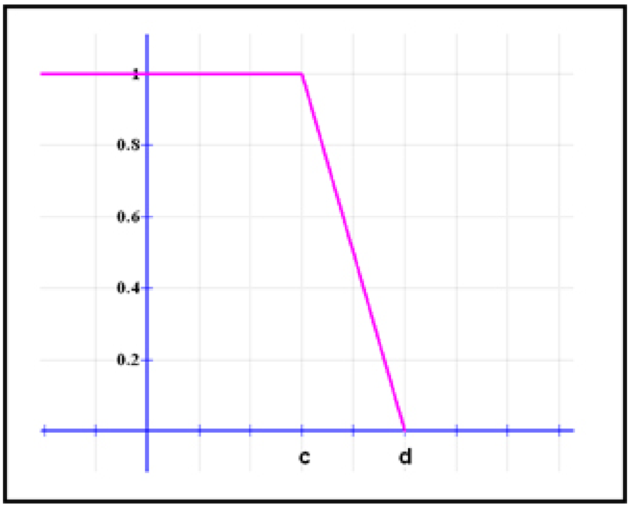
$$\mu_A(x) = \begin{cases} 0, & x \prec a \ or \ x \succ d \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \dfrac{d-x}{d-c}, & c \le x \le d \end{cases} \tag{2.7}$$



There are two special cases of a trapezoidal function, which are called R-functions and L-functions:

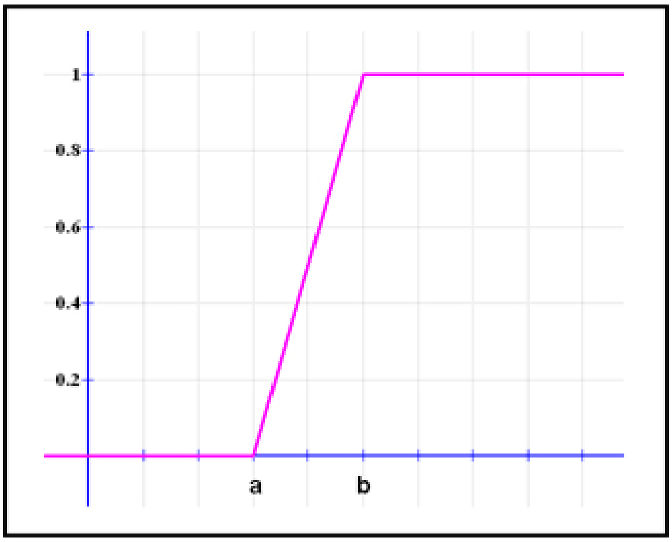
R-functions: with parameters a = b = - ∞

$$\mu_A(x) = \begin{cases} 0, & x \succ d \\ \dfrac{d-x}{d-c}, & c \le x \le d \\ 1, & x \prec c \end{cases} \tag{2.8}$$



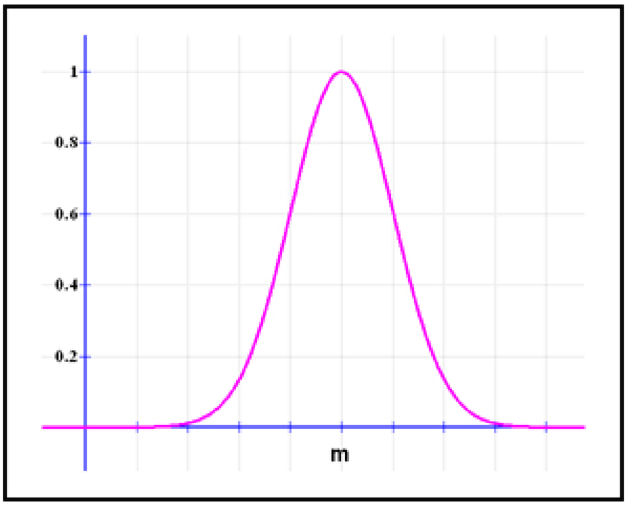
L-Functions: with parameters c = d = + ∞

$$\mu_A(x) = \begin{cases} 0, & x \prec a \\ \dfrac{x-a}{b-a}, & a \leq x \leq b \\ 1, & x \succ b \end{cases} \tag{2.9}$$



Gaussian function: defined by a central value m and a standard deviation $k > 0$. The smaller k is, the narrower the “bell” is.

$$\mu_A(x) = e^{-\frac{(x-m)^2}{2k^2}} \tag{2.10}$$



2.3.3 Fuzzy comprehensive evaluation steps

Fuzzy comprehensive evaluation is an application of fuzzy mathematics [20]. It uses the principle of fuzzy transformation and maximum membership degree, evaluating all relevant factors to make a comprehensive evaluation. This is an efficient evaluation method to evaluate objects that are affected by various factors. For objects that are influenced by a few factors, we can use one layer models. If the objects are complicated and the number of the factors is large, we can use models with two or more layers. The application steps of fuzzy comprehensive evaluation can be described as follows:

Step1 Establish the evaluation index set:

According to the nature of the characteristics of the evaluation index system, the factor set in the evaluating relationship is as follows:

$$U = (u_i)_{1\times n} = \{u_1,\ u_2, \ldots, u_n\} \tag{2.11}$$

Where, n stands for the number of evaluation indexes, u_i as the i-th evaluation indicator, with $i = 1, 2, \ldots, n$.

Step2 Establish assessment criteria set:

Assessment criteria set is a collection consisted of standards by regulation or experts.

$$S = \left(s_{i,j}\right)_{n\times m} = \begin{Bmatrix} s_{1,1}, s_{1,2}, \cdots, s_{1,\mathrm{m}} \\ s_{2,1}, s_{2,2}, \cdots, s_{2,\mathrm{m}} \\ \vdots \quad \vdots \quad \vdots \quad \vdots \\ s_{\mathrm{n},1}, s_{\mathrm{n},2}, \cdots, s_{\mathrm{n},\mathrm{m}} \end{Bmatrix} \tag{2.12}$$

Where the number of columns j, with $j = (1, \ldots, m)$ represents the number of assessment criteria categories, corresponding to the different standard levels. The number of rows i, with $i = (1, \ldots, n)$, refers to the number of assessment indicators. Consequently, each element of the matrix S, $s_{i,j}$, indicates a standard value of the i-th index for j-th class.

Step3 Define the membership function:

There are different forms of membership function, such as triangular, trapezoidal, piecewise linear, Gaussian, and singleton [21]. The trapezoidal membership function is the most reliable and widely used [22-24]. Therefore, the trapezoidal membership function is applied to our study, defined according to previous literature criteria [25, 26]:

Step4 Membership degree matrix calculation:

Substituting the value of u_i with specific indicators value into the selected membership function, we can obtain the fuzzy matrix R:

$$R = \left(r_{ij}\right)_{n\times m} = \begin{bmatrix} r_{11}, r_{12}, \cdots, r_{1m} \\ r_{21}, r_{22}, \cdots r_{2m} \\ \vdots \quad \vdots \quad \vdots \quad \vdots \\ r_{n1}, r_{n2}, \cdots \ r_{nm} \end{bmatrix} \tag{2.13}$$

Where, $r_{i,j}$ represents the i-th indicator membership degree for the j-th class, with $i = 1,2, \ldots, n$ and $j = 1,2, \ldots, m$.

Step5 Determining the index weights:

Weight means the proportion of each evaluation factor in the evaluation index system based on relative importance. If a weight is given to an element, the weight distribution set W can be seen as a fuzzy set of set U. How to determine the weight of each factor is the core task of the evaluation system. Generally, the Analytic Hierarchy Process (AHP) method and the entropy weight method (EWM) are employed to determine the indicators weights in the evaluation index system.

$$W = \left\{w_1, w_2, w_3, \ldots w_n\right\} \tag{2.14}$$

Step6 Assessment coefficient set calculation:

The fuzzy composite operator is important for the final result. As a comprehensive evaluation mathematic model dominated by critical indicator, the supremum-infimum operator M (∧, ∨) takes ∧ and ∨, denoting intersection and union operators [27]. M (∧, ∨) operator is commonly used in the fuzzy comprehensive evaluation of environmental systems. However, some studies showed that the supremum-infimum operator might exclude some useful information, especially for those non-critical indicators, when there are many qualitative indicators, whose weight is small [28]. This is multiplication-summation operator, M (•, ⊕) is adopted here as a weight average method. *B*, being the fuzzy evaluation result set, is defined as:

$$B = W \bullet R = \left(b_j\right)_{1\times m} \tag{2.15}$$

Step7 Effectiveness test of the comprehensive evaluation

There are two methods the weight average method and maximum membership degree method are widely used to process the evaluation result. According to the principle of maximum membership degree, the object class is the membership class, to which corresponds the final maximum assessment coefficient b_f.

$$b_f = MAX\left(b_j\right) = MAX(b_1, b_2, \ldots, b_m) \tag{2.16}$$

The range of application of the maximum membership degree principle is limited, due to the fact that it underestimates the effects of non-largest components. When the values of some components in the assessment coefficient set are approximate, the application of maximum membership degree is inefficient. In such cases, it is unreasonable to judge the overall degree according to this criterion. To measure the effectiveness of the maximum membership degree principle, an index α is defined [29, 30]:

$$\alpha = \frac{m\beta - 1}{2\gamma\left(m-1\right)} \tag{2.17}$$

Where, m represents the number of assessment criteria categories; β refers to the largest component in the assessment coefficient set; γ is the second-largest component.

If $\alpha \geq 0.5$ the principle of maximum membership degree is valid and b_f can be set to be the largest component to satisfy the corresponding criteria demand. If $\alpha<0.5$ the weight average method is applied.

2.4 Basic theory of set pair analysis

The set pair analysis (SPA), proposed by scholar Keqin Zhao in 1989 [31], is a modified uncertainty theory considering both certainty and uncertainty as an interpreted certain-uncertain system and depicting the certainty and uncertainty systematically from three aspects as identity, discrepancy and contrary. Set pair is a pair which has a certain connection of two sets. The core idea of set pair analysis is to analyze the certainty and uncertainty of the objects as a certain-uncertain system [32]. In some specific context, the characteristics of the two target sets are analyzed from such perspectives as their similarities, their differences. Meanwhile a quantitative analysis is made. In this way, the connection degree expression of the two sets is got. Based on these analyses, such aspects as contact, decision-making, forecast, control, simulation, evaluation, evolution and mutation is the target of the further analysis [33].

Definition: two sets A and B are given, and $H = (A, B)$ is a set pair made up with the two sets. In some specific context W, set pair H has N features, among which S features are mutual of A and B. They are opposite on P features. They are neither opposite nor similar in the rest F features $(F = N - S - P)$. We define the ratio as follow:

S/N is the identity degree of A and B under background W, shortened as identity degree;

F/N is the discrepancy degree of A and B under background W, shortened as discrepancy degree;

P/N is the contrary degree of A and B under background W, shortened as contrary degree;

All these can be represented by the formula $\mu(W) = S/N + (F/N)i + (P/N)j$. $\mu(W)$ is the degree contact of set A and set B . For simplicity, if we let $a = S/N$, $b = F/N$, $c = P/N$, then it can be recorded as the following: $u = a + bi + cj$. i is the mark of difference degree, and $i \in [-1,1]$, j is the mark of contrary degree, and $j = -1$. Obviously, $0 \le a, b, c \le 1$ and $a + b + c = 1$

2.5 Basic theory of system dynamics

2.5.1 Concept of System Dynamics

System dynamics (SD) is an approach to understanding the nonlinear behavior of complex systems over time using stocks, flows, internal feedback loops, table functions and time delays. It deals with internal feedback loops and time delays that affect the behavior of the entire system. What makes using system dynamics different from other approaches to studying complex systems is the use of feedback loops and stocks and flows. These elements help describe how even seemingly simple systems display baffling nonlinearity.

System dynamics is a powerful methodology and computer simulation modeling technique for framing, understanding, and discussing complex issues and problems. Originally developed in the

1950s to help corporate managers improve their understanding of industrial processes, system dynamics is currently being used throughout the public and private sector for policy analysis and design. System dynamics is an aspect of systems theory as a method for understanding the dynamic behavior of complex systems. The basis of the method is the recognition that the structure of any system-the many circular, interlocking, sometimes time-delayed relationships among its components-is often just as important in determining its behavior as the individual components themselves.

2.5.2 Application of System Dynamics

A stock-flow diagram of UWSS is shown in Fig.2-2. The indicators related to water resources security are highlighted with red color. The indicators related to water environment security are presented in green color and those standing for water disaster security are indicated in blue color. In these indicators, there were six most important variables, e.g., driving forces index, pressure index, status index, influence index, response index and water security composite index, and they were highlighted in purple color. They corresponded to the five sub-systems in the whole water security system. Totally, the five sub-systems determine the probable scenarios of water security system through interaction and feedback among them. It has become clear that complex systems are counterintuitive. That is, they give indications that suggest corrective action which will often be ineffective or even adverse in its results. Very often one finds that the policies that have been adopted for correcting a difficulty are actually intensifying it rather than producing a solution. Choosing an ineffective or detrimental policy for coping with a complex system is not a matter of random chance. The intuitive processes will select the wrong solution much more often than not. A complex system-a class to which a corporation, a city, an economy, or a government belong-behaves in many ways quite the opposite of the simple systems from which we have gained our experience. Most of our intuitive responses have been developed in the context of what are technically called first-order, negative-feedback loops. Such a simple loop is goal-seeking and has only one important state variable. For example, warming one's hands beside a stove can be approximated as a first-order, negative-feedback loop in which the purpose of the process is to obtain warmth without burning one's hands. The principal state variable of the loop is the distance from the stove. If one is too close he burns his hands, if too far away he receives little heat. The intuitive lesson is that cause and effect are closely related in time and space. Temperature depends on the distance from the stove. Too much or too little heat is clearly related to the position of the hands. The relation of cause and effect is immediate and clear. Similarly, the simple feedback loops that govern walking, driving a car, or picking things up all train us to find cause and effect occurring at approximately the same moment and location. But in complex systems cause and effect are often not closely related in either time or space. The structure of a complex system is not a simple feedback loop where one system state dominates the behavior. The complex system has a multiplicity of interacting feedback loops. Its internal rates of flow are controlled by nonlinear relationships. The complex system is of high order, meaning that there are many system states (or levels). It usually contains positive-feedback loops describing growth processes as well as negative, goal-seeking loops. In the complex system the cause of a difficulty may lie far back in time from the symptoms, or in a completely different and remote part of the system. In fact, causes are usually found, not in prior events, but in the structure and policies of the system. To make matters still worse, the complex system is even more deceptive than merely hiding causes. In the complex system, when we look for a cause near in time and space to a symptom, we usually find what appears to be a plausible cause. But it is usually not the cause. The complex system presents apparent causes that are in fact coincident symptoms. The high degree of time correlation between variables in complex systems can lead us to make cause-and-effect associations between variables that are simply moving together as part of the total dynamic behavior of the system. Conditioned by our training in simple systems, we apply the same intuition to complex systems and are led into error. As a result we treat symptoms, not causes. The outcome lies between ineffective and detrimental.

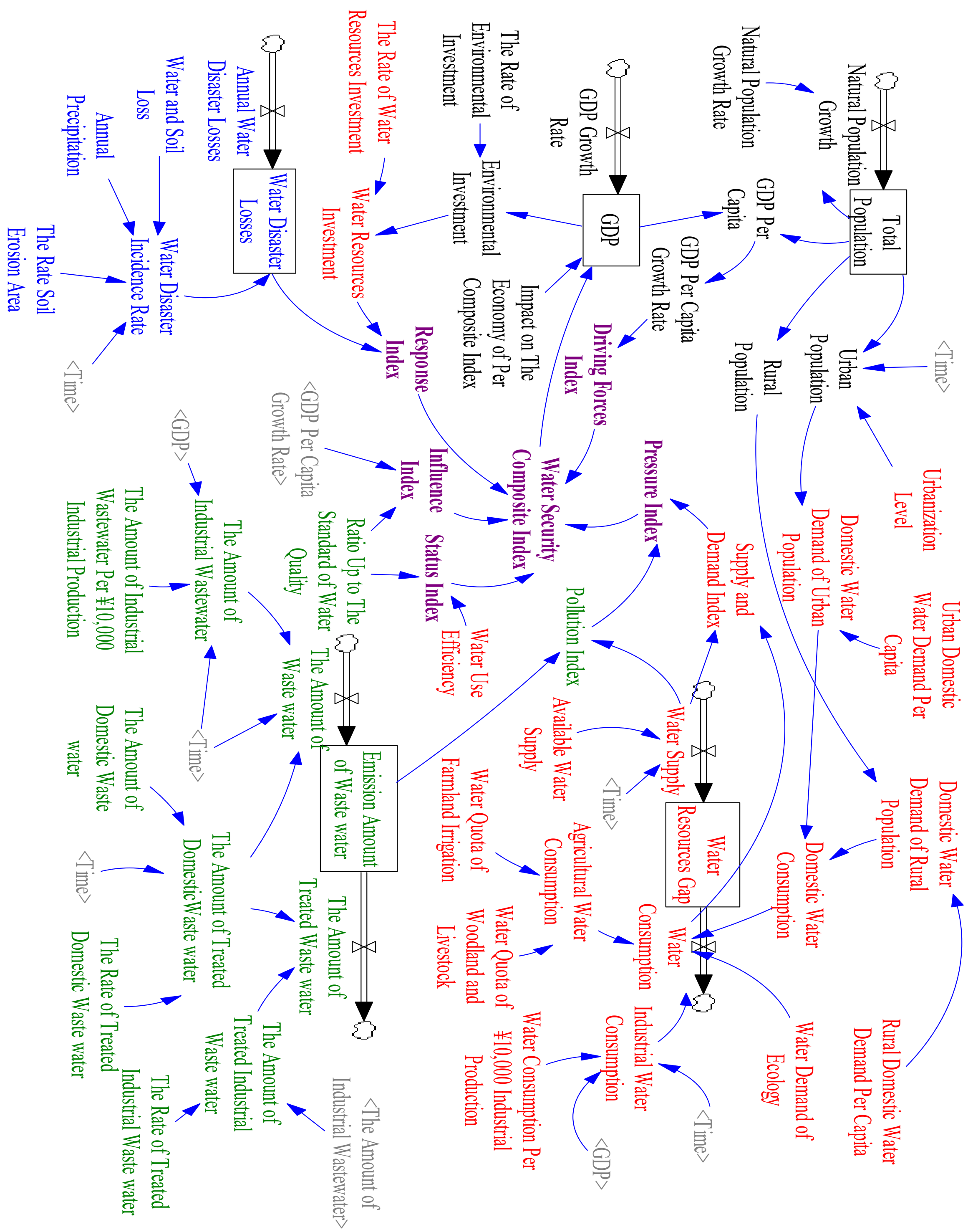


Fig.2-2. The flow graph of water security system

2.5.3 Validation of System Dynamics

It is important to empirically calibrate the SD model for testing reasonability and feasibility of simulation results. On one hand, this can be fulfilled by a matching test of historical behavior in the current scenario. On the other hand, this can be tested by sensitivity analysis. The two methods are important ways to validate the effectiveness of the SD model.

Conspicuous by their absence from the preceding tests of model structure are the historical statistical tests usually applied to social and economic models. For example, econometric model building relies almost completely on statistical tests which involve direct comparison of individual model equations to statistical data. However, the application of such tests to causal models has been the subject of a long-standing debate. Although there is today fairly wide-spread agreement regarding the limitations of standard statistical tests of model structure, many modelers still rely heavily on such tests.

Sensitivity analysis is an important method to verify the validity of the model. A stable and effective model should have low sensitivity. Sensitivity analysis analyzes the effects of parameter changes on the output of model variables by adjusting the parameters in the model. The behavior-sensitivity test focuses on sensitivity of model behavior to changes in parameter values. The behavior-sensitivity test ascertains whether or not plausible shifts in model parameters can cause a mode to fail behavior tests previously passed. To the extent that such alternative parameter values are not found, confidence in the model is enhanced. For example, does there exist another equally plausible set of parameter values that can lead the model to fail to generate observed patterns of behavior or to behave implausibly under conditions where plausible be Javier was previously exhibited? The behavior-sensitivity test is typically conducted by experimenting with different parameter values and analyzing their impact on behavior. Frequently, after extensive model analysis, the system dynamics modeler has a good idea where sensitive parameters might lie and this understanding effectively guides sensitivity analysis.

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Chapter 3

DYNAMIC ASSESSMENT AND FORECAST OF WATER RESOURCES SECURITY

CHAPTER 3: DYNAMIC ASSESSMENT AND FORECAST OF WATER RESOURCES SECURITY

3.1 Introduction

In recent years, the rapid development of China's urbanization process has created some problems, such as water pollution, air quality degradation, biodiversity loss [1, 2] and a gap between urban and rural development, the people even have no time to consider how to deal with this sudden upheaval. Meanwhile, however, the law of development of urbanization that China is in the middle stage of urbanization confirms that China's urbanization will continue to maintain the rapid pace of development in the next 20-30 years. At present, two-thirds of Chinese cities are confronting one of the top problems in the process of urbanization, water shortages. Water scarcity is increasingly becoming the biggest bottleneck for urban future development. In this sense, how to coordinate the sustainability between social-economy and water resources is very significant [3]. In order to achieve sustainable utilization of water resources and meet regional demand for water use, some commonly used methods, such as analytical hierarchy process [4], data envelopment analysis [5], are applied to comprehensively evaluate the water resources. In another way, some researchers were inspired by the concept of ecological footprint [6, 7]. This method measures the sustainable development of the region by estimating the difference value of ecological carrying capacity and the amount of required productive space (ecological footprint) for sustaining the human consumption of natural resources and assimilating human waste. For example, Wiedmann et al. [8] allocated the ecological footprint according to input and output analysis; Jia et al. [9] combined ecological footprint with ARIMA model; Miao et al. [10] performed a grade classification of environmental quality based on ecological footprint; Liu et al. [11] calculated the ecological footprint of campus based on life cycle assessment. The application of ecological footprint model is also very extensive depending on different scales. Verhofstadt et al. [12] applied it to individual consumption assessments. It can also be used in tourist activities [13], even households studies [14]. Commonly, it was applied to city's ecological footprint assessments [15], regional ecological footprint studies [16], and the research of ecological footprint in a country [17]. Additionally, it can be embedded in hybrid multi-scale analysis [18]. Within this context, the study direction of water resources gradually towards the water demand side. Simultaneously, the study of water supply side was ignored. Water footprint model was originally proposed by Hoekstra [19], who defined it as the volume of water needed for the production of the goods and services consumed by the inhabitants of the country. A number of studies have been oriented to quantify the water footprint of countries or the water embodied in specific products. However, the use of water footprint in assessing water resource carrying capacity is questioned. In fact, water footprint focusing on the consumption and the trade of the water resource has been seldom applied in assessing the latter's sustainability due to its inability to demonstrate the capacity of the water resource supply [20].

Therefore, water ecological footprint is not only paying attention to the water demand side, but also focuses on the water supply side. The water ecological footprint model was proposed by the Chinese scholar Fan [21]. Water ecological footprint assessment focuses on analyzing freshwater use in view of limited freshwater resources. It is a concise indicator, as it shows when, where and how consumers and producers put a claim on this limited resource. Water ecological footprint assessment is a useful tool to quantify and locate water consumption, to evaluate whether water utilization is sustainable and to identify options to reduce water ecological footprints where necessary. In ecological footprint model, the biologically productive lands were divided into six categories: cropland, grassland, forestry, water area, built-up land and fossil land. While in water ecological footprint model, the biologically productive land only refers to the water area type [22]. WEF is also a land-based indicator for assessing water sustainability, through comparing the amount of water area needed (namely, the water ecological footprint) to ensure supply for a given population or system with the amount of water area available (namely, the water ecological carrying capacity) in that population' territory. WEF can be used to analyze and evaluate the gap between human dependence on water resources and water availability, through quantitative measurement of human demands (of water area), as well as water area capacity of supplying water resources and assimilating waste water. When local water ecological carrying capacity can support the local water ecological footprint, we call it as the water ecological surplus (WES); otherwise, we call it as the water ecological deficit (WED). As above mentioned, the WEF model is suitable for sustainable development analysis of local water supplies. Nowadays, academic community of China has mainly focused on the basic theory, calculation methods, and model improving water ecological footprint. Water ecological footprint has been applied in the assessment of local regional sustainable utilization of water resources widely. Therefore, the study adopted water ecological footprint indicator to have a try to combine water footprint and ecological footprint from both the water demand and water supply sides. However, in the previous studies, the yield factor is determined by the average annual total water resources and the regional area. Since the total water resources change with rainfall every year, the yield factor is also changed year by year. But the yield factor in the traditional model is a constant. The consequence is local water resources carrying capacity is underestimated (when yield factor less than actual value) or overestimated (when yield factor greater than actual value). The water resources carrying capacity value is completely not accurate.

In order to ensure the accuracy of the yield factor during the calculation process, the yield factor for each year is calculated separately in this study. Furthermore, considering that most research has focused on the WEF of a single case or ignored the comparison between water-rich area and water-poor area easily, this study took into account the comparison analysis and summarized three typical types of the urban WEF development. Such the comparison research can help identify the key gaps between different cities under different developing background so that cities from different regions can learn knowledge from each other and avoid unsustainable development pattern that cities in different regions had ever experienced. This study selected four municipalities in China, i.e., Beijing, Shanghai, Tianjin, and Chongqing as cases, to compare the WEF of these cities. The municipality is the highest level of classification of cities in China. These cities have the same rank as provinces, and part of the first tier of administrative divisions of China. Beijing, the capital of China, is the nation's political, cultural and educational center. Shanghai is one of the global financial centers and transport hubs, with the world's busiest container port. Tianjin is a metropolis in northern coastal of Mainland China and one of the four national central cities. Chongqing is the only direct-controlled municipality located in the southwest inland far away from the coast. Therefore, these four cities have typical kinds of characteristics with different water-related problems.

Based on the WEF model and the obtained data of water resources utilization in the four cities, this paper improved the calculation method of yield factor so that the evaluation indicators will be more reliable and accurate. Followed by the evaluation indicators of water resources such as the WEF and the WEC in the year of 2004-2015 were calculated and analyzed. In order to better interpret the series of evaluation indicators, the study compared the corresponding indicators in the four cities to further understand the sustainable utilization of water resources. At last exponential smoothing model was applied to forecast the WEF so as to define the future trends of WEF of these four cities. We hope that our results will be helpful to facilitate the mutual development and cooperation among these cities and provide valuable insights for policymakers so that more sustainable water utilization policies can be raised by considering the local realities.

3.2 Object and data

3.2.1 Study areas

Beijing is situated at the northern tip of the roughly triangular North China Plain. Annual rainfall distribution there is very uneven, around three-fourths of total rainfall concentrates in a period of June to August mostly in the form of thundershowers and rainstorms. The precipitation averages around 483.9 mm annually. In 2015, the total water supply of the city was 3.82 G m^3 and the total water resources in Beijing were 2.68 G m^3. Therefore, the water demand in Beijing cannot be satisfied and water supply from the outside region is urgent. It is worthwhile to mention that the South–North Water Transfer Project has been constructed in the past decade to bring water from the Yangtze River basin. Tianjin lies within the semi-arid zone, having a low annual mean total precipitation of 600 mm whose near three-fifths occurs in July and August. In order to relieve the water shortage, the Water Diversion Project from Luanhe River to Tianjin City has been implemented. Every year the project can transmit 1 G m^3 water resources. Shanghai city, a core of the Yangtze River Delta, sits on the south edge of the estuary of the Yangtze in the middle portion of the East China coast. The annual average rainfall is 1,173.4 mm; more than 60 % of rainfall concentrates in the flood season of May to September. In 2015, the water consumption of per 10 thousand Chinese yuan GDP was 31 m^3. Water consumption for every 10 thousand Chinese yuan worth of industrial value added was 53 m^3. Chongqing is located in the humid subtropical region. Its total annual average water volume is about 50 G m^3, with the biggest per square kilometers water yield in China. The annual average rainfall is more abundant, and precipitation is between 1,000 mm and 1,350 mm in the most areas. In 2015, the per capita water consumption of Chongqing was 262 m^3, which is decreased by 2.67 % compared with that of 2014. The water consumption of per 10 thousand Chinese yuan GDP was 50 m^3 with a drop of 10.93 % from 2014. Water consumption for every 10 thousand Chinese yuan worth of industrial value added was 59 m^3 with a drop 7.0 % from 2014.

3.2.2 Data sources

Data on the cities' areas and the population are all obtained from the statistical yearbooks [23-26]. For water-related data, the total consumption of water resources, the sector account's water consumption, and the total quantity of water resources are derived from the cities' water resources bulletins [27-30].

3.3 The analysis of water ecological footprint in water resources security

3.3.1 The application of water ecological footprint analysis model

According to ecological footprint theory, the biological production capacity of water resources is used to measure the water ecological carrying capacity (WEC), that is, the corresponding biological survival area that the water resources can carry. The water ecological footprint (WEF) can be defined as: the water footprint of any given population (a person, a city, a region, or globally) is the amount of water required to produce all the resources (including the direct consumption of water resources and environmental resources for human life to provide ecosystem services and functions) consumed by these people.

The calculation model of water ecological carrying capacity is:

$$WEC = N \bullet wec = \left(1 - 0.12\right) \bullet \psi_w \bullet r_w \bullet (Q / p_w) \tag{3.1}$$

Where, *WEC* (gha) is the total ecological carrying capacity of water resources, *N* is the population, *wec* (gha/cap) is the *WEC* per capita, ψ_w is the land production factor of water resources in the area, r_w is the global balance factor of water resources. Q (m^3) is the regional total amount of water resource. p_w (m^3/hm^2) is the average production capacity of the global water resources. It is a normal practice to allocate 12 % of the available supply land to protect the local biodiversity [7].

The calculation model of ecological footprint of water resources is:

$$WEF = N \bullet wef = r_w \bullet (W / p_w) \tag{3.2}$$

Where, WEF (gha) is the total ecological footprint of water resources, wef (gha/cap) is the WEF per capita, and W (m^3) is the consumption of various types of water resource.

According to Huang's supplementation of WEF, it mainly includes three secondary accounts of the WEF: productive water, household water, ecological water. Productive water, including primary industrial water, secondary industrial water and tertiary industrial water; household water, including urban domestic water and rural domestic water (drinking water is included except for resident demand for essential water); and ecological water use, including urban green space water and water consumption of dilute pollutants beyond water pollutant capacity in the region (including urban environmental water and rural ecological water use), are calculated as follows:

$$WEF_p = r_w \bullet (W_p / p_w) \tag{3.3}$$

$$WEF_h = r_w \bullet (W_h / p_w) \tag{3.4}$$

$$WEF_e = r_w \bullet (W_e / p_w) \tag{3.5}$$

Where, WEF_p (gha) refers to ecological footprint of productive water, W_p (m^3) is the productive water consumption, WEF_h (gha) refers to ecological footprint of household water, W_h (m^3) is the household water consumption, WEF_e (gha) is ecological footprint of ecological water, W_e (m^3) is water used for environmental production.

$$WEF_{pi} = r_w \bullet (W_{pi} / p_w) \tag{3.6}$$

$$WEF_{si} = r_w \bullet (W_{si} / p_w) \tag{3.7}$$

$$WEF_{ti} = r_w \bullet (W_{ti} / p_w) \tag{3.8}$$

Where, WEF_{pi} (gha) is the ecological footprint of primary industrial water, W_{pi} (m^3) is the primary industrial water consumption, WEF_{si} (gha) is the ecological footprint of secondary industrial water, W_{si} (m^3) is the secondary industrial water consumption, WEF_{ti} (gha) is the ecological footprint of tertiary industrial water, W_{ti} (m^3) is the tertiary industrial water consumption.

3.3.2 Parameters treatment of water resources

Production capacity of water resources: the modulus of water in hydrology is used to describe the production capacity of water resources and according to the literature the average production capacity of water resources in the world is 3,140 m^3/hm^2.

Global balance factor of water resources: the global balance factor of water resources is equal to the average ecological productivity of biological production area of water resources divided by the average ecological productivity of various biomass production areas in the world. For comparison, this study selects WWF2002 to determine the water balance factor as 5.19.

Water resources yield factor: to determine the different regional water resources yield factors, it is assumed that the world water resources yield factor is 1, the regional water resources yield factor is the ratio of the average production capacity of water resources in the region to the average production capacity of world water resources. The average production capacity of water resources in the region is the ratio of regional total water quantity to regional areas. Because the regional total water quantity changes every year, the regional water resources yield factor also changes. Table 3-1 shows the regional water resources yield factors of the four cities in 2004-2015.

Table3-1 Yield factors in different cities 2004-2015

Y	Beijing	Shanghai	Tianjin	Chongqing
2004	0.41	1.33	0.38	1.08
2005	0.45	1.30	0.28	0.99
2006	0.43	1.43	0.27	0.73
2007	0.46	1.44	0.30	1.28
2008	0.66	1.53	0.49	1.11
2009	0.42	1.76	0.41	0.88
2010	0.45	1.57	0.25	0.90
2011	0.52	1.05	0.41	0.99
2012	0.77	1.71	0.88	0.92
2013	0.48	1.42	0.39	0.92
2014	0.39	2.38	0.30	1.24
2015	0.52	3.24	0.34	0.88

3.3.3 The total water ecological footprint and water ecological carrying capacity

The difference between water ecological footprint and water ecological carrying capacity determines whether deficit if the former is larger or surplus if the former is smaller, which can then be used to identify to what extent the local water availability, can support the local water consumption. Table3-2 shows the total water ecological footprints (WEF), water ecological carrying capacity (WEC) and water ecological deficit (WED) or water ecological surplus (WES) for these four cities from 2004 to 2015. The total WEF of Beijing in 2004 was 5.72 M gha, increasing to 6.33 M gha in 2015. Meanwhile, the WEC had increased from 1.29 M gha to 2.03 M gha, resulting in the WED of 4.43 M gha in 2004 and 4.3 M gha in 2015. The main reason for Beijing to have a different WEC was that the total water resource quantity changed during the study period. It indicates that Beijing had to import 4.43 M gha and 4.3 M gha worth water resources or products from the outside to meet the local demands in 2004 and 2015, respectively. The total WEF of Tianjin had a 16.16 % growth, increasing from 3.65 M gha in 2004 to 4.24 M gha in 2015. However, its WEC decreased 20 % from 0.8 M gha to 0.64 M gha, associating within an increase in its WED from 2.85 M gha in 2004 to 3.6 M gha in 2015. The data imply that Tianjin imported a large number of water resources from other areas for its consumption. The total WEF of Shanghai was larger than WEC before 2014, while the WEF was less than WEC from 2014. The WEC of Shanghai in 2014 was 16.35 M gha, increasing to 30.16 M gha in 2015. Meanwhile, the WEF was 13.02 M gha and 12.67 M gha, leading to the WED transforming to WES, with 3.33 M gha and 17.49 M gha, respectively. As a net consequence, Shanghai importing water resources has changed to exporting water resources since 2014. The total WEF of Chongqing in 2004 was 11.15 M gha, increasing to 13.05 M gha in 2015. Meanwhile, the WEC had decreased from 43.88 M gha to 29.24 M gha, resulting in the WES of 32.73 M gha in 2004 and 16.19 M gha in 2015. In summary, Beijing and Tianjin required larger water ecological carrying capacity than they hold in order to support their urban water consumption activities, attributing to a fast urban development and a larger burden to the water resources. Though the WED in Shanghai was larger than Beijing and Tianjin before 2014, it suddenly dropped and changed to WES. The WEC in Chongqing was so large that it not only met self-sufficiency but also exported to other areas in a way of water production or interbasin water transfer.

Table 3-2 The total WEF, WEC, and WED or WES of cities (Unit: 1 M gha)

	Beijing			Tianjin			Shanghai			Chongqing		
	WEC	WEF	WED	WEC	WEF	WED	WEC	WEF	WED	WEC	WEF	WES
2004	1.29	5.72	4.43	0.80	3.65	2.85	5.05	18.41	13.36	43.88	11.15	32.73
2005	1.52	5.70	4.18	0.44	3.82	3.38	4.86	18.94	14.08	36.52	11.76	24.76
2006	1.38	5.67	4.29	0.40	3.79	3.39	5.90	18.44	12.54	20.33	12.10	8.23
2007	1.60	5.75	4.15	0.50	3.86	3.36	5.98	19.87	13.89	61.77	12.80	48.97
2008	3.31	5.80	2.49	1.30	3.69	2.39	6.78	19.80	13.02	46.78	13.68	33.10
2009	1.35	5.87	4.52	0.90	3.86	2.96	8.95	20.69	11.74	29.21	14.10	15.11
2010	1.50	5.82	4.32	0.33	3.71	3.38	7.10	20.87	13.77	30.30	14.28	16.02
2011	2.03	5.96	3.93	0.92	3.82	2.90	3.15	16.11	12.96	37.21	14.35	22.86
2012	4.41	5.93	1.52	4.22	3.82	-0.40	8.45	14.38	5.93	31.96	13.71	18.25
2013	1.74	6.02	4.28	0.83	3.93	3.10	5.78	14.71	8.93	31.62	13.87	17.75
2014	1.16	6.20	5.04	0.50	4.33	3.83	16.35	13.02	-3.33	58.03	13.30	44.73
2015	2.03	6.33	4.30	0.64	4.24	3.60	30.16	12.67	-17.49	29.24	13.05	16.19

In the terms of urban total WEF accounts, the total WEF in Beijing had a tendency to rise slowly. The productive WEF was decreasing, while it had an overt growth in the ecological WEF since 2005. The household WEF fluctuated from year to year, but the fluctuation range was small (Fig.3-1). The total WEF was 20.87 M gha in 2010 which was the highest from 2004 to 2015 in Shanghai. The changing trend of the total WEF in Shanghai firstly increased and then decreased mainly due to the change of the productive WEF. The total WEF in Tianjin had a little change from 3.65 M gha in 2004 to 4.24 M gha in 2015. In Tianjin, the productive WEF and the household WEF were more or less steady. The total WEF in Chongqing was 11.15 M gha which was the minimum value in 2004 and the maximum value was 14.35 M gha in 2011. In 2004, the proportion of the productive WEF was 83.18 % in Chongqing, while the household WEF accounted for 16.34 %. In 2015, the proportion of the productive WEF decreased to 80.03 % in Chongqing, while it increased to 18.74 % in the household WEF. The percentage of the ecological WEF became greater gradually from 0.48 % of 2004 to 1.23 % of 2015.

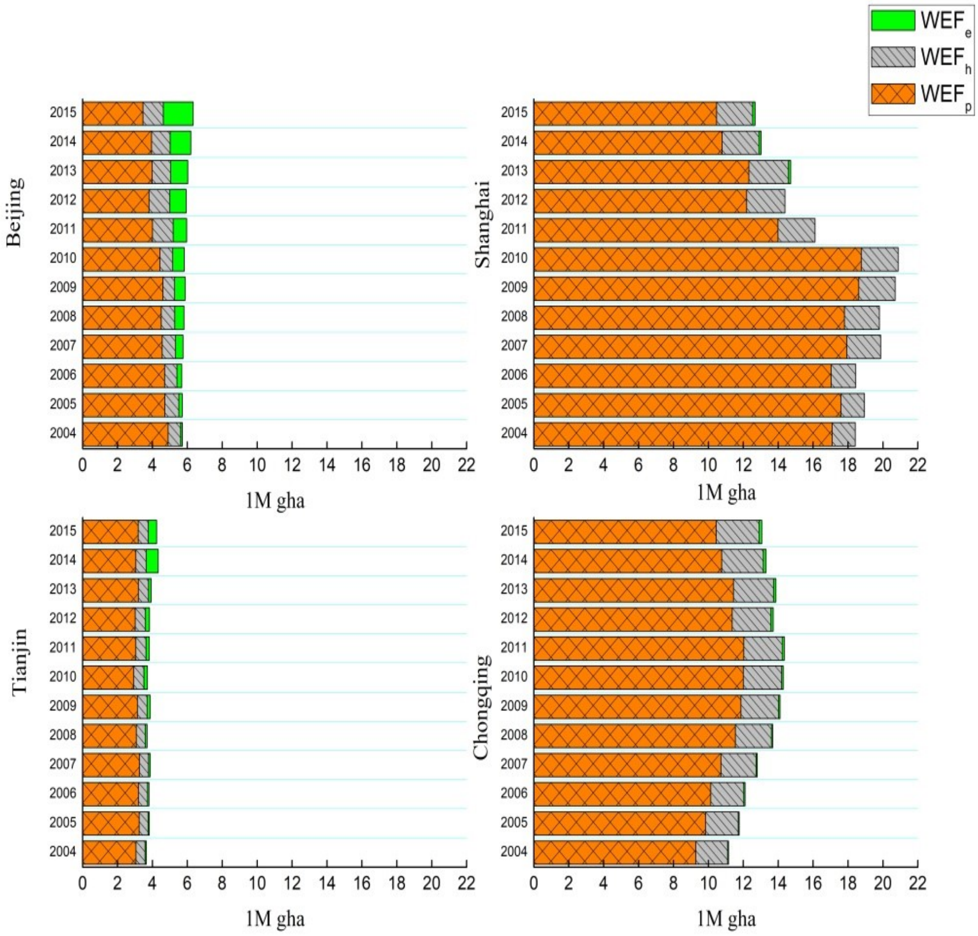

Fig.3-1 The urban total WEF accounts (Unit: 1M gha)

Because the productive WEF was the biggest account, it played a vital role in total WEF. It is of great importance to analyze the productive WEF so that we will put forward proper measures toward freshwater use. We knew from Fig.3-2 that the productive WEF includes primary industry WEF, secondary industry WEF, and tertiary industry WEF. In Beijing, the primary industry WEF in the three productive WEF decreased by 3.85 % from 2005 to 2010, while it reduced by 11.43 % in the period of 2010-2015. It is obvious that the decreased rate of later five years was nearly about three times as great as that of the former five years. The secondary industry WEF decreased by 4.83 % from 2005 to 2010, while it decreased by 0.4 % from 2010 to 2015. The secondary industry WEF reduced in the former five years faster than that in the later five years. The tertiary industry WEF always increased from 1.4 M gha in 2005 to 1.73 M gha in 2015 with a growth rate of 23.5 %. In Shanghai, the primary industry WEF decreased from 3.1 M gha in 2005 to 2.35 M gha in 2015. At the same time, the secondary industry WEF firstly increased from 13.12 M gha in 2005 to 14.02 M gha in 2010, and then decreased from 14.02 M gha in 2010 to 6.19 M gha in 2015. The tertiary industry WEF increased from 1.38 M gha in 2005 to 1.92 M gha in 2015 at a growth rate of 39.1 %. Hence, the tertiary industry WEF in Shanghai increased larger than that in

Beijing. Following a different pattern, in Tianjin the primary industry WEF decreased in the period of 2005-2010 and then increased in the period of 2010-2015. The secondary industry WEF was always increased from 0.77 M gha in 2005 to 0.93 M gha in 2015. The tertiary industry WEF increased from 0.19 M gha in 2005 to 0.25 M gha in 2010, due mainly to urban development control, resulting in which the tertiary industry WEF in Tianjin decreased from 0.25 M gha in 2010 to 0.19 M gha in 2015. In Chongqing, the primary industry WEF first reduced and then increased like the pattern of Tianjin. The secondary industry WEF first increased and then reduced, opposite to the primary industry WEF. The tertiary industry WEF also kept increasing from 0.3 M gha in 2005 to 0.62 M gha in 2015.

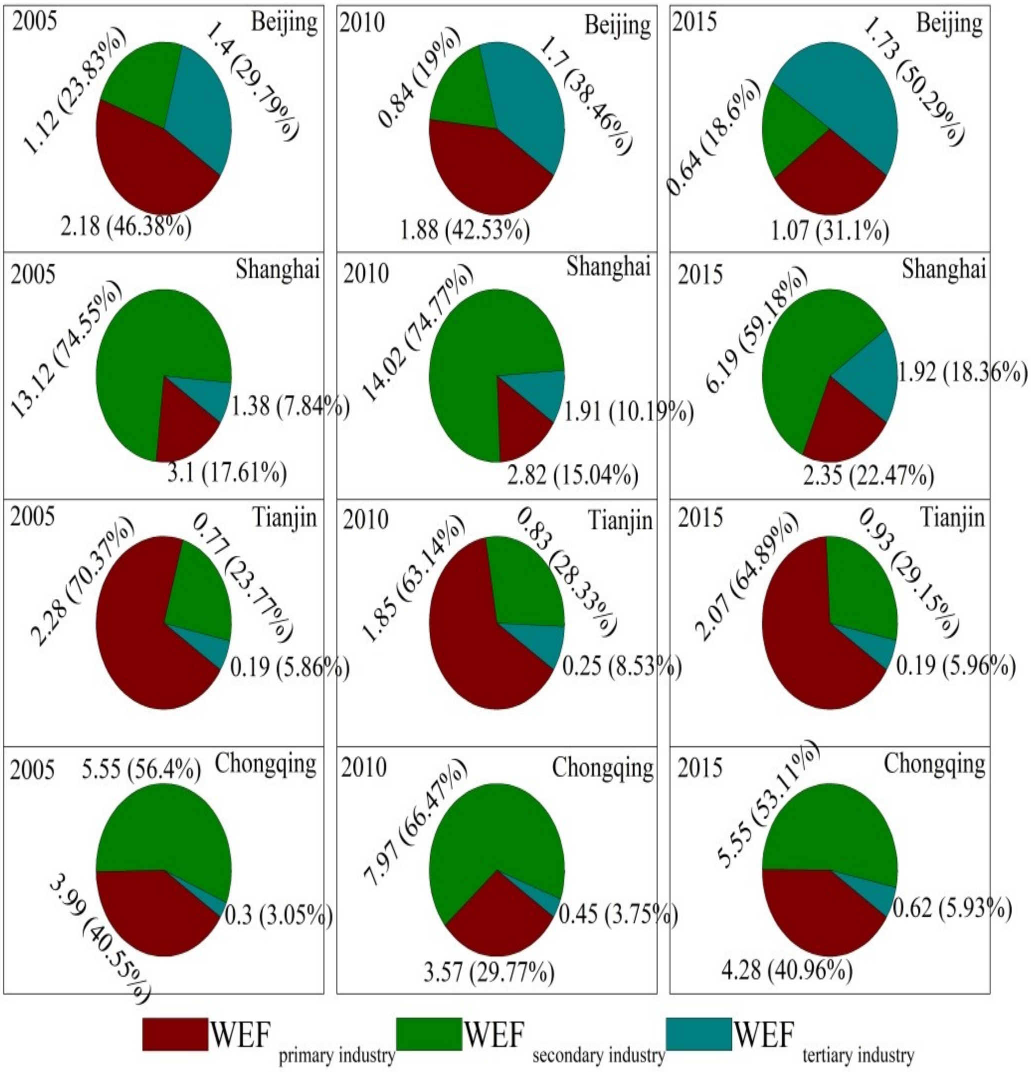

Fig.3-2 The productive WEF accounts (Unit: 1M gha)

In general, the total WEF has a gradually increasing trend except for Shanghai. It means the economic development caused the increasing total water consumption. The total WEC is fluctuant because of the different water resources endowment. The productive WEF has the biggest account in the WEF accounts and it affects the total WEF remarkably.

3.3.4 The water ecological footprint and water ecological carrying capacity per capital

Fig.3-3 shows the final results of the WEFs per capital and the WECs per capital among Beijing, Shanghai, Tianjin, and Chongqing in the period of 2004 to 2015. The WEF per capital in Beijing decreased from 0.38 gha in 2004 to 0.29 gha in 2015. During the same period, the WEF per capital in Shanghai almost half in the past 12 years, decreased from 1.00 gha in 2004 to 0.52 gha in 2015, and were 2.60 and 1.79 times bigger that in Beijing in 2004 and 2015, respectively. The WEF per capital in Tianjin changed from 0.36 gha in 2004 to 0.27 gha in 2015. And the WEF per capital in Chongqing kept steady in past 12 years from 0.40 gha in 2004 to 0.43 gha in 2015. The WEC per capital in Shanghai increased from 0.28 gha in 2004 to 1.25 gha in 2015 at a growing rate of 77.6 %, meanwhile such a value in Tianjin decreased from 0.08 gha in 2004 to 0.04 gha in 2015 at a decreasing rate of 50 %. The value in Chongqing also decreased from 1.57 gha in 2004 to 0.97 gha in 2015, while it was the same value 0.09 gha as that in Beijing from 2004 to 2015. Accompanied with such values, the water ecological deficit per capita in Beijing decreased from 0.30 gha in 2004 to 0.20 gha in 2015, while the water ecological deficit per capita in Tianjin decreased from 0.28 gha in 2004 to 0.23 gha in 2015, indicating that on average one person living in Beijing had the same demand to water ecological carrying capacity to support his/her urban life as one in Tianjin. It also reflected a clear fact that Beijing and Tianjin were the representative cities in northern China, so the water consumption of living standards, urbanization rate, and industrial development levels was the basic similarity. The water ecological deficit per capita was changed into water ecological surplus in Shanghai from 2014, with the surplus value of 0.14 gha. The surplus value increased to 0.72 gha in 2015. In Chongqing, the WEC per capital had always been surplus from 2004 to 2015, although the surplus value had a decreasing trend.

In order to further compare the WEF per capital accounts consisting of primary industry, secondary industry, tertiary industry, household, and ecology among the four cities, a more detailed study on the five types was undertaken. Fig.3-4 shows the different WEF per capital accounts among these cities. For Beijing, the primary industry WEF per capital, the secondary industry WEF per capital, and the tertiary industry WEF per capital all decreased from 2004 to 2015, at the reducing rates of 66.7 %, 66.7 %, and 11.1 %, respectively. Whilst the household WEF per capita kept 0.05 gha in the period and the ecological WEF per capita increased from 0.01 gha in 2004 to 0.08 gha in 2015. For Shanghai, the primary industry and secondary industry WEF per capita decreased at the reducing rates of 41.2 %, 62.3 %, respectively. However, the tertiary industry WEF per capita and the household WEF per capital increased during the same period at the rates of 14.2 %, 28.4 %, respectively. The ecological WEF per capita remained unchanged. For Tianjin, the WEFs of primary industry, secondary industry, tertiary industry, and household all also decreased from 2004 to 2015. The primary industry WEF per capital decreased with reduction rates of 35 %. The ecological WEF per capital increased from 0.01 gha to 0.03 gha in the same period. For Chongqing, primary and secondary industry WEF per capital kept steady and it increased by 0.01 gha in the tertiary industry, household, and ecological WEF per capital, respectively.

In summary, the WEF per capital in Beijing, Shanghai, and Tianjin all decreased from 2004 to 2015, it means that the water consumption per capital was decreasing. The results consist of the water management policies of these cities. In recent years, because the contradiction of water supply and demand is more severe, local governments in these cities have constituted strict water consumption policies to control water consumption per capita. The WEF per capital in Chongqing is steady since the local government doesn't take the strict measure. The WEC per capital changes irregularly with time increasing in the four cities as a result of total water volume fluctuation. The total water volume is related to precipitation and groundwater recharge.

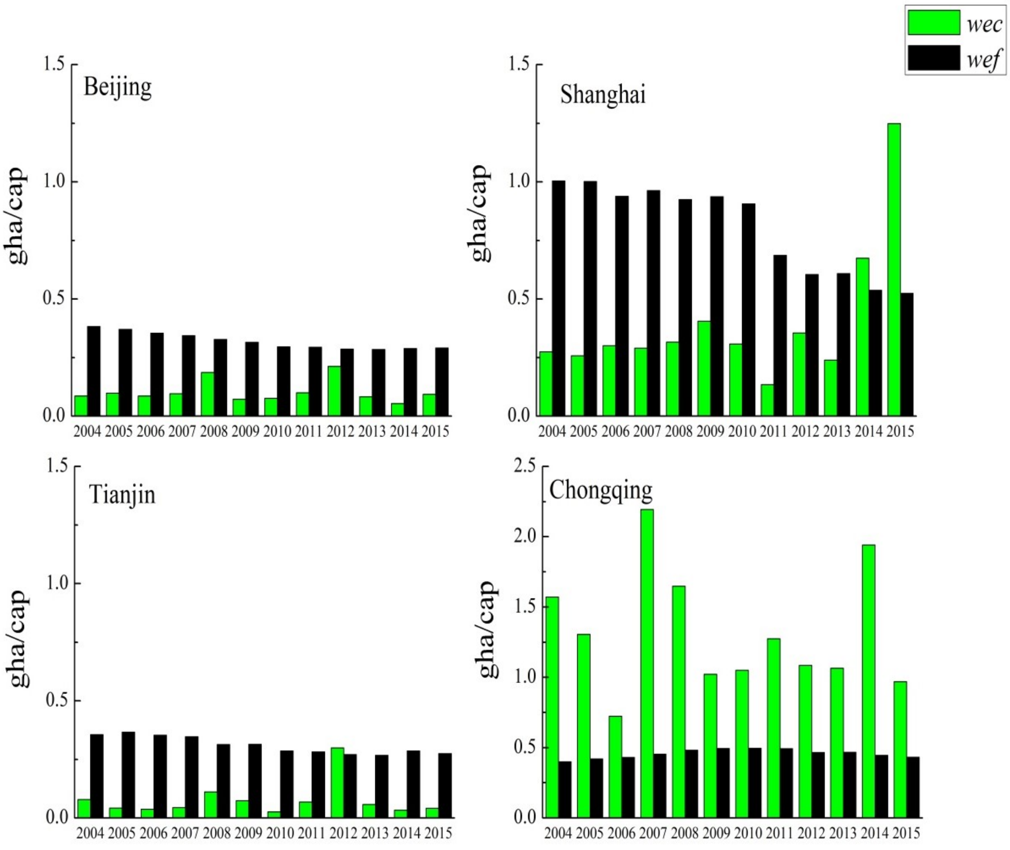

Fig.3-3 The WEF and WEC per capital in different cities (Unit: gha)

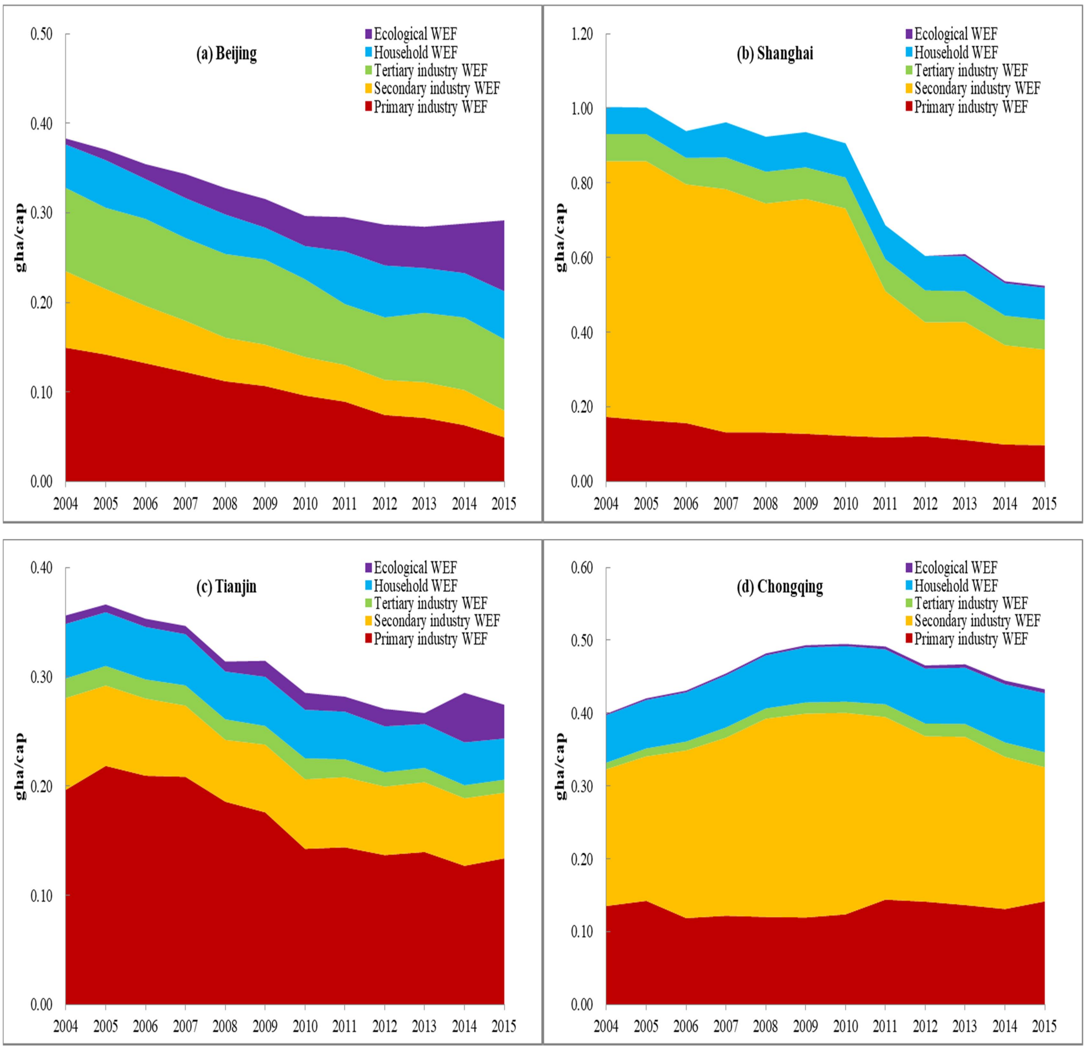

Fig.3-4 The WEF per capital accounts (Unit: gha)

3.4 The forecast of water ecological footprint with exponential smoothing method

3.4.1 The basic information of exponential smoothing model

Exponential smoothing was first suggested in the statistical literature without any citation to previous work by Robert Goodell Brown in 1957 [31], and then expanded by Charles C. Holt in 2004 [32]. Exponential smoothing is one of the moving average methods. Forecasts produced using exponential smoothing methods are weighted averages of past observations, with the weights decaying exponentially as the observations get older. In other words, the new observations are given relatively bigger weight in forecasting than the old observations. The prediction value is the weighted sum of observed values. The basic idea of smoothing model is that the trend of the time series is stable or regular, and the time series trend can be reasonably postponed. The latest past trend will persist into the future. It is suitable for short-term and medium-term forecasting, with good accuracy. Thus, we selected the method to predict the future value of the WEF per capita. Single exponential smoothing is ideal when time series is free of seasonal or trend components to create patterns which smoothing equation tends to miss due to lags. Single exponential smoothing produces forecasts beyond actual results when the time series exhibits a decreasing linear trend, and forecasts below actual results when the time series exhibits an increasing trend. Double exponential smoothing can overcome this problem. Furthermore, forecasting with single smoothing usually projects a straight horizontal line, which is not very likely to occur in reality. In this case, double smoothing is preferred. The simplest form of exponential smoothing is given by the formulas.

$$S_t = \alpha y_t + (1-\alpha) S_{t-1} \tag{3.9}$$

$$\hat{y}_{t+1} = \alpha y_t + (1-\alpha)\hat{y}_t \tag{3.10}$$

Where, S_t is the smoothing value at time t, α is the smoothing factor with $0 < \alpha < 1$, y_t is the observed value at time t , S_{t-1} is the smoothing value at time $t-1$, $\hat{y}_{t+1}$ is the prediction value of basic exponential smoothing at time $t+1$, $\hat{y}_t$ is the prediction value of basic exponential smoothing at time t.

Basic exponential smoothing does not achieve the goal that decision maker wants to get the intertemporal prediction [33]. In such situations, the method is devised into "double exponential smoothing" or "second-order exponential smoothing". These terms mean the recursive application of an exponential filter twice. It works as formulas [34].

$$S_t^{(1)} = \alpha y_t + (1-\alpha) S_{t-1}^{(1)} \tag{3.11}$$

$$S_t^{(2)} = \alpha S_t^{(1)} + (1-\alpha) S_{t-1}^{(2)} \tag{3.12}$$

Where $S_t^{(1)}$ is the basic exponential smoothing value at time t, $S_{t-1}^{(1)}$ is the basic exponential smoothing value at time $t-1$, $S_t^{(2)}$ is the second exponential smoothing value at time t, $S_{t-1}^{(2)}$ is the second exponential smoothing value at time $t-1$,

The prediction value of double exponential smoothing is calculated by the following equations:

$$\hat{y}_{t+k} = a_t + b_t k \tag{3.13}$$

$$a_t = 2S_t^{(1)} - S_t^{(2)} \tag{3.14}$$

$$b_t = \frac{\alpha}{1-\alpha}(S_t^{(1)} - S_t^{(2)}) \tag{3.15}$$

Where, $\hat{y}_{t+k}$ is the prediction value of the second exponential smoothing at time *t+k*, a_t, b_t are coefficients at time *t*, *k* is the number of periods.

3.4.2 Smoothing factor and initial value

The accuracy of prediction value is mainly dependent on the value of smoothing factor α. There is no formally correct procedure for choosing the value of α. In order to minimize the error influence of smoothing factor, we applied the proven trial-and-error method to choose the best value of smoothing factor α. This is an iterative procedure beginning with a range of α between 0.1 and 0.9. Based on previous experience, we selected 0.1, 0.3, 0.6, and 0.8 as the trial values. We chose the best value for α to ascribe to the smallest sum of the squared errors (SSE) and standard deviation of error (SDE). We illustrated this principle with Beijing as an example. Consider the following dataset consisting of 12 water ecological footprint per capita observations in Beijing taken over time. According to the calculation, the SSE and SDE were the smallest, when smooth factor α was 0.3 in Table3-3. The selection procedure was also applied in other cities as shown in Fig.3-5. Empirically, if the number of items in the original sequence is less than 15, the average value of the original sequence (usually the first three) is selected as the initial value.

Table3-3 The prediction accuracy of water ecological footprint per capita in Beijing with different smoothing factors (Unit: gha)

		α=0.1		α=0.3		α=0.6		α=0.8	
Y	Observation	Prediction	Error	Prediction	Error	Prediction	Error	Prediction	Error
2004	0.3829								
2005	0.3706	0.3693	0.0013	0.3693	0.0013	0.3693	0.0013	0.3693	0.0013
2006	0.3543	0.3694	-0.0151	0.3697	-0.0153	0.3775	-0.0232	0.3802	-0.0259
2007	0.3433	0.3679	-0.0246	0.3651	-0.0218	0.3733	-0.03	0.3725	-0.0292
2008	0.3276	0.3654	-0.0378	0.3585	-0.0309	0.3619	-0.0343	0.358	-0.0304
2009	0.3155	0.3616	-0.0462	0.3492	-0.0338	0.3507	-0.0353	0.3462	-0.0308
2010	0.2965	0.357	-0.0605	0.3391	-0.0426	0.3369	-0.0403	0.3313	-0.0348
2011	0.2952	0.351	-0.0558	0.3063	-0.0111	0.324	-0.0288	0.3186	-0.0234
2012	0.2868	0.3454	-0.0586	0.307	-0.0202	0.3075	-0.0207	0.301	-0.0142
2013	0.2845	0.3395	-0.0551	0.2979	-0.0135	0.3001	-0.0157	0.2964	-0.0119
2014	0.288	0.334	-0.046	0.2909	-0.0029	0.2921	-0.0041	0.2887	-0.0007
2015	0.2916	0.3294	-0.0378	0.297	-0.0054	0.2875	0.0041	0.2853	0.0063
Sum of squared errors			0.0212		0.0053		0.007		0.0055
Standard deviation of errors			0.0243		0.0163		0.0176		0.0166

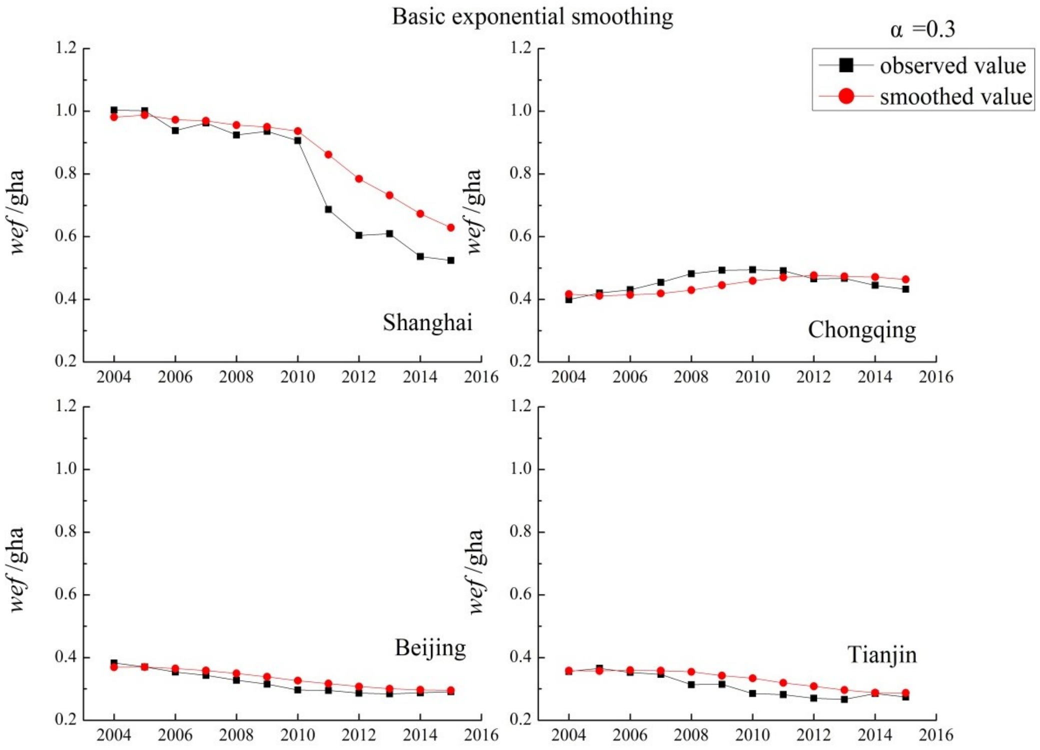

Fig.3-5 The basic exponential smoothing prediction values of the WEF per capital

3.4.3 Forecast of the water ecological footprint per capital

According to formulas 3.9-3.15, we calculated the basic exponential smoothing values, the second exponential smoothing values, the coefficients a_t and b_t (Table3-4, Table3-5, Table3-6, Table3-7), and the WEF per capital of the four cities in 2020 and 2025 (Table3-8). The WEF per capital is mainly affected by the total WEF and population. From Tab.8, the WEF per capital of Beijing will increase to 0.4193 in 2025 at an increasing rate of 43.8 %. The growth of the WEF per capital means the quick increase of water consumption in the future 10 years with threating the water supply system. Beijing will need more water resources to maintain the sustainable development of society. For Shanghai, with current water consumption mode in the next 10 years the WEF per capital will decrease to 0.0344 in 2025. The reasons are that Shanghai adjusts the structure of water resources consumption and the population is growing. For Tianjin, there is a slowly decreasing trend; the water management policy still takes a positive effect. For Chongqing, the WEF per capital will keep the steady trend, because of the stable population and a slow-moving economy. So the water demand increases slowly.

Table3-4 The exponential smoothing values of the WEF per capita in Beijing (α=0.3)

Y	t	*wef*/gha	$S^{(1)}$	$S^{(2)}$	a_t	b_t
2004	1	0.3829	0.3693	0.3693	0.3693	0.0000
2005	2	0.3706	0.3694	0.3694	0.3694	0.0000
2006	3	0.3543	0.3679	0.3681	0.3677	-0.0001
2007	4	0.3433	0.3654	0.3652	0.3656	0.0001
2008	5	0.3276	0.3616	0.3604	0.3628	0.0005
2009	6	0.3155	0.3570	0.3540	0.3600	0.0013
2010	7	0.2965	0.3510	0.3457	0.3563	0.0023
2011	8	0.2952	0.3454	0.3371	0.3537	0.0036
2012	9	0.2868	0.3395	0.3284	0.3506	0.0048
2013	10	0.2845	0.3340	0.3201	0.3479	0.0060
2014	11	0.2880	0.3294	0.3132	0.3456	0.0069
2015	12	0.2916	0.3256	0.3079	0.3433	0.0076

Table3-5 The exponential smoothing value of the WEF per capita in Shanghai (α=0.3)

Y	t	*wef*/gha	$S^{(1)}$	$S^{(2)}$	a_t	b_t
2004	1	1.0035	0.9815	0.9815	0.9815	0.0000
2005	2	1.0020	0.9876	0.9833	0.9920	0.0019
2006	3	0.9389	0.9730	0.9802	0.9658	-0.0031
2007	4	0.9625	0.9699	0.9771	0.9626	-0.0031
2008	5	0.9246	0.9563	0.9709	0.9417	-0.0062
2009	6	0.9364	0.9503	0.9647	0.9359	-0.0062
2010	7	0.9064	0.9371	0.9564	0.9178	-0.0083
2011	8	0.6866	0.8620	0.9281	0.7958	-0.0283
2012	9	0.6043	0.7847	0.8851	0.6843	-0.0430
2013	10	0.6092	0.7320	0.8392	0.6249	-0.0459
2014	11	0.5367	0.6734	0.7894	0.5574	-0.0497
2015	12	0.5245	0.6288	0.7412	0.5163	-0.0482

Table3-6 The exponential smoothing value of the WEF per capita in Tianjin (α=0.3)

Y	t	*wef*/gha	$S^{(1)}$	$S^{(2)}$	a_t	b_t
2004	1	0.3561	0.3584	0.3584	0.3584	0.0000
2005	2	0.3661	0.3577	0.3582	0.3572	-0.0002
2006	3	0.3530	0.3602	0.3588	0.3616	0.0006
2007	4	0.3464	0.3581	0.3586	0.3575	-0.0002
2008	5	0.3138	0.3546	0.3574	0.3518	-0.0012
2009	6	0.3146	0.3424	0.3529	0.3318	-0.0045
2010	7	0.2853	0.3340	0.3472	0.3208	-0.0057
2011	8	0.2818	0.3194	0.3389	0.2999	-0.0083
2012	9	0.2705	0.3081	0.3296	0.2866	-0.0092
2013	10	0.2667	0.2968	0.3198	0.2739	-0.0098
2014	11	0.2853	0.2878	0.3102	0.2654	-0.0096
2015	12	0.2743	0.2870	0.3033	0.2708	-0.0069

Table3-7 The exponential smoothing value of the WEF per capita in Chongqing (α=0.3)

Y	t	*wef*/gha	$S^{(1)}$	$S^{(2)}$	a_t	b_t
2004	1	0.3992	0.4168	0.4168	0.4168	0.0000
2005	2	0.4203	0.4115	0.4152	0.4078	-0.0016
2006	3	0.4309	0.4142	0.4149	0.4134	-0.0003
2007	4	0.4545	0.4192	0.4162	0.4222	0.0013
2008	5	0.4819	0.4298	0.4203	0.4393	0.0041
2009	6	0.4932	0.4454	0.4278	0.4630	0.0075
2010	7	0.4949	0.4597	0.4374	0.4821	0.0096
2011	8	0.4915	0.4703	0.4473	0.4933	0.0099
2012	9	0.4655	0.4766	0.4561	0.4972	0.0088
2013	10	0.4670	0.4733	0.4612	0.4854	0.0052
2014	11	0.4447	0.4714	0.4643	0.4785	0.0030
2015	12	0.4327	0.4634	0.4640	0.4627	-0.0003

According to formula 3.14, and 3.15, we calculated the predicted formula of these four cities

For Beijing,

$$\hat{y}_{12+k} = 0.3433 + 0.0076k \tag{3.16}$$

For Shanghai,

$$\hat{y}_{12+k} = 0.5164\text{-}0.0482k \tag{3.17}$$

For Tianjin,

$$\hat{y}_{12+k} = 0.2707\text{-}0.0069k \tag{3.18}$$

For Chongqing,

$$\hat{y}_{12+k} = 0.4628\text{-}0.0003k \tag{3.19}$$

Table3-8 Predicted values of the WEF per capita in these four cities

	wef/gha		
	2015	2020	2025
Beijing	0.2916	0.3813	0.4193
Shanghai	0.5245	0.2754	0.0344
Tianjin	0.2743	0.2362	0.2017
Chongqing	0.4327	0.4613	0.4598

3.5 Summary

This chapter studied the water resources security of four cities to investigate the dynamic characteristics of water resources and water consumption forecast. Based on the water ecological footprint model, the total WEF and WEC, the WEF per capital and the WEC per capital for Beijing, Shanghai, Tianjin, and Chongqing in 2004-2015 were analyzed, respectively. It gives us a holistic implication about the water utilization in different types of cities to facilitate to analyze the driving factors of the WEF and WEC. After analyzing the WEF accounts, we find which sector is the biggest water consumption account, the structure of water consumption and water efficiency in different sectors. Then the exponential smoothing method was applied to predict the WEF per capital in the future, the forecasting series can provide a scientific basis for the future utility of water resources. Finally, according to the analysis and prediction results, we summarized three typical types of urban WEF development. The main countermeasures and suggestions for urban water resources sustainable development were:

(1) The type I of urban WEF development, the WEF is higher than the WEC. The total WEF has continuously increased with the development of urban population and economy, the scale of city

has expanded rapidly. Such as Beijing and Tianjin, the WEF always exceeded the WEC from 2004 to 2015. The cities are in a state of WED. The pressure on the sustainable use of water resources in Beijing and Tianjin is gradually increasing. From the characteristics of the water resources utilization structure, it can be seen that the main demand pressure comes from the development of industry and agriculture. So, to adjust the structure of the industry, to reduce the water resources consumption intensity is the key. In order to realize the economic development and social stability, manager also needs to seek new water sources or divert water from other places. But it could not only rely on The South to North Water Transfer Project since the project has a limited impact on meeting the increasing demand for water. At the same time, Beijing and Tianjin should adopt strict water resources management in the future. For Tianjin, the WEF of primary industry accounted for the biggest proportion. It is suggested that the city achieves water conservation either by importing water-intensive farm products from water-rich areas or by importing the advanced water-saving equipment to improve the efficiency of agriculture water.

(2) The type II of urban WEF development: At first, the urban WEF increased like the type I. But through a series of measures, the WEF is becoming lower than the WEC. The city is in a state of WES. There is no need to transfer water from other areas, and the city relies on self-regulation to realize WES from WED. For example, the WEF of Shanghai increased from 2004 to 2010, and then decreased from 2010 until the WES occurred in 2014. But the WEF per capita is the biggest in Shanghai, so we advise that it is essential to improve citizens’ awareness of water resources protection, change the consumption way of production and life, and establish a water-saving social production and consumption system.

(3) The type III of urban WEF development: the WEF is lower than the WEC. The city is always in a state of WES. Chongqing locates in a water-rich area. The WEC was always higher than the WEF from 2004 to 2015. Chongqing is still in a state of WES. According to the analysis of Chongqing’s WEF accounts, there is a need to transfer the industry production from water-intensive industrial products to water-saving cleaner products. Because the WEF of the secondary industry is the biggest occupation account, water-intensive industrial sectors, such as thermal power, textiles, paper, iron and steel, have the most potential for water conservation.

According to the prediction of the study, the WEF per capita of Beijing will be increasing and it will be a decreasing trend in Shanghai and Tianjin. In Chongqing, it will basically remain steady and unchanged. So for Beijing and Tianjin, water conservation should follow the principle of unified planning, total volume control, planned water consumption, comprehensive utilization and emphasis on benefits. For Shanghai, it is important to keep on current countermeasures and change the way of domestic water use. For Chongqing, it needs to take a slight note on readjusting industrial structure.

This chapter mainly does a water resources security analysis from water demand side and water supply side management. In the calculation of the WEF, we only consider the productive WEF (including irrigation water, forestry, livestock, industrial water use and services water use), the household WEF, and the ecological WEF. The WEF of polluted water is not considered in the WEF accounts. With the development of urbanization, water pollution will become one significant component of water ecological footprint account. Therefore, in the following chapter, how to combine the water pollution account with the water ecological footprint model will be considered in details.

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Nomenclature

WEF	*water ecological footprint (gha)*	N	*the total population (person)*
WEC	*water ecological carrying capacity (gha)*	r_w	*the equivalence factor of water resource*
WED	*water ecological deficit (gha)*	p_w	*the world average water yield factor* (m^3/hm^2)
WES	*water ecological surplus (gha)*	ψ_w	*the yield factor*
WEF_h	*water ecological footprint of household (gha)*	Q	*the regional total water resource quantity* (m^3)
WEF_e	*water ecological footprint of ecology (gha)*	S_t	*the smoothing value at time t*
WEF_p	*water ecological footprint of production (gha)*	α	*the smoothing factor*
WEF_{pi}	*water ecological footprint of primary industry (gha)*	y_t	*the observed value at time t*
WEF_{si}	*water ecological footprint of secondary industry (gha)*	S_{t-1}	*the smoothing value at time t-1*
WEF_{ti}	*water ecological footprint of tertiary industry (gha)*	$S_t^{(1)}$	*the basic exponential smoothing value at time t*
W	*total water consumption* (m^3)	$S_{t-1}^{(1)}$	*the basic exponential smoothing value at time t-1*
W_h	*household water consumption* (m^3)	$S_t^{(2)}$	*the second exponential smoothing value at time t*
W_e	*ecological water consumption* (m^3)	$S_{t-1}^{(2)}$	*the second exponential smoothing value at time t-1*
W_p	*productive water consumption* (m^3)	$\hat{y}_t$	*the prediction value of basic exponential smoothing at time t*
W_{pi}	*water consumption of primary industry* (m^3)	$\hat{y}_{t+1}$	*the prediction value of basic exponential smoothing at time t+1*
W_{si}	*water consumption of secondary industry* (m^3)	$\hat{y}_{t+k}$	*the prediction value of second exponential smoothing at time t+k*
W_{ti}	*water consumption of tertiary industry* (m^3)	a_t	*coefficients at time t*
wef	*water ecological footprint per capita (gha)*	b_t	*coefficients at time t*
wec	*water ecological carrying capacity per capita (gha)*	k	*the number of periods*
SSE	*the sum of the squared errors*	SDE	*standard deviation of error*

Chapter 4

SPATIO-TEMPORAL CHARACTERISTICS OF WATER RESOURCES SECURITY AND WATER ENVIRONMENT SECURITY

CHAPTER 4: SPATIO-TEMPORAL CHARACTERISTICS OF WATER RESOURCES SECURITY AND WATER ENVIRONMENT SECURITY

4.1 Introduction

This chapter adopts water ecological footprint model (WEFM) to assess water sustainability and efficiency use of water in Japan not only in water resources account but also water environment account. The water ecological footprint accounts (WEFA) is applied to track the water ecological footprint (WEF) in agricultural purposes, urban activities, industry and water environment. Furthermore, the regional contrastive analysis of WEF is also performed and the water sustainability indicators are compared in different regions of Japan to further facilitate the sustainable utilization of water. The whole framework is introduced in Fig.4-1.

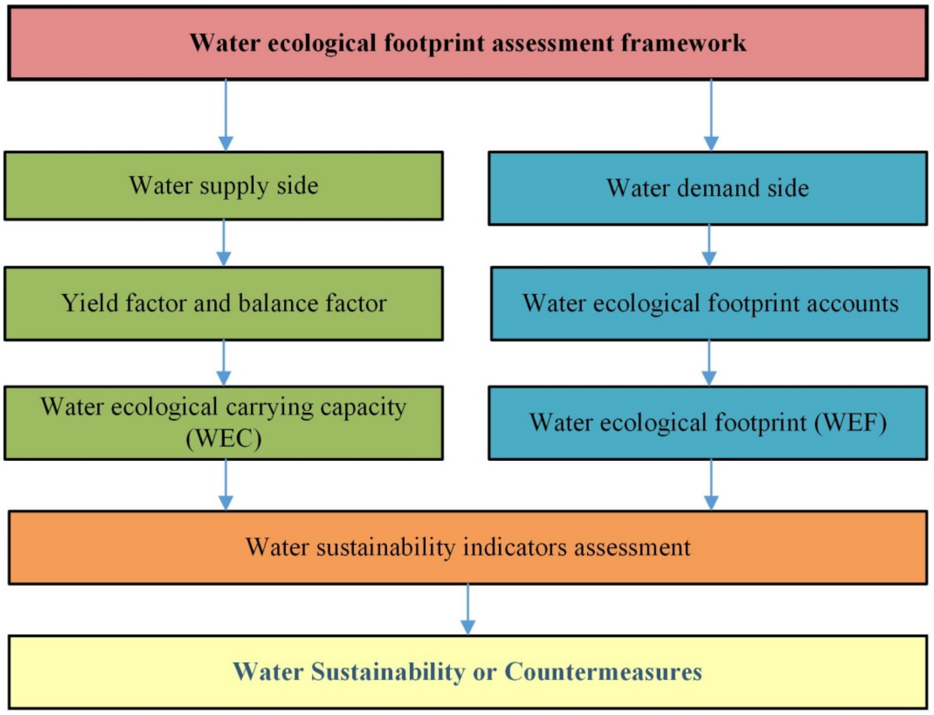


Fig. 4-1 A framework for water ecological footprint evaluation

4.1.1 Case study area

Japan has a total of 6,852 islands extending along the Pacific coast of East Asia. The country, including all of the islands, locates between latitudes 24° and 46°N, and longitudes 122° and 146°E. Although the annual total precipitation in Japan is about 1,700 mm, about twice the global average 970 mm [1]. Japan appears to be a high rainfall area and is rich in water. However, Japan has a small land area and a high population density. The precipitation per person is about one-third of the global average. Therefore, in order to estimate the amount of water per person, it cannot be concluded that Japan is rich in water. In addition, Japan is at a disadvantage when using water resources: the rainfall centers on rainy, typhoon, and snowfall seasons and is significantly dependent on the weather. Besides, the country is so steep that most rainfall quickly runs off into the sea. Japan has made various efforts to ensure water resources under such conditions and built life's rich foundations.

4.1.2 Data sources

Data for the administrative division areas and the population are all obtained from the statistical handbook of Japan [2]. For water-related data, the total consumption of water resources, the sector account's water consumption, and the total quantity of water resources are derived from the report of the current status of water resources in Japan [3-7]. Water pollutants emissions data are derived from the report of a comprehensive survey on water pollutant release [8-12].

4.2 The analysis of water ecological footprint in water resources security

4.2.1 Water resources accounts of ecological footprint

In this study, the WEFA is presented in two aspects: first, the amount of water productive area needed by human beings in production and life is the WEF of water resources account; second, the area consumed by absorbing the pollutants which exceed the standard of pollutants concentration is the WEF of water environment account. Generally, WEFA consists of the water quantity account (WEF_{qn}) and the water quality account (WEF_{ql}).

$$WEC = \left(1\text{- }0.12\right) \bullet \psi_w \bullet r_w \bullet (Q / p_w) \tag{4.1}$$

Where, WEC (gha) is the water ecological carrying capacity; ψ_w is the water resources yield factor in the area; r_w is the global balance factor of water resources; Q (m^3) is the regionally total amount of water resource; p_w (m^3/hm^2) is the average production capacity of the global water resources. It is a normal practice to allocate 12 % of the available supply land to protect the local biodiversity.

$$WEF = WEF_{qn} + WEF_{ql} \tag{4.2}$$

Where, WEF (gha) is the total water ecological footprint; WEF_{qn} (gha) is the WEF of water quantity account; WEF_{ql} (gha) is the WEF of water quality account.

In this study, the WEFAs are divided into water quantity account and water quality account two parts based on the classification of Japanese water use accounts and the convenience of discussion and analysis. According to the classification method of water quantity accounts in Japan, the water quantity accounts are divided into two major accounts, e.g., urban water and agricultural water. Urban water includes industrial water and domestic water. Agricultural water includes three subaccounts: paddy field irrigation water, upland field irrigation water, and animal husbandry water. The calculation formulas are,

$$WEF_{qn} = r_w \bullet (W / p_w) \tag{4.3}$$

$$W = W_i + W_d + W_p + W_{up} + W_{an} \tag{4.4}$$

Where, W (m^3) is the consumption of various types of water resource; W_i (m^3) represents the industrial water consumption; W_d (m^3) represents the domestic water consumption; W_p (m^3) represents the paddy field irrigation water consumption; W_{up} (m^3) represents the upland field irrigation water consumption; W_{an} (m^3) represents the animal husbandry water consumption.

4.2.2 Parameters treatment of water resources

Just as the ecological footprint model, the main parameters in the WEFM include the balance factor of water resources and the yield factor of water resources. This study adopts World Wide Fund for Nature Living Planet Report 2002 (WWF 2002) to determine the balance factor of water resources as 5.19. In order to determine the yield factors of water resources in different regions, it is assumed that the world yield factor of water resources is 1. The regional yield factor of water resources is the ratio of the average production capacity of water area in the region to the average production capacity of water area in the world. The average production capacity of water area in the world is 3140 m^3/gha. The average production capacity of water area in the region is the ratio of regional total water quantity to the regional area (Table4-1 & Table4-2).

Table 4-1 Water resources use situation in Japan during 1995-2014

Y	Total water resources (0.1 G m^3)	Water use (0.1 G m^3)					Total (0.1 G m^3)	Yield factors
		Paddy filed irrigation	Upland filed irrigation	Animal husbandry	Industrial water	Domestic water		
1995	4235	555	25	5	540.5	163.4	1288.9	3.57
1999	4235	546	29	5	545.9	163.7	1289.6	3.57
2004	4235	520	28	5	536.2	161.9	1251.1	3.57
2009	4235	512	28	4	470.2	154.1	1168.3	3.57
2014	4235	507	30	4	456.4	148.4	1145.8	3.57

Note: Total water resources value is obtained from annual mean value during 1981-2015. The Ministry of Land, Infrastructure and Transport Investigation

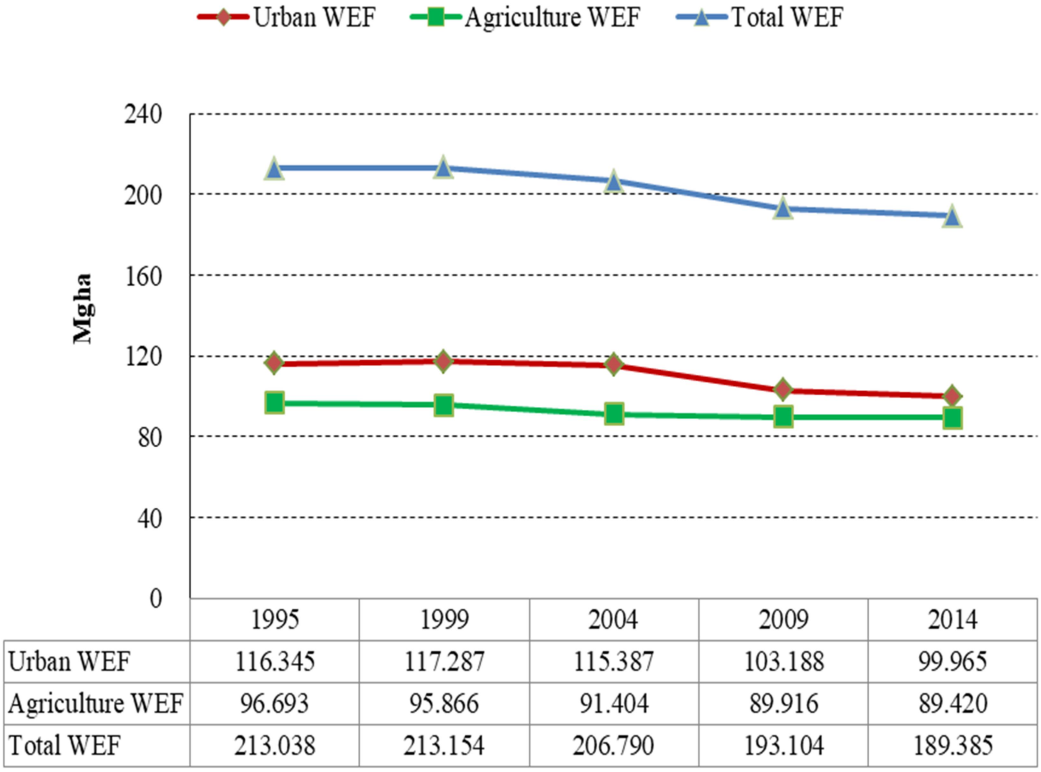
Table 4-2 Water resources situation in different administrative divisions of Japan in 2014

Administrative divisions	Population (1 K)	Total quantity of annual mean water resources (0.1 G m^3)	Area (1 M gha)	Regional average water production per unit area(m^3/gha)	Global average water production per unit area(m^3/gha)	Yield factors
Hokkaido	5,506	563	8.35	6,745.99	3,140	2.15
Tohoku	11,710	868	7.95	10,913.43	3,140	3.48
Kanto	43,468	393	3.69	10,653.29	3,140	3.39
Chubu	55,529	853	5.55	15,361.34	3,140	4.89
Kinki	20,904	307	2.73	11,228.15	3,140	3.58
Chugoku	7,563	328	3.19	10,275.37	3,140	3.27
Shikoku	3,977	277	1.88	14,729.34	3,140	4.69
Kyushu	14,597	646	4.45	14,527.63	3,140	4.63
Japan	163,254	4235	37.79	11,205.27	3,140	3.57

Note: Population data source from Ministry of Internal Affairs and Communications Statistics

4.2.3 Temporal analysis of water ecological footprint

Fig.4-2 illustrates the total WEF of water quantity contents of urban and agricultural accounts in Japan in 1995, 1999, 2004, 2009, and 2014. The total WEF of water quantity in Japan experienced a steady decrease from 213.0 M gha in 1995 to 189.4 M gha in 2014. Urban accounts include industrial and domestic sub-accounts, and agricultural accounts are made of paddy field irrigation, upland field irrigation, and animal husbandry sub-accounts. During the studied period, urban WEF was always higher than agricultural WEF. While in 2014, the difference between urban WEF and agricultural WEF was the minimum 10.54 M gha. As we all know, agriculture is the largest account of water consumption in various types of water quantity accounts. However, water consumption in urban areas in Japan is higher than that in agriculture. The main reason is that Japan's agriculture is not a pillar industry of the economy, and it accounts for a relatively low proportion in various economic industries.



	1995	1999	2004	2009	2014
Urban WEF	116.345	117.287	115.387	103.188	99.965
Agriculture WEF	96.693	95.866	91.404	89.916	89.420
Total WEF	213.038	213.154	206.790	193.104	189.385

Fig. 4-2 Transition in water ecological footprint of water quantity account in Japan during 1995-2014

For the WEF of sub-accounts sectors change, during the studied period, paddy field irrigation sector had the highest WEF except in 2004 (Fig.4-3), followed by the WEF of the industrial sector, and the animal husbandry sector had the lowest WEF. From the absolute value perspective, the WEF of all sectors decreased during 1995-2014 (8.6 %-20.5 %) especially with a sharp decrease for both animal husbandry and industry whose WEF decreased by 20.5 % and 15.6 %, respectively. The only exception was the sector of upland field irrigation whose WEF increased from 4.13 M gha in 1995 to 4.96 M gha in 2014, increased by 16.7 %. The continuous reduction in the WEF of paddy field irrigation sector was due to the reduction of paddy area from 2,745 K gha in 1995 to 2,465 K gha in 2014. Conversely, while the area of upland field irrigation has also decreased, the WEF of upland field irrigation has not decreased but increased. The results reflect that the efficiency of agricultural water use in Japan has not improved during the study period. In contrast, according to the report [3], the supply of fresh water for industrial use decreased from 123.5 G m^3 in 1995 to 96.7 G m^3 in 2014. Therefore, the decrease in WEF of the industrial sector is caused by the improvement of industrial water use efficiency.

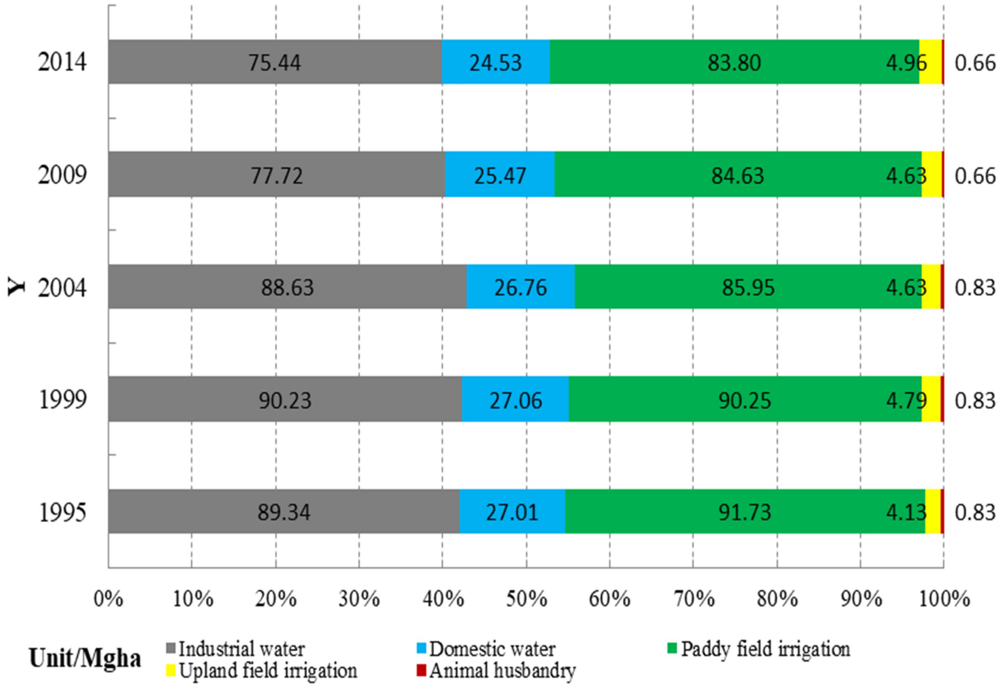


Fig. 4-3 Transition in water ecological footprint of water quantity sub-accounts in Japan during 1995-2014

4.2.4 Spatial analysis of water ecological footprint

In order to uncover the spatial characteristics of WEF in Japan, we also analyzed the WEF from the perspectives of water quantity and water quality in 2014. In Japan, "eight regional divisions" are often used. From north to south, the regions are Hokkaido, Tohoku, Kanto, Chubu, Kinki, Chugoku, Shikoku, and Kyushu region. In water quantity accounts, the WEF of the agricultural sector in Tohoku was the largest 25.79 M gha and the smallest 3.47 M gha was in Shikoku (Fig.4-4). It means that the agricultural water consumption was the main driving force of water quantity accounts in Tohoku. In the WEF of the industrial sector, Chubu accounted for the highest proportion, followed by Kanto. The WEF of domestic sector in Kanto was the largest. The WEF of industrial and domestic sectors was higher in Kanto because it is the political, economic, and cultural center of Japan. It has the highest population density and the largest industrial district in Japan, the Keisei Industrial Zone. For whichever agricultural account, industrial account, or domestic account in all water quantity accounts, the WEF of Shikoku was the smallest. It is mainly because Shikoku has the smallest area and the smallest population.

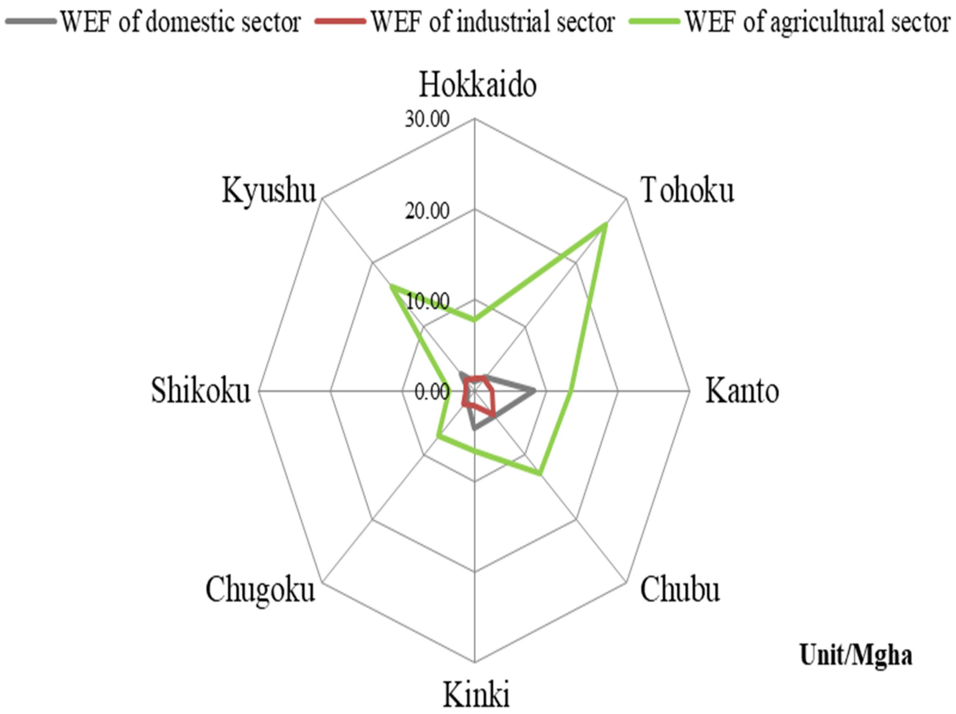


Fig. 4-4 Water ecological footprint of water quantity in different administrative divisions of Japan in 2014

4.3 The analysis of water ecological footprint in water environment security

4.3.1 Water environment accounts of ecological footprint

In water quality accounts, the paper selects total nitrogen (TN), total phosphorus (TP) and chemical oxygen demand (COD) as the representative pollutants. As these three kinds of pollutants have obvious overlap in water quality impact, the largest WEF among them is taken as the final WEF of water quality account. The formulas are [13],

$$WEF_{ql} = \max(WEF_{TN}, WEF_{TP}, WEF_{COD})$$
$$\begin{cases} WEF_{TN} = r_w \bullet (U_{TN} / p_N) \\ WEF_{TP} = r_w \bullet (U_{TP} / p_P) \\ WEF_{COD} = r_w \bullet (U_{COD} / p_{COD}) \end{cases} \tag{4.5}$$

Where, WEF_{TN} (gha) is the WEF of total nitrogen; WEF_{TP} (gha) is the WEF of total phosphorus; WEF_{COD} (gha) is the WEF of chemical oxygen demand; U_{TN} (t) is total nitrogen emissions of the study area; U_{TP} (t) is total phosphorus emissions of the study area; U_{COD} (t) is total chemical oxygen demand emissions of the study area; P_N (t/gha) is the average TN absorption per unit area; P_P (t/gha) is the average TP absorption per unit area; P_{COD} (t/gha) is the average COD absorption per unit area.

4.3.2 Parameters treatment of water environment

In Japan, the basic Environment Law establishes two kinds of environmental water quality standard relating to water pollution: environmental water quality standards for protecting human health, and environmental water quality standards for protecting the living environment. Based on the environmental water quality standards, the upper limits of chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) are 8 mg/L, 1 mg/L, and 0.1 mg/L, respectively. Subsequently, the values of PCOD, PTN, and PTP are 0.02512, 0.00314, and 0.00031, respectively (EQS). The upper limit values of COD, TN, TP are that are able to maintain the ecological service function of the water body and, limit of not disrupting daily lives of the population no matter in rivers, lakes or coastal waters. On the contrary, if it is lower than this standard value, the ecological service function of the water body will decline or be lost.

4.3.3 Temporal analysis of water ecological footprint

In Japan, the three most typical water polluted areas are the Tokyo Bay, Ise Bay, and the Seto Inland Sea. So the paper selected the total pollutions discharge of Tokyo Bay, Ise Bay, and the Seto Inland Sea as the whole national water quality accounts. The indicators of chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) are chosen as the organic pollution and eutrophication of water bodies.

The discharge of COD, TN, and TP in Japan is the total amount of the Tokyo Bay, Ise Bay, and the Seto Inland Sea. Due to the apparent overlap of the three pollutants in the environmental impact, the largest WEF among the three pollutants is used as the final WEF of water quality. From Fig.5, we can see that in Japan's water quality accounts, the WEF of TN was the largest, followed by the WEF of TP, and lowest the WEF of COD. Therefore, we considered the WEF of TN as the final WEF of water quality. This means that in Japan's water quality pollutants, TN has the greatest impact on the water quality, and it needs to consume more fresh water to dilute, that is to say, it needs to occupy more water productive areas. Therefore, reducing the TN pollution in Japan can greatly improve water pollution issue and reduce the final WEF of water quality.

At the same time, the WEF of water quality in Japan experienced a steady decrease among the WEF of COD, the WEF of TN, and the WEF of TP with a decreasing rate of 44.6 %, 40.7 %, and

44.6 %, respectively during 20 years. The main reason is that the Total Pollutant Load Control System (TPLCS) was applied to reduce the total amount of pollution loads including industrial wastewater and domestic sewage in Japan from 1978, and it was also used for pollution control in the Seto Inland Sea, Tokyo Bay, and Ise Bay. Through these control measures, the deterioration of water quality has been suppressed, and the water quality has been improved since then.

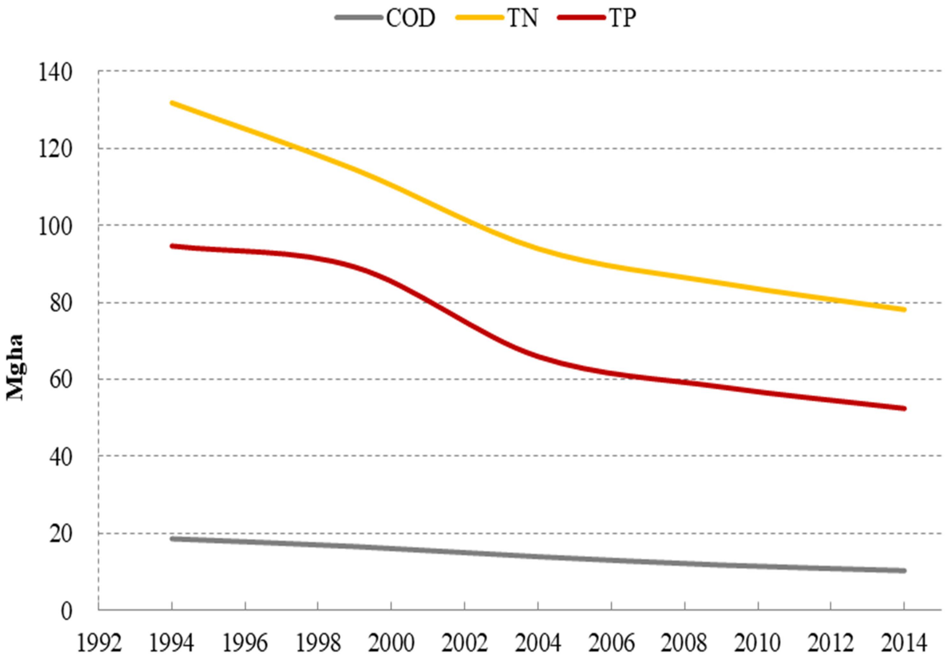


Fig. 4-5 Transition in water ecological footprint of water quality accounts in Japan during 1994-2014

4.3.4 Spatial analysis of water ecological footprint

From Figure 4-6, we can see that in water quality accounts of each region, the WEF of TN was also the largest. The WEF of water quality in the regional scale is consistent with the WEF of water quality on the national scale. Therefore, the WEF of TN is used as the final WEF of water quality in each region. Just as the table showed, the WEF of TN in Chugoku was the first, reaching 41.47 M gha. The second largest was the Kyushu region, followed by the Kanto region. The WEF of TN in the Tohoku region was the smallest at 8.28 M gha. The WEF of TN in Chugoku was about five times that of the Tohoku.

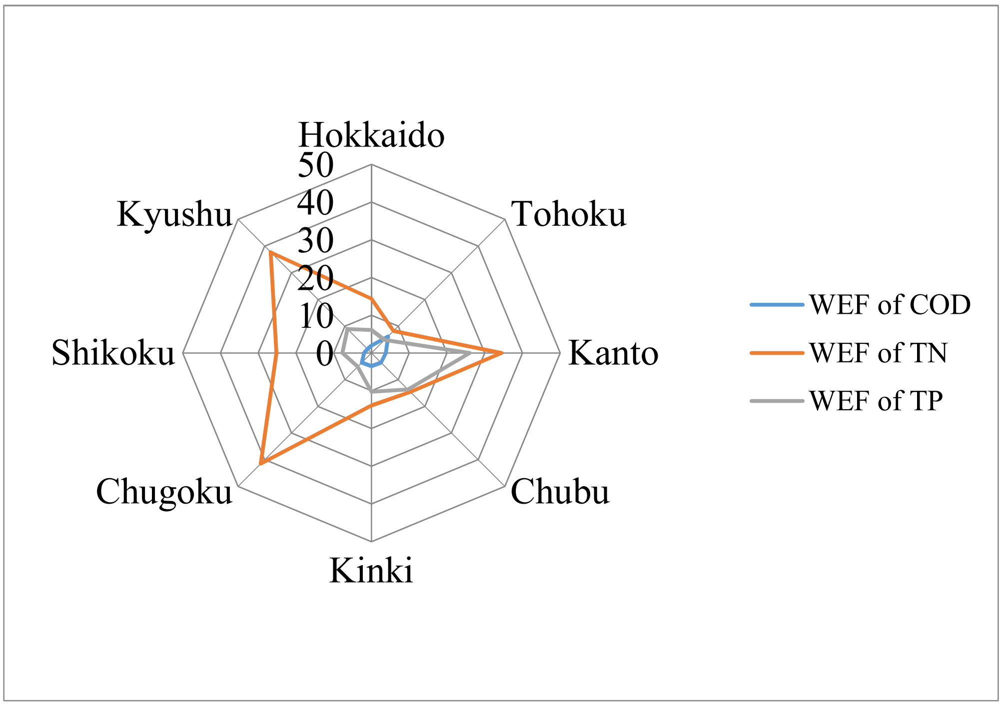


Fig. 4-6 Water ecological footprint of water quality in different administrative divisions of Japan in 2014 (Unit：1 M gha)

4.4 Sustainability indicators of water security

4.4.1 Water ecological surplus or water ecological deficit

In terms of time, when the WEC in a region is less than the demand for WEF, it goes into water ecological deficit (WED), and vice versa. The WED indicates that human pressure on water exceeds the local WEC in the region and that its regional water utilization is relatively unsustainable. On the contrary, water ecological surplus (WES) indicates that the regional WEC meets the water demand of current economic activity, and its regional water utilization is relatively sustainable. Table 4-3 shows the total WEF, WEC, and WES for Japan from 1995 to 2014. The total WEF of Japan in 1995 was 345.32 M gha, decreasing to 267.27 M gha in 2014. Meanwhile, the WEC was 987.289 M gha in 1995 and 1002.248 M gha in 2014, resulting in the WES of 641.968 M gha in 1995 and 734.98 M gha in 2014. From Table 4-3 we found that the total WEF kept falling down no matter in water quantity account or in water quality account. But the proportion of water quantity account was increasing from 61.7 % in 1995 to 70.9 % in 2014. Simultaneously, the proportion of water quality account was decreasing from 38.3 % in 1995 to 29.1 % in 2014. The WES in Japan was so large that it not only met self-sufficiency but also was exported to other regions in a way of water production.

Table 4-3 The total WEF, WEC, and WES in Japan from 1995-2014 (Unit: 1 M gha)

	WEC	WEF			WES
		Water resources	Water environment	Total	
1995	987.289	213.038	132.283	345.321	641.968
1999	996.737	213.154	115.428	328.582	668.155
2004	1006.185	206.790	94.505	301.295	704.890
2009	1007.759	193.104	85.554	278.659	729.101
2014	1002.248	189.385	77.882	267.268	734.980

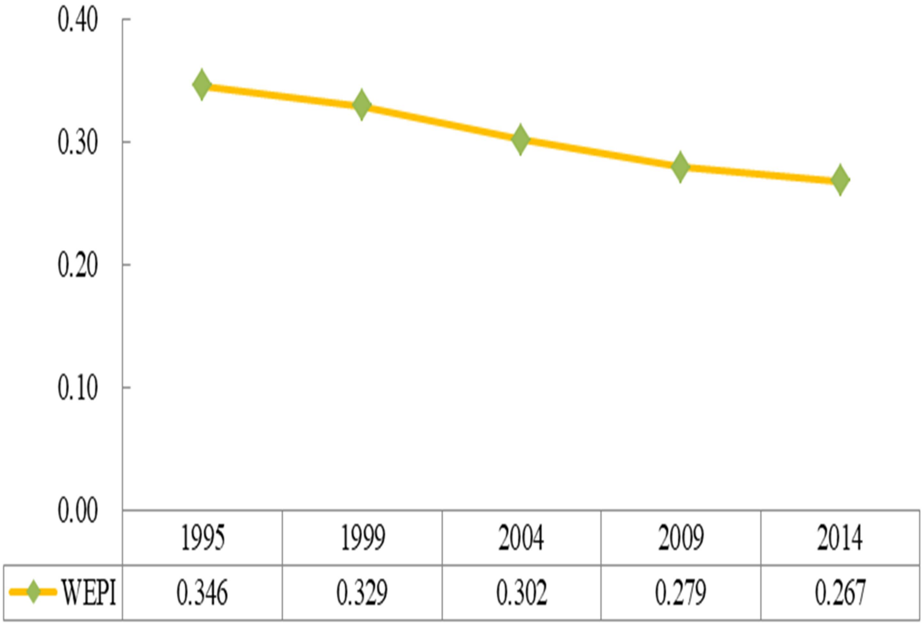
In terms of space, as can be seen from Table 4-4, the WEC of each region in 2014 was greater than the WEF, and different levels of WES existed in different regions. The WEC in Chubu region of Honshu Island was the largest, and the WES was also the largest; the WEC in Chugoku was the smallest, and the WES was also the smallest. It shows that water resources in the Chubu region were relatively sufficient to meet all aspects of water use. It indicates that the water resources in Chubu were rich with great development potential, while the development potential in Chugoku was low. In the total WEF of all regions, the total WEF of the Kanto region was the largest 58.67 M gha, which means the largest occupation of water. The main reason is that the Kanto region is Japan's economic center and the most densely populated area. Simultaneously, water quantity account and water quality account accounted for 41.3 % and 58.7 %, respectively. So, the water use intensity in the Kanto region in both water quantity and quality was roughly the same. Since Hokkaido’s economy and industry were dominated by tourism, with a small population size, the total WEF was the lowest 24.57 M gha in Hokkaido.

Table 4-4 The total WEF, WEC, and WES of different regions in 2014 (Unit: 1 M gha)

	WEC	WEF			WES
		Water quantity	Water quality	Total	
Hokkaido	79.969	10.165	14.400	24.565	55.404
Tohoku	199.457	29.785	8.281	38.065	161.392
Kanto	88.155	24.198	34.461	58.659	29.496
Chubu	275.897	20.727	14.638	35.365	240.532
Kinki	72.580	12.314	13.955	26.269	46.311
Chugoku	70.964	10.529	41.471	52.000	18.964
Shikoku	85.908	5.405	25.198	30.603	55.305
Kyushu	197.604	20.429	37.713	58.142	139.461

4.4.2 Water ecological press index

On the basis of the water ecological surplus or water ecological deficit, the indicator of water ecological pressure index (WEPI) determines the security status of water resources utilization through further quantitative methods. From the perspective of Japan's national scale, between 1995 and 2014, the WEPI was below 0.5 (see Fig.4-8). Furthermore, it was declining year by year. It indicates that the use of water resources was in a secure state during the study years. While judging from the local scale of the eight administrative divisions of Japan shown in Fig.4-7, Kanto and Chugoku regions were in a sub-secure state, which was consistent with the least water ecological surplus in the two regions. Other regions were in a state of security and there was no region in a critical or insecure state.



	1995	1999	2004	2009	2014
WEPI	0.346	0.329	0.302	0.279	0.267

Fig. 4-7 Transition in water ecological press indicator of Japan during 1995-2014

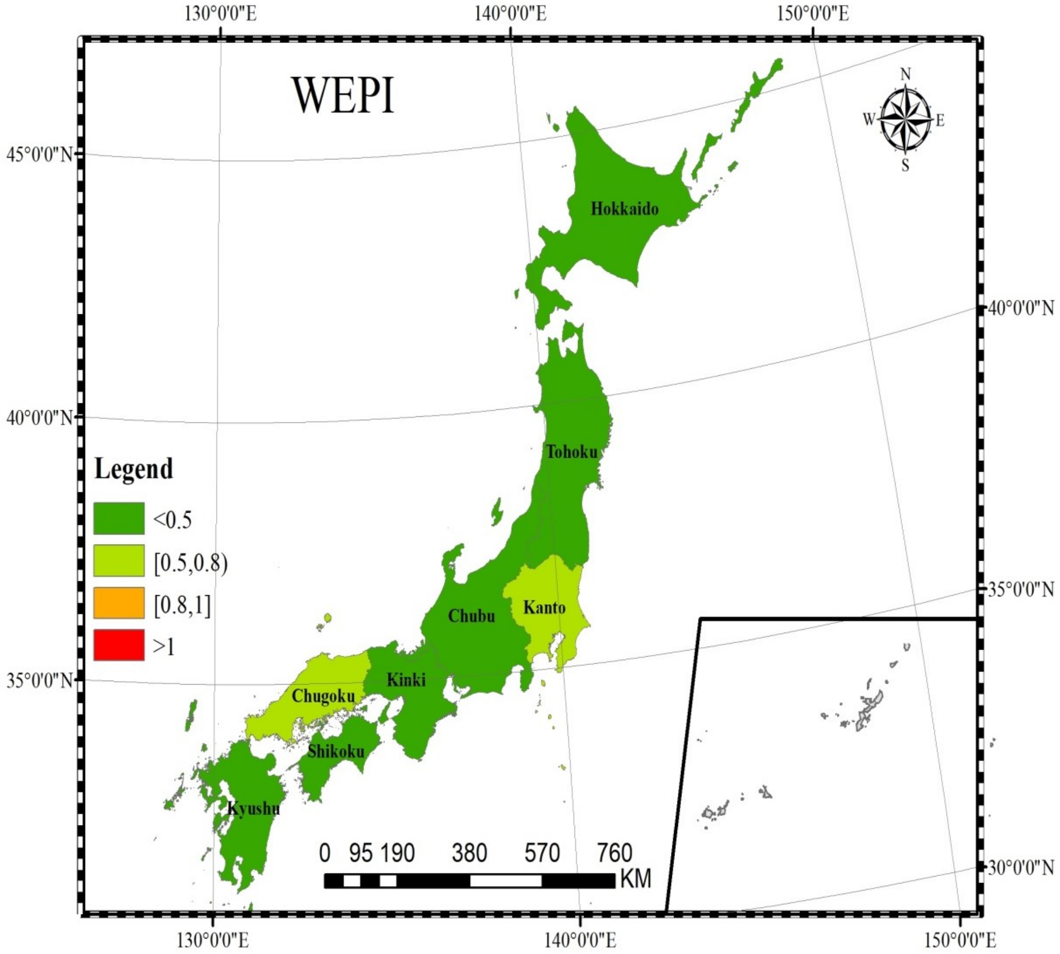


Fig. 4-8 Water ecological press indicator in different administrative divisions of Japan in 2014

4.4.3 Water use efficiency index

The water use efficiency index (Fig.4-9) has been calculated as it is a comprehensive index of different economic sectors including the agricultural sector corresponding to agricultural water use, the industrial sector corresponding to urban industrial water use, and the public sector (including service sector) corresponding to municipal water use. It comprehensively reflects the regional water use efficiency. In terms of agricultural sector, the WEF of per ten thousand dollars GDP among the three sectors was the highest during 1995-2014, with a higher WEF level as well as a lower level agricultural GDP. The reason is that the proportion of the agricultural sector in Japan's economic structure has decreased year by year, but the water consumption of the agricultural sector has not changed significantly. It means that the utilization rate of water resources in the agricultural sector was relatively low. In terms of the industrial sector, the WEF of per ten thousand dollars GDP presented degenerative trend annually. It had decreased six-fold from 4.2

gha in 1995 to 0.6 gha in 2014. The water use efficiency in the industrial sector has significantly improved. And in terms of the public sector, the WEF of per ten thousand dollars GDP was basically stable and the value was less than 1 gha from 1995 to 2014. The value of the public sector remained at around 0.5 gha and has not changed much over the years. The public sector had a low demand for water resources, and the WEF was relatively small. In the GDP composition structure of Japan, the public sector accounted for a large proportion. Therefore, from the view of the WEF, the water use efficiency in the public sector was the highest. With the highest water efficiency, the public sector should be vigorously developed.

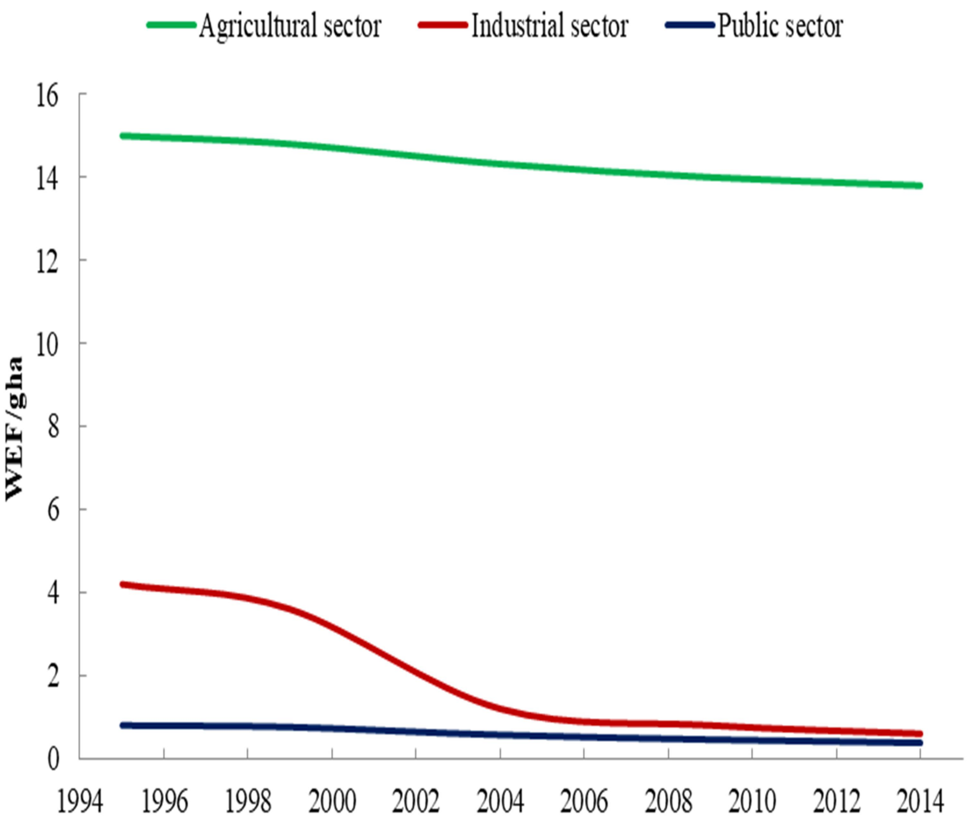


Fig. 4-9 Transition in water use efficiency indicator of different accounts during 1995-2014

Following policy implications are raised based on the above results. Although the water ecological surplus was abundant in Japan, the adjustment of the economic structure has significantly decreased the WEF during the last two decades. However, it is of great potential for further improvements. During 1995-2014 the adjustment focused on the industrial sector, rather than the public service sector. In fact, Japan could have achieved far more economic benefits from tourism since it has become a major tourism destination. The increasing visitors from all over the world posed increasing pressure on its water resource. Therefore, it is necessary for Japan government to initiate more efforts on guiding its tourism industries for their water conservation. In terms of the improvement of water use efficiency, the WEF of per ten thousand dollars GDP in the agricultural sector is the largest. This means that the water use efficiency of the agricultural sector is the lowest. It is recommended that Japan save water by increasing the efficiency of agricultural water use by importing water-intensive alternatives from external sources or applying advanced water-saving equipment. In terms of the improvement of the water environment, the WEF of TN in water environment accounts is the largest. This means that diluting TN pollution will consume more water. It is recommended that Japan improve water quality by controlling the emissions of TN.

4.5 Summary

Based on the WEFM and the obtained data on water resources utilization in Japan, this chapter improved the calculation method of yield factor so that the evaluation indicators will be more reliable and accurate. Followed by the WEF indicators were calculated and analyzed taking water quantity and water quality in an account from the temporal and the spatial dimensions in Japan. At last water sustainability indicators were applied to evaluate the water sustainable utilization. The experience in water management of Japan is relevant to the many developing countries in Asian currently facing major water challenges. We hope that it will be helpful to provide valuable insights for policymakers so that more sustainable water utilization policies can be raised by considering the local realities. The main conclusions of this chapter are listed as follows:

1. The temporal characteristic of WEF in Japan is a decreasing trend no matter in water resources account or water environmental account during the study periods. Paddy field irrigation sector has the highest WEF in water resources accounts and the WEF of TN is the largest in water environment accounts.

2. The spatial distribution characteristic of WEF in Japan is that no matter in water resources account or water environment account, the WEF is all concentrated along the Pacific coastal strip industrial corridor. For example, the WEF of Kanto, Chugoku, and Kyushu are the highest because the urbanization zone runs mainly along the Pacific coast of Japan from Kanto region to Osaka and the Inland Sea (on both sides) to Fukuoka.

3. Policy implications are put forward. For Japan, water efficiency should be further improved to reduce the WEF of agriculture in water resources accounts and reducing the WEF of TN in water environment accounts should be paid much attention to. For less developed water-poor regions its industrial structure should be optimized, water use efficiency should be improved, and more feasible water recycled technologies should be applied in order to achieve water sustainability.

This chapter mainly does a water resources security and water environment security analysis from water demand side and water supply side management. In the calculation of the WEF, we consider the water quantity accounts (including paddy filed irrigation, upland filed irrigation, animal husbandry, industrial water and domestic water), and the water quality accounts (including TN, TP, COD). In next chapter, the last pillar i.e. water disaster security of water security will be considered in details.

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Chapter 5

ASSESSMENT OF WATER DISASTER SECURITY AND IDENTIFICATION OF ADAPTATION STRATEGIES

CHAPTER 5: ASSESSMENT OF WATER DISASTER SECURITY AND IDENTIFICATION OF ADAPTATION STRATEGIES

5.1 Introduction

Water-related hazards or hydro-hazards are the results of complex interactions in the ocean atmosphere-land process cascade. Floods and droughts are expected to increase due to global warming. Increased hydro-hazard impacts and costs are attributable to such factors as increased event frequency and magnitude, unplanned urbanization, degradation of ecosystem services, vulnerable livelihoods, and inaccurate public perception of risk. The challenge is to identify appropriate and timely adaptation measures in a continuously changing environment. This chapter will discuss water disaster (refers to flood) security based on fuzzy comprehensive evaluation method.

In recent years, urban water management is growing more and more important overall the world [1-3] because of the frequent extreme weather events and meteorological disasters in the context of climate change [4,5] Among these natural hazards, urban flood disaster occurs frequently and seriously, which has become a critical issue in China. Nowadays, China's cities are facing different kinds of water scarcity, water pollution, and water environmental degradation due to the rapid urbanization and human disturbance. Simultaneously, the natural water bodies such as lake areas and wetlands have shrunk over the past decade [6]. The number of flood disaster has been increasing significantly last several years, and the lives and properties of citizens are heavily threatened. For example, urban flooding event "July 2012 Beijing flood" caused more than 10 billion yuan (CNY) economic losses and 79 deaths [7], whilst similar events occurred "October 2013 flood" in Shanghai, and "May 2013 flood" in Guangzhou and Shenzhen [8-10]. In June, 2015, the daily average rainfall of Nanjing was 63.95mm, namely the city received as much as 330 million tons of water in 1 hour, resulting in a lot of waterlogging regions. Furthermore, pollution of rainwater runoff is increasing in urban area as a result of grey infrastructure and hard engineering-based management approaches that have been adopted in the process of urbanization. The pollution of rainwater runoff has become a pollution source which cannot be neglected. Thus, urban flood vulnerability assessment is a hot topic at present in China.

Under this context, a national initiative "Sponge City" project was proposed by Chinese government in 2014 (Ministry Of Housing And Urban-Rural Development, 2014). It means that cities, like sponges, have good flexibility in adapting to environmental change and responding to flood disaster. Sponge city was based on the low-impact development and construction model [11], supported by flood control and drainage system. It aims to implement ecological civilization construction, repair urban water ecology, improve urban water environment, and achieve urban water security by making full use of the natural accumulation, infiltration, and purification. At present, the Chinese government has been setting and publishing the targets and guidelines for sponge city. The first batch of selected 16 pilot cities and the second batch of selected 14 pilot cities have been funded, respectively in 2015 and 2016. However, the effects of present practices and actions are far beyond the expected and there have been a large number of troubles and perplexing problems in the construction of sponge city. Because the preliminary investigating work is not sufficient, the urban designers ignore the local conditions and outstanding problems at current stage. Moreover, they do not consider whether the same construction model is applicable in different pilot sponge cities, which is contrary to the initial goal of sponge city construction. The national guide for sponge city can only make an outline, while the specific constructed flowchart needs to be explored step by step. As we all know, regionalism is one of the characteristics of geography. In different pilot sponge cities, the vulnerability and physical environment is distinct. In addition, although sponge city are facing similar flood risk, the reasons caused urban water loggings are fundamentally different. These differences are the foundations for the design and construction of sponge cities in accordance with local conditions. How to design and which section should be the focus of attention is the essences of sponge city construction. To our best knowledge, there is no study about this question. Therefore, it is urgent to scientifically explore the vulnerable situation of sponge city as well as the spatial distribution relation between urban vulnerability and flood inducement (i.e. precipitation), so as to formulate sustainable strategies for sponge city. It is an opportunity and challenge for both the new urban areas construction and old areas reconstruction.

Vulnerability has become a central focus of the global environmental change and sustainability science research communities in recent years [12]. In relation to hazards and disasters, vulnerability is a concept that expresses the multi-dimensionality of disasters by focusing attention on the totality of relationships in a given social situation which constitute a condition that, in combination with environmental forces, produces a disaster [13]. It is also the extent to which changes could harm a system, or to which the community can be affected by the impact of a hazard or exposed to the possibility of being attacked or harmed. It is a function of the system's exposure to hazards, its sensitivity, and its adaptive capacity [14].

In this chapter, based on the concept of vulnerability and fuzzy comprehensive evaluation method (FCE), our paper is arranged as follows: Firstly, a vulnerability assessment framework of sponge city is proposed, which includes establishment of index system, assessment of exposure, sensitivity, adaptive capacity and comprehensive vulnerability. Secondly, geographical information system (GIS) is applied to reflect the spatial distribution relation between precipitation condition and urban vulnerability. Then, according to the analysis of relation between precipitation condition and vulnerability, the sponge cities are divided into 4 different categories. Finally, the appropriate and sustainable strategies are presented for different categories sponge cities.

5.1.1 Study objects

A sponge city is a city that is designed to passively absorb, clean and use rainfall in an ecologically friendly way that reduces dangerous and polluted runoff. Associated techniques include permeable roads, rooftop gardens, rainwater harvesting, rain gardens, green space and blue space such as ponds and lakes. Properly implemented a sponge city can reduce the frequency and severity of floods, improve water quality and allow cities to use less water per person. Associated strategies such as green space can also improve quality of life, improve air quality and reduce urban heat islands. This chapter analyzes the 30 pilot cities of the “sponge city” project in China.

5.1.2 Data sources

Statistic origin data are from: 1. China Statistical Yearbook, 2013, National Bureau of Statistics of the People’s Republic of China [33]; 2. China urban construction statistical yearbook, 2013, Ministry of Housing and Urban-Rural Development, People’s Republic of China [34]; 3. Precipitation data is derived from the China Meteorological Science data sharing service (cdc.cma.gov.cn) from the China International Site Exchange.

GIS vector data are from National Geomatics Center of China (www.ngcc.cn) including shp format documents of China map, shp format documents of China provincial administrative center, shp format of world country map and river map.

5.2 Fuzzy comprehensive evaluation analysis

5.2.1 Establishment of index system

The establishment of a scientific and reasonable index system would help to provide a basis for the accurate vulnerability assessment of sponge city [15, 16]. The goal of sponge city is to solve the problem of urban water logging. With these considerations, the selected evaluated indicators include not only meeting the definition of vulnerability but also associated with water factors. In this study, we establish the index system from the three interacting factors (exposure, sensitivity, and adaptive capacity) of vulnerability. The specific evaluation index system of vulnerability is shown in figure 5-1.

✧ 2.1.1. Exposure index

Exposure: the nature, degree, duration, and/or extent to which the system is in contact with, or subject to perturbations [17]. Exposure indicators express the characteristics of the examined water-related pressures come from nature, society and economy. Exploitation ratio of water resources and per capita water resources present the situation of water scarcity. The economic structure reveals the economic strength of sponge city, so the proportion of the tertiary industry in GDP is selected.

✧ 2.1.2. Sensitivity index

Sensitivity: the degree to which a system can be modified or affected (adversely or beneficially, directly or indirectly) by a disturbance or set of disturbances [18]. Here, sensitivity indicators express the prevailing socio-economic conditions with regard to water use. Generally, sensitivity indicators include natural sensitivity and socio-economic sensitivity. Given that this study focuses on urban water logging, per capita area of parks and green land, population density, and per capita GDP are emphasized when building the sensitivity index system.

✧ 2.1.3. Adaptive capacity index

Adaptive capacity: the ability of a system to adjust to disturbances, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences of transformations that occur [19]. Adaptive capacity indicators express the system's potential to adapt to changes. The economic capacity reveals the ability of sponge city to make use of the project to ensure water, so investment in water infrastructure is selected as the evaluated indicator. The socio capacity mainly expresses people's awareness and participation in flood risk as well as the overall convenience. The socio structure indicators are identified as holding high educational qualifications per ten thousands of people, per capita urban road area and treatment rate of sewage. In natural capacity, the green covered area as % of completed area and ratio of ecological water to total water demand are picked.

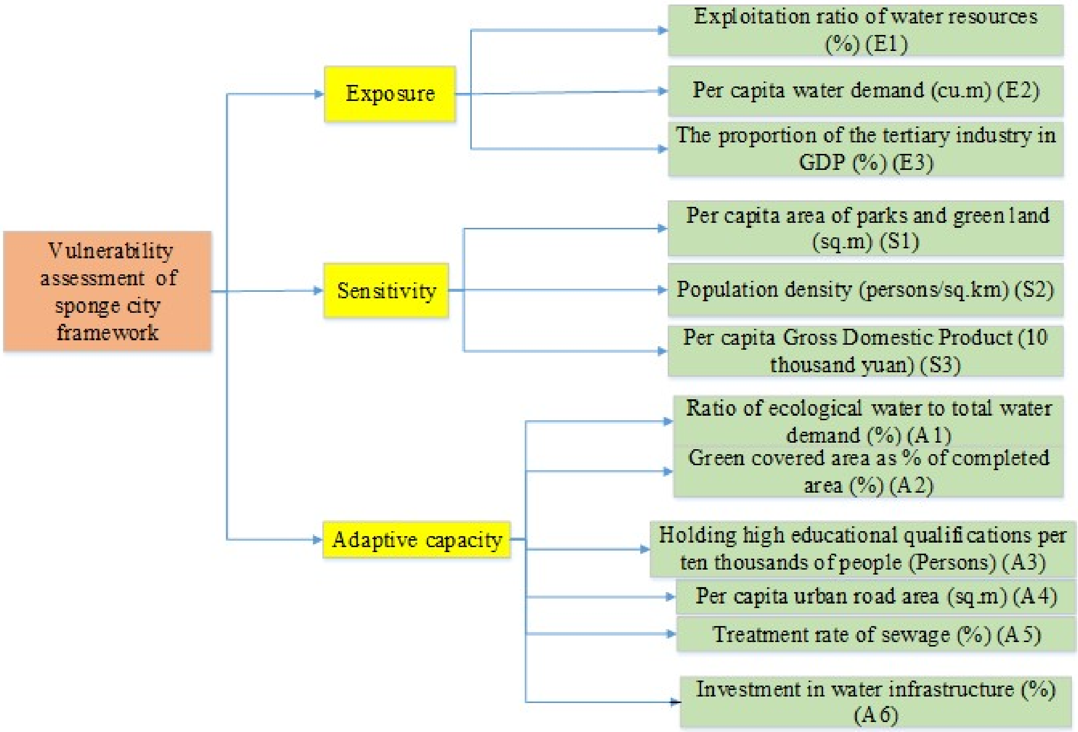


Fig.5-1 Vulnerability evaluation index system

5.2.2 Fuzzy comprehensive evaluation process

The FSE model, combined with fuzzy theory and mathematical model [20], was established by introducing fuzzy set theory into the comprehensive evaluation process [21]. Fuzzy set theory permits the gradual assessment of the membership of elements in a set; this is described with the aid of a membership function valued in the real unit interval [0, 1]. Its advantage is that it can naturally solve the uncertainty and ambiguity problem, thus overcoming the unity of the results of traditional mathematical methods. In this study, FSE is used to assess exposure, sensitivity, adaptive capacity and comprehensive vulnerability of sponge city. FSE can be summarized in a series of steps and here taking the exposure in one sponge city as a case:

Step1 Establish the evaluation index set:

According to the nature of the characteristics of the evaluation index system, the factor set in the evaluating relationship is as follows:

$$U = (u_i)_{1\times n} = \{u_1,\ u_2, \dots, u_n\}, \qquad (5.1)$$

Where, n stands for the number of evaluation indexes, u_i as the i-th evaluation indicator, with $i = 1, 2, \dots, n$.

Step2 Establish the assessment criteria set:

Assessment criteria set is a collection consisted of standards by regulation or experts.

$$S = \left(s_{i,j}\right)_{n\times 5} = \begin{Bmatrix} s_{1,1}, s_{1,2}, \cdots, s_{1,5} \\ s_{2,1}, s_{2,2}, \cdots, s_{2,5} \\ \vdots \quad \vdots \quad \vdots \quad \vdots \\ s_{n,1}, s_{n,2}, \cdots, s_{n,5} \end{Bmatrix}, \qquad (5.2)$$

Where the number of columns j, with $j = (1, \ldots, 5)$ represents the number of assessment criteria categories, corresponding to the different standard levels. The number of rows i, with $i = (1, \ldots, n)$, refers to the number of assessment indicators. Consequently, each element of the matrix $\boldsymbol{S}$, $s_{i,j}$, indicates a standard value of the i-th index for j-th class.

At present, there is no standard of vulnerability assessment [22]. The paper adopts the previous study [23-25] suggested value as a “High-high”-grade 5 threshold value and the international minimum value as the threshold value of the “Low-low”-grade 1 state. Values of trisection points between the two threshold values of grade 5 and grade 1 are the threshold values of “Low-high”-grade 2, “Moderate”-grade 3, and “High-low”-grade 4. Values of representative criteria corresponding to the five grades are shown in Table 5-1.

Table 5-1 Criteria of assessment indicator

Indicator	Grade1	Grade 2	Grade 3	Grade 4	Grade 5
E1	110	102.5	95	87.5	80
E2	100	262.5	425	587.5	750
E3	1.5	2.375	3.25	4.125	5
S1	50	61.25	72.5	83.75	95
S2	7	10.25	13.5	16.75	20
S3	10	14.5	19	23.5	28
A1	30	42.5	55	67.5	80
A2	0.70	2.53	4.35	6.18	8.00
A3	100	325	550	775	1000
A4	1000	500	400	200	50
A5	20	27.5	35	42.5	50
A6	2	2.75	3.5	4.25	5

Step3 Membership degree matrix calculation:

We need to define the membership function before calculating the membership degree. It is possible to use different fuzzy membership functions such as triangular, trapezoidal, piecewise linear, Gaussian, and singleton under various situations [26]. The trapezoidal membership function is the most reliable and widely used [27-29]. Therefore, Lower semi-trapezoid distribution function is applied to our study, defined according to previous literature criteria [30,31]:

$$R_{i,1}=\begin{cases}1, & u_i \le s_{i,1} \\ \left|\dfrac{u_i - s_{i,2}}{s_{i,2} - s_{i,1}}\right|, & s_{i,1} < u_i < s_{i,2} \\ 0, & u_i \ge s_{i,2}\end{cases},$$

$$R_{i,z}=\begin{cases}\left|\dfrac{u_i - s_{i,z-1}}{s_{i,z} - s_{i,z-1}}\right|, & s_{i,z-1} < u_i < s_{i,z} \\ 0, & u_i \le s_{i,z-1},\ u_i \ge s_{i,z+1}, \\ \left|\dfrac{u_i - s_{i,z+1}}{s_{i,z+1} - s_{i,z}}\right|, & s_{i,z} < u_i < s_{i,z+1}\end{cases},$$

$$R_{i,5}=\begin{cases}1, & u_i \ge s_{i,5}, \\ \left|\dfrac{u_i - s_{i,4}}{s_{i,5} - s_{i,4}}\right|, & s_{i,4} < u_i < s_{i,5} \\ 0, & u_i \le s_{i,4},\end{cases}, \tag{5.3}$$

Where $R_{i,1}$ refers to the i-th index membership function for the class I, while $R_{i,5}$ indicates the i-th index membership degree for the 5-th class. Similarly, $R_{i,z}$ represents the i-th index membership degree for the z-th class, with $1 < z < 5$, where 5 is the highest class. In parallel, $s_{i,1}$ is the value of the i-th index assessment criterion for the class I, $s_{i,5}$ refers to the i-th index standard value for the 5-th class and $s_{i,z}$ indicates the i-th index standard value for the z-th class. Then the fuzzy matrix R of each indicator can be obtained based on the Eq. (3) as:

$$R=\left(r_{ij}\right)_{n\times 5}=\begin{bmatrix} r_{11}, r_{12}, \cdots, r_{15} \\ r_{21}, r_{22}, \cdots r_{25} \\ \vdots \quad \vdots \quad \vdots \quad \vdots \\ r_{n1}, r_{n2}, \cdots\ r_{n5} \end{bmatrix}, \tag{5.4}$$

Where, $r_{i,j}$ represents the i-th indicator membership degree for the j-th class, with $i = 1,2, \ldots, n$ and $j = 1,2, \ldots, 5$.

Step4 Determining the index weights:

Weight means the proportion of each evaluation factor in the evaluation index system based on relative importance. If a weight is given to an element, the weight distribution set W can be seen as a fuzzy set of set U. How to determine the weight of each factor is the core task of the evaluation system. Here, the entropy weight method (EWM) is employed to determine the indicators weights in the evaluation index system. It can be calculated as follows:

$$E_i=-k\sum_{i=1}^{m} p_i \ln p_i\ ,\ p_i=\frac{u_i}{\sum_{i=1}^{m} u_i} \quad i=1,\ 2,\ \ldots,\ n \tag{5.5}$$

$$w_i=(1-E_i)/\sum_{i=1}^{n}(1-E_i)\ (0\le w_i\le 1,\ \sum_{i=1}^{n} w_i=1), \tag{5.6}$$

$$W\ =\ \left\{w_1, w_2, w_3, \ldots w_n\right\}, \tag{5.7}$$

Where, E_i is the i th index entropy; k =1/ln n; when p_i=0, p_i ln p_i =0. W_i is weight of the i th assessment index, $\boldsymbol{W}$ is the weight set.

According to formulas 5-7, assessment index weights of sponge city is obtained in Table 5-2.

Table 5-2 Weights of evaluation indicators

Indicator	E1	E2	E3	S1	S2	S3
Weight	0.03	0.10	0.07	0.04	0.04	0.14
Indicator	A1	A2	A3	A4	A5	A6
Weight	0.22	0.08	0.05	0.06	0.03	0.15

Step5 Assessment coefficient set calculation:

The fuzzy composite operator is important for the final result. As a comprehensive evaluation mathematic model dominated by critical indicator, M (•, ⊕) operator is commonly used in the fuzzy comprehensive evaluation of environmental systems. This is multiplication-summation operator. B, being the fuzzy evaluation result set, is defined as:

$$B = W \bullet R = \left(b_j\right)_{1\times 5}, \tag{5.8}$$

Where, b_j represents the assessment coefficient from the evaluation object for j-th class, while, $b_j = \sum_{i=1}^{5} w_i r_{ij}$ the symbol "•" denotes the multiplication-summation operator.

Step6 Evaluation result processing

To get the relative position of the evaluated object, the weighted average method is used to deal with fuzzy comprehensive exposure evaluation results:

$$EX = \frac{\sum_{j=1}^{5} b_j^2 \bullet j}{\sum_{j=1}^{5} b_j^2}, \tag{5.9}$$

Where EX is the exposure of the evaluated sponge city. Likewise, the fuzzy synthetic evaluation results of a sponge city's sensitivity (SE), adaptive capacity (AC) and comprehensive vulnerability (CV) can be obtained based on the above equations. According to weighted average principle, the final fuzzy comprehensive evaluation result is discussed as follows: Low-low, $EX < 1.5$; Low-high, $1.5 \le EX < 2.5$; moderate, $2.5 \le EX < 3.5$; High-low, $3.5 \le EX < 4.5$; High-high, $EX \ge 4.5$.

5.2.3 Assessment results of exposure, sensitivity, adaptive capacity, and comprehensive vulnerability

First of all, we analyze the exposure in different cities. Just as the results Fig. 5-2 (a) shows that the maximum exposure values for Sanya, Shenzhen and Nanning are 2.5-3.5, which are classified as grade 3. The moderate exposure means water supply can basically meet water demand and the high proportion of tertiary sector of the economy resulting in developed services. On the contrary, Xixian, Gui'an, Suining, Hebi, Pingxiang, Qingyang, Yuxi, Chizhou, Chongqing, and Zhuhai have the lowest exposure values. They are all belonging to grade 1, whose value is <1.5. Because exploitation of water resources in these cities is less than water availability, water scarcity is a not an issue in these sponge cities. The exposure values of Qian'an, Baicheng and Shanghai are also <1.5 due to lower socio-economic exposure. The exposure of the rest cities is grade 2 and there is no sponge city owning grade 4 or 5. As a result, the exposure values of the 30 sponge cities are all <3.5, which is optimistic.

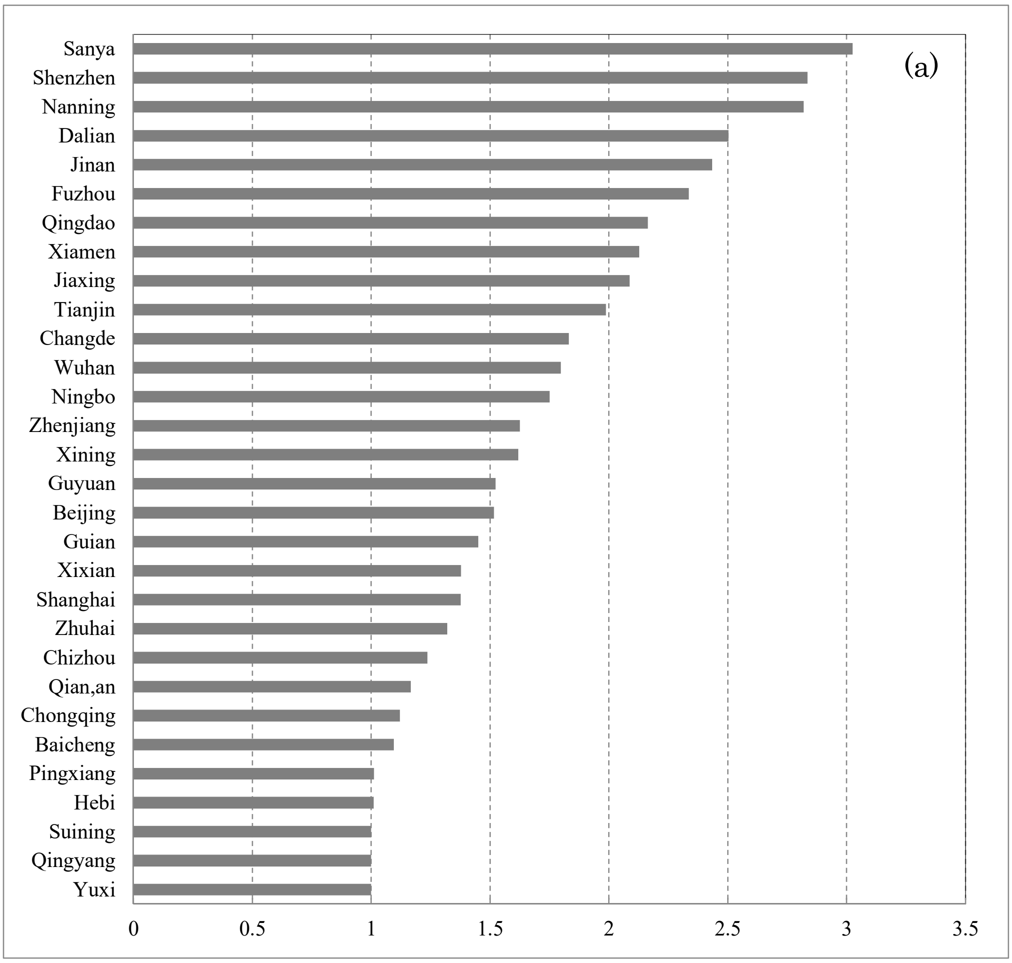
As Fig. 5-2 (b) shows, Suining, Guyuan, Qingyang, Nanning, Chongqing, Changde, and Xining own the minimum sensitivity values of grade 2. It means they will be not easily influenced by external disturbance. There are 13 sponge cities possess the highest sensitivity values of grade 5, but the reasons are distinct. Zhuhai, Qian'an, Jinan, Zhenjiang, Dalian, Wuhan, and Sanya are sensitive since the indicator of per capita area of parks and green land is lowest in the 30 cities. Tianjin, Qingdao, Jiaxing, Ningbo, Shenzhen, and Xiamen are sensitive resulting from high population density. And the rest cities are grade 3 or 4 of sensitivity. Thus, except for 7 cities belonging to grade 2, other cities are all sensitive.

The cities are ranked from the lowest to the highest in terms of their adaptive capacity as follows: Guian, Qingyang, Xining, Sanya, Zhuhai, Shanghai, and Beijing (Fig. 5-2 (c)) own the lowest value of adaptive capacity, namely grade 1. However, the reasons that lead to the poorest adaptive capacity are different in the seven cities. Shanghai, and Beijing performs poor in per capital urban road area and green covered area, which is consistent with the situation of traffic congestion. The reason is that the stock amount of automobiles increased tremendously with the rapid economic development and urbanization process, and resulting from a lot of people flooding into cities from rural areas. For the rest five cities, it is mainly because the investment in water infrastructure is insufficient and treatment rate of sewage is low as well. The highest value of grade 5 in adaptive capacity includes Qingdao, Jiaxing, and Yuxi since the adaptive capacity in nature, society, and economy is all advanced. In addition, except the highest and the lowest grades, other cities belong to the grade 2, 3, and 4.

Comprehensive vulnerability is a combination of exposure, sensitivity, and adaptive capacity. It is a point to consider the three aspects integrally, just as Fig. 5-2 (d) shows. Beijing, Qingdao, and Jiaxing have the highest value of grade 5, while Qingyang has the lowest value of grade 1. Although Qingdao and Jiaxing own the highest adaptive capacity, the "overall" vulnerability value is high due to the exposure and sensitivity are higher. It means when facing the same flood hazard, Beijing, Qingdao, and Jiaxing are the most vulnerable and Qingyang is not vulnerable. The rest sponge cities belong to the grade 2, 3, and 4, while vulnerability is gradually increased.

In terms of vulnerability, exposure and sensitivity are negative types, while adaptive capacity is positive type. Different combinations of positive and negative types can cause different levels of vulnerability, which can give decision makers necessary references for districts that need priority aid. A city must be vulnerable with high exposure and sensitivity, insufficient coping capacity and measures (e.g. bad infrastructure, bad governance) to decrease vulnerability, while another city also must be invulnerable because of low exposure, sensitivity, but well-adaptive capacity. These two extreme situations are easy to distinguish and control. An example of relatively high exposure and sensitivity combined with low adaptive capacity is Beijing. In this case, when facing flood risk, it is extremely vulnerable. Another example of relatively low exposure and sensitivity combined with high adaptive capacity is Suining. When facing the same flood risk, it is much less vulnerable. However, the other two situations are difficult to distinguish and regulate because they have a similar overall ‘vulnerability’, but they are fundamentally different. In the one case, a city with relatively high exposure and sensitivity may still have moderate vulnerability due to, for instance, better adaptive capacity. In the other case, a city with relatively poor adaptive capacity may still have moderate vulnerability resulting from quite good exposure and sensitivity. For example, the combination of high exposure, sensitivity and high adaptive capacity is probably valid for Sanya, while the combination of low exposure, sensitivity and low adaptive capacity is found in Baicheng. These two situations may result in similar ‘overall’ vulnerable levels, but differ in terms of exposure, sensitivity and adaptive capacity.

Through above analysis, it is easy to see that the decision making process takes full account of the relationship between the three vulnerability elements so as to formulate appropriate management policy for different kinds of sponge cities. First of all, for sponge cities like Beijing, it is necessary to improve the adaptive capacity while reducing the exposure and sensitivity of the city. The specific measures are mainly to increase green covered area and investment in water infrastructure. Secondly, for sponge cities like Suining, it should continue to maintain the favorable vulnerability situation. Meanwhile, monitoring of flood disaster should be maintained and emergency measures should be made at all times. In addition, for sponge cities like Sanya, it should be paid more attention in exposure and sensitivity, in particular, it is advised to increase greening proportion and reduce the population density of urban centers. Finally, for sponge cities like Baicheng, adaptive capacity is relatively weak and needs to be steadily improved.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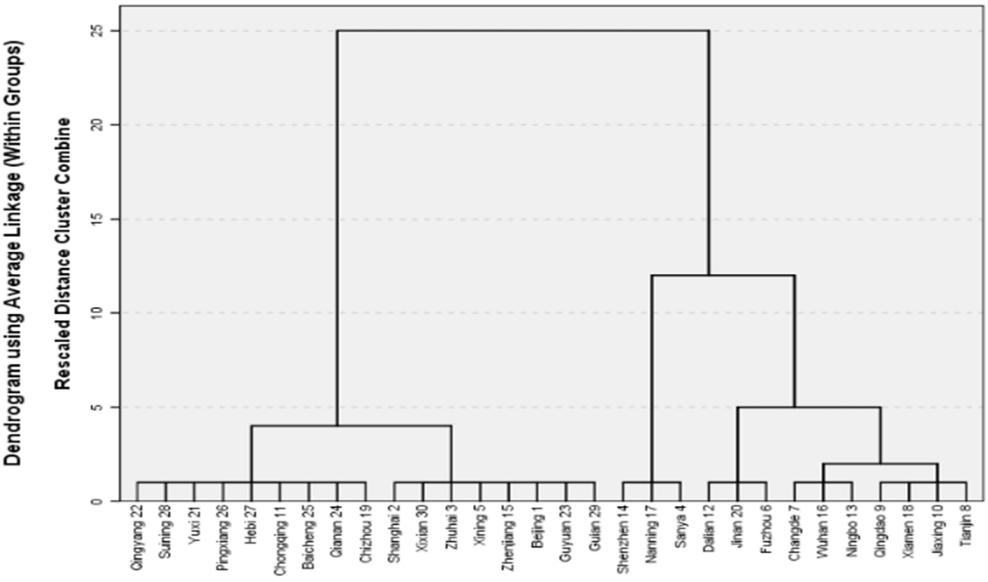
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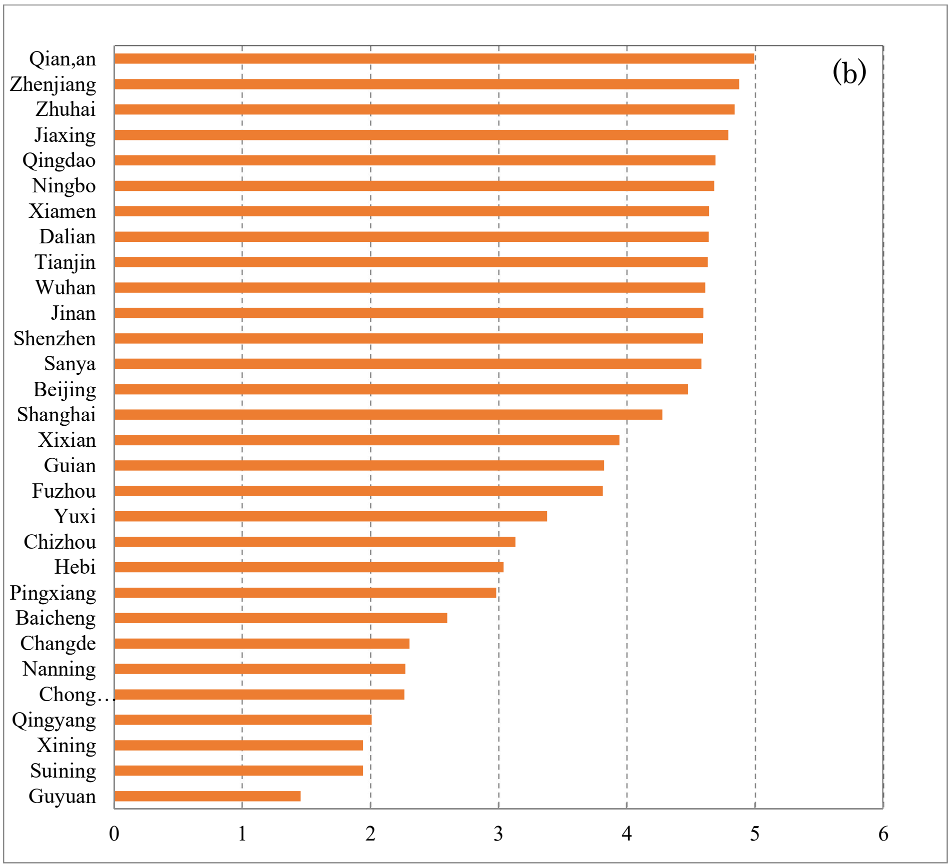
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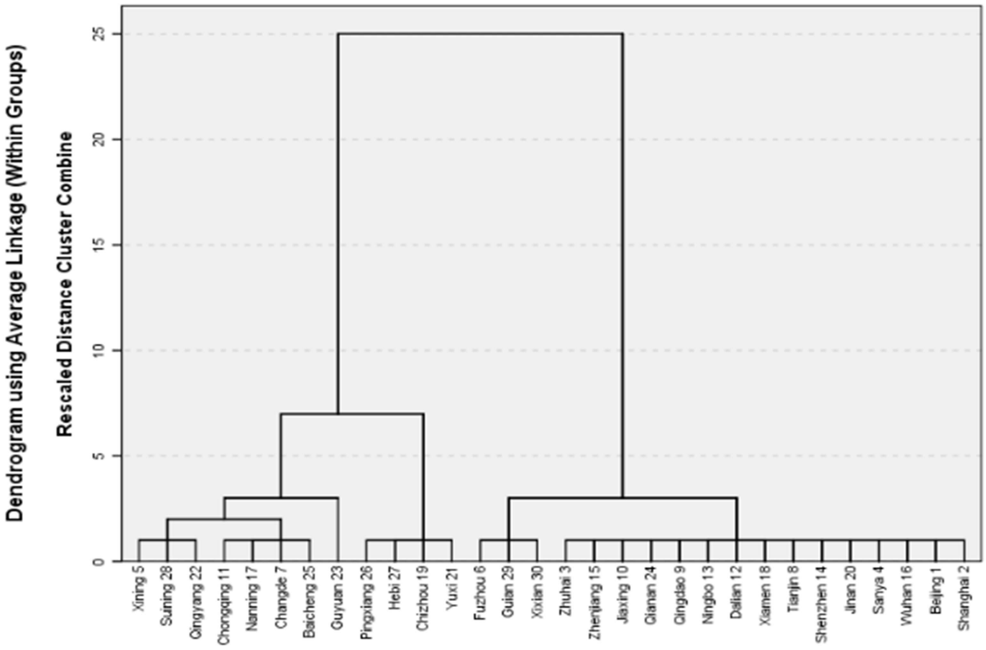
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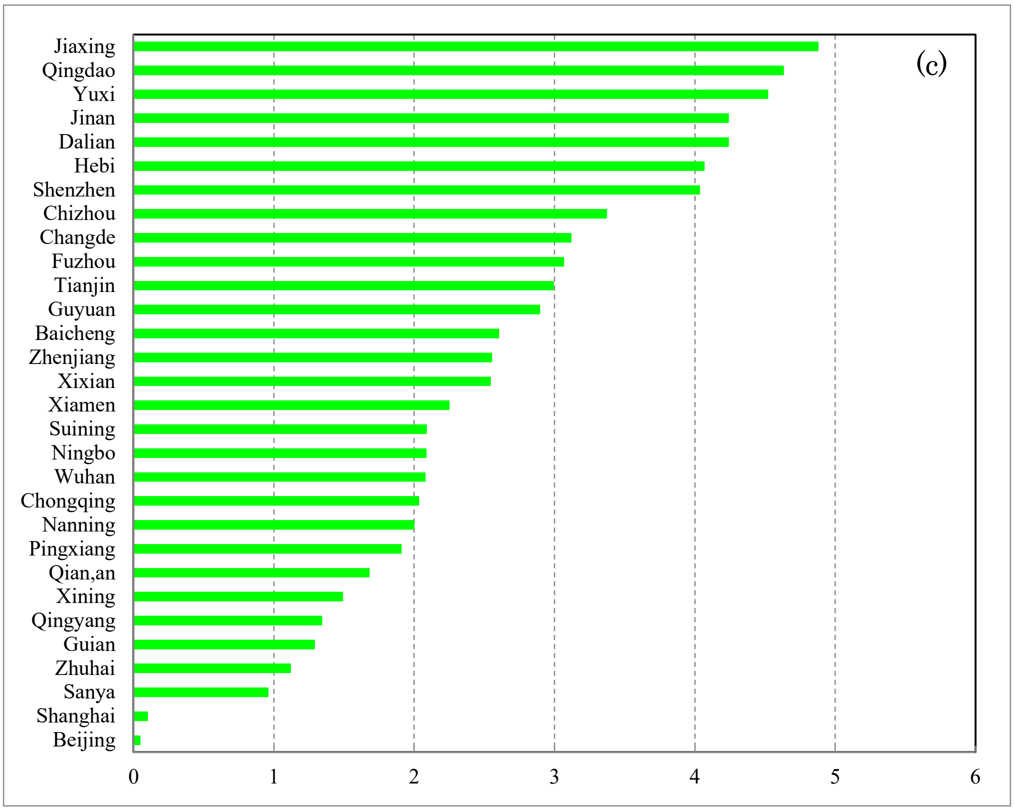
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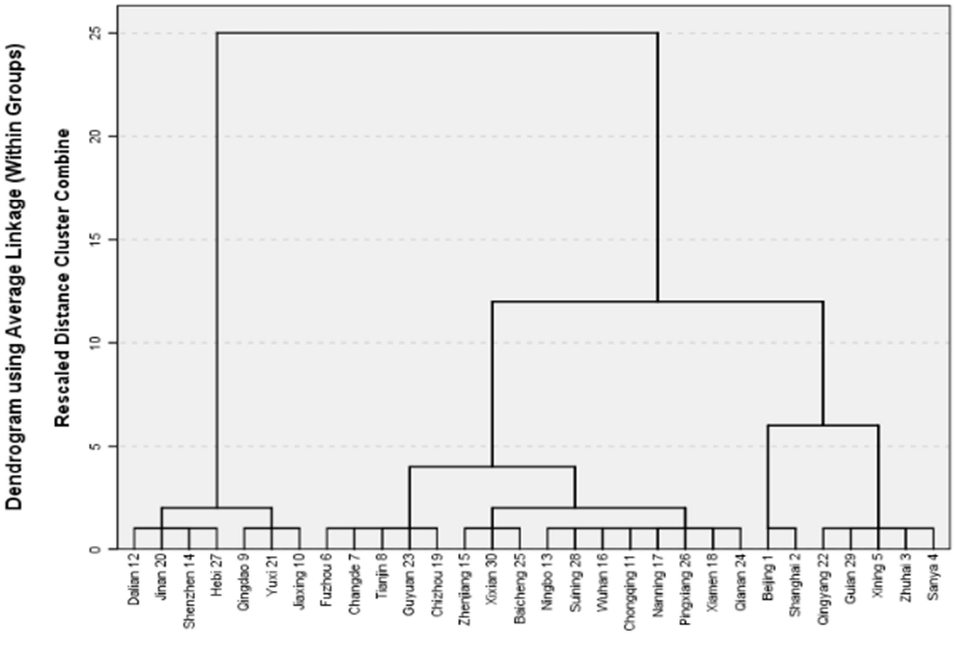
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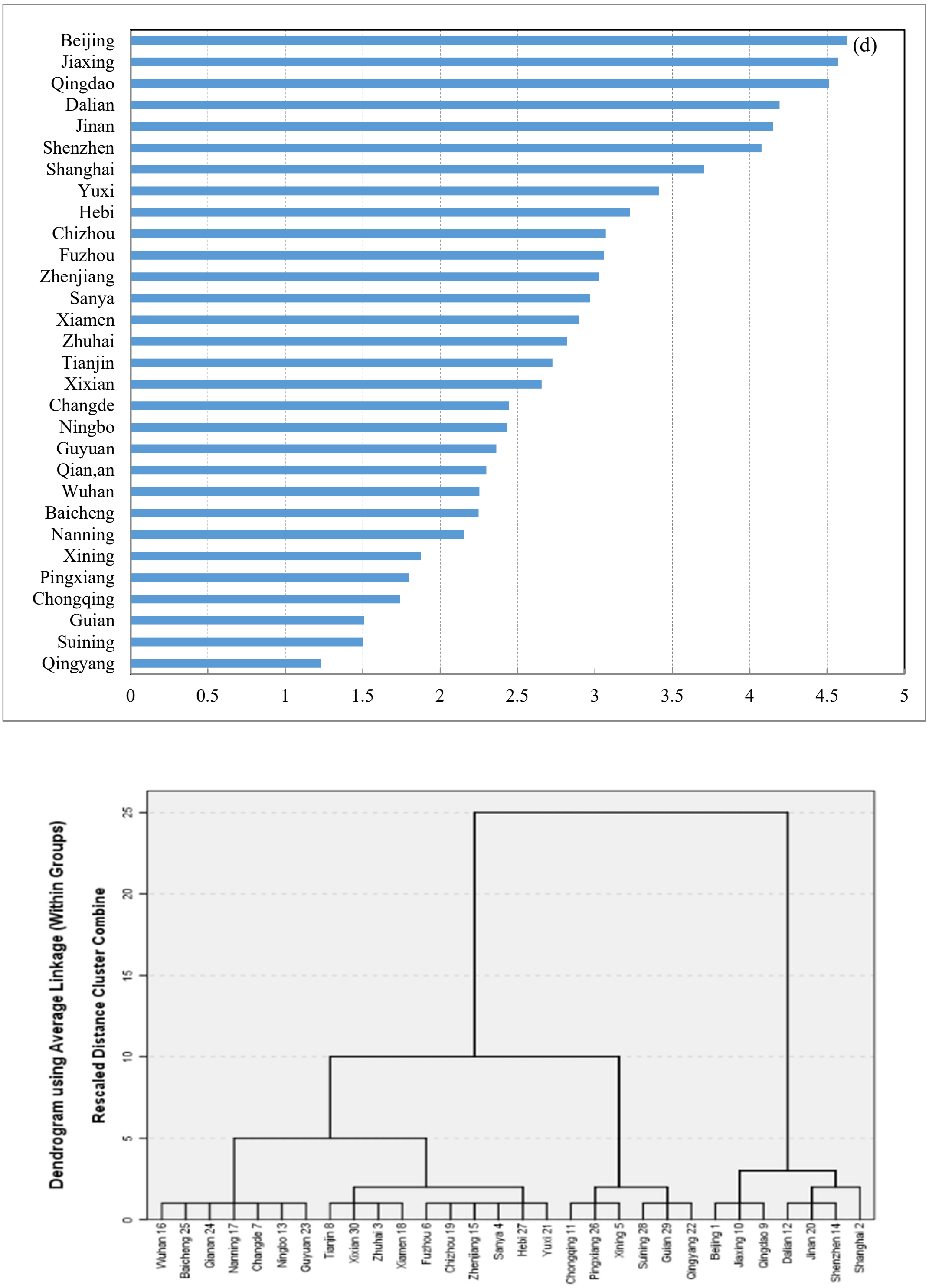

Fig. 5-2 (a) The exposure result, (b) The sensitivity result, (c) The adaptive capacity result, (d) The comprehensive vulnerability result

5.3 Spatial distribution analysis based on GIS

5.3.1 Process of spatial distribution analysis with GIS

A GIS is a system which is designed to store, edit, analyze, share, and display spatial or geographic information [32]. In order to explore the spatial distribution relation between precipitation and urban vulnerability, ArcGIS10.2 software is applied to do the spatial analysis. Spatial analysis is an approach to applying statistical analysis and other analytic techniques to data which has a geographical or spatial aspect. Firstly, according to a series of steps data acquisition, preprocessing, spatial precipitation interpolation until the final mapping, the annual precipitation distribution map of China can be derived. Subsequently, we use the assessment results of comprehensive vulnerability in 30 sponge cities based on FSE method at the same time to construct a new GIS database to reflect the rank of urban vulnerability. Finally, the spatial distribution relation between precipitation and urban vulnerability in 30 sponge cities is obtained by using ArcGIS10.2 software.

5.3.2 Spatial distribution results between comprehensive vulnerability and precipitation

Based on the assessment results of FCE method about vulnerability in sponge cities above, we put the assessment results into ArcGIS 10.2 software and it is clear to see the spatial distribution relation between vulnerability and precipitation. The 800 mm annual precipitation line is the dividing line between the humid and arid areas in China. The annual precipitation in the south of the line is generally above 800 mm, which is a humid area. The annual precipitation in the north of this line is generally below 800 mm, which is an arid area. Here, we define the humid area is a potential high flood risk area, while the arid area is a potential low flood risk area. In that way, there will be four combination situations. A sponge city may be located in high flood risk area without vulnerability such as Suining, Chongqing, Gui'an and so on (see Fig. 5-3). A sponge city may be located in high flood risk area with vulnerability, the representative city is Jiaxing. On the country, for example, Baicheng, Xining, Guyuan, and Qingyang locate in low flood risk area without vulnerability. The last case is Beijing which locates in low flood risk area with vulnerability.

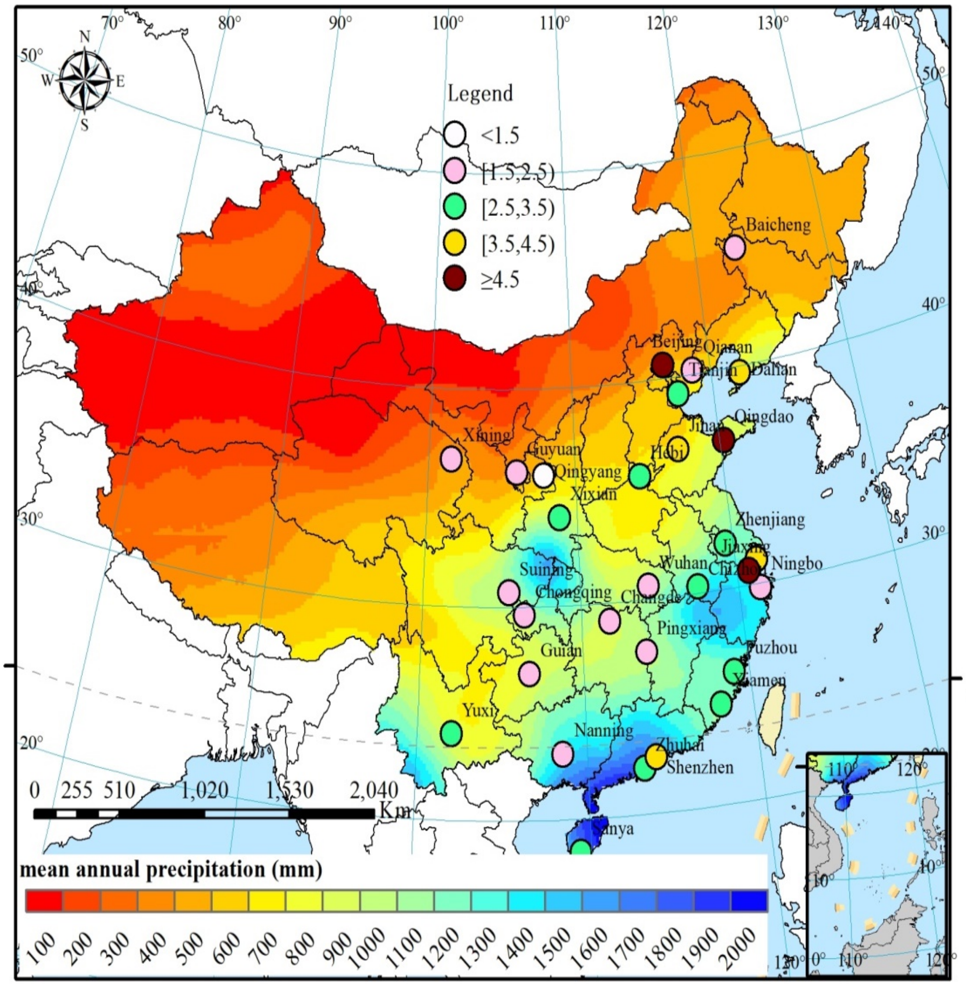

Fig. 5-3 Spatial distribution between vulnerability and precipitation in sponge cities

Based on the FSE method, this study analyzes the vulnerability of cities to flood disaster from the internal factors of sponge city. In response to flood disaster, improving urban adaptive capacity and reducing urban vulnerability are reasonable and appropriate ways. However, if a city in a region with a low probability of flooding, enriching city's ability of fending off disaster risks and reducing vulnerability will not only benefit the city to cope with risk, but also lead to immense waste of manpower and material. Therefore, it is particularly necessary to explore the spatial distribution of urban vulnerability and potential flood risk areas. This study uses GIS software to make a distribution relationship between precipitation and sponge city vulnerability. Areas with precipitation greater than 800mm are high flood risk areas, and below 800mm are low flood risk areas. In this case, there are four combination types between sponge cities and flood risk area.

(1) The type I sponge cities are the combination of high vulnerability and high flood risk area including Yuxi, Sanya, Shenzhen, Zhuhai, Xiamen, Fuzhou, Jiaxing, Zhenjiang, Shanghai, Chizhou and Qingdao. Such sponge cities have low ability to defense against flood and are located in flood-prone areas. When facing flood disaster, they are the most vulnerable to be damaged. In

order to realize the sustainable development of sponge cities and social stability, managers need to strengthen both internal urban adaptive capacity and external flood warning capability. At the most basic level, it is suggested that the type I sponge cities should formulate flood safety planning and seek higher ground for high-value uses while balancing the foreseeable risks with the benefits of occupying flood hazard zones. In areas prone to urban flooding, one solution is the repair and expansion of man-made sewer systems and storm water infrastructure. Another strategy is to reduce impervious surfaces in streets, parking lots and buildings through natural drainage channels, porous paving, and wetlands.

(2) The type II sponge cities are the combination of low vulnerability and high flood risk area (such as Suining, Chongqing, Gui'an, Nanning, Wuhan, Changde, Ningbo, and Pingxiang). Such sponge cities have higher adaptive capacity ability in the face of flood disaster, so there is no need for these cities to invest large amounts of funds and resources to reduce urban vulnerability. Despite that, the cities are located in flood-prone areas, and the most important is to make flood forecasting. Anticipating floods before they occur allows for precautions to be taken and people to be warned so that they can be prepared in advance for flooding conditions. It is recommended to improve citizens' awareness of flood defense and that funds should be invested in the construction of the flood forecasting system.

(3) The type III sponge cities are located in low flood risk area with high vulnerability. The combination is found in Beijing, Tianjin, Dalian, Hebi, Xixian, and Jinan. Although the probability of a flood is small in such a sponge city, but it will be greatly damaged once it encounters a flood disaster. It is reasonable to reduce urban vulnerability appropriately, but it should not be invested as much as a type I sponge city.

(4) The type IV sponge cities are located in low flood risk area with low vulnerability i.e. Baicheng, Guyuan, Qingyang, and Qian'an. Such sponge cities are much less vulnerable when meets flood disaster. Furthermore, they are located in areas with low flood probability. It is a quite good condition from the viewpoint of the threat of flood disaster. Under such condition, the funds invested in urban vulnerability are limited, as long as defense measures are taken.

5.4 Summary

The chapter analyzes the vulnerability of sponge city in China so as to provide basic policy for further study of sponge city construction and flood management. We adopt the FCE method to calculate the membership degrees of vulnerability in each city so that the different factors of vulnerability can be aggregated. The three factors of vulnerability assessment approach in sponge city developed in this study are more conducive to the rational allocation of limited resources. In addition, the indicators system and techniques of weight determination can be updated based on the actual situation, while the FCE method can still be applied. First, taking 30 sponge cities as study objects, the indicator system of vulnerability assessment is established from exposure, sensitivity, and adaptive. Secondly, the exposure, sensitivity, and adaptive capacity in different pilot cities are compared. In terms of exposure, Sanya ranks top 1. Regarding sensitivity, Qian'an is number 1. Concerning adaptive capacity, Jiaxing owns the highest. Following we analyze the comprehensive vulnerability and put forward four distinct vulnerable situations. At last, we focus on the spatial relation between comprehensive vulnerability and flood risk area, which is divided into four types. The corresponding sustainable countermeasures and strategies are put forward. In next chapter, we will consider water resources security, water environment security, and water disaster security integrally.

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Chapter 6

INTEGRATED ASSESSMENT AND COMPARISON OF WATER SECURITY

CHAPTER 6: INTEGRATED ASSESSMENT AND COMPARISON OF WATER SECURITY

6.1 Introduction

The study of water resources has evolved from a focus on physical availability to also include social factors such as governance. Increased understanding of diverse physical and social influences has led to a more comprehensive notion of water security. Despite the clear recognition that water security encompasses quantity, quality, and societal considerations, discussions often focus on only one or two of these aspects. This practice masks critical ways in which water quality issues intersect with water quantity issues as well as social factors for many water security decisions. Therefore, this chapter will analyze water security from water resources, water environment, and water disaster comprehensively. We select Guizhou province in the Southwest of China and Japan as research cases due to they have similar geographical conditions. However, the economic and social conditions have a significant gap. In this way, we can compare the different effects of different socio-economic conditions on water security.

6.1.1 Study areas

Guizhou is a province of the People's Republic of China located in the southwestern part of the country. Its capital city is Guiyang. Guizhou is a relatively poor and economically undeveloped province, but rich in natural, cultural and environmental resources. Demographically it is one of China's most diverse provinces. Minority groups account for more than 37% of the population. Guizhou is a mountainous province, although its higher altitudes are in the west and center. The elevation increases gradually from east to west with an average altitude of 1,100 meters. The average precipitation in recent years is 1,179 mm and the average evaporation amount is 1220 mm. The regional water resource per capita is 2800 m^3, which is more than the national water resources per capita of 2,100m^3. Despite that the rainfall of southwest Karst area is rich, special geological condition and regionalization characteristics lead to that the mining and distribution of water resources are very complex. Water scarcity in Guizhou province mainly includes the shortage of water quality reduction and engineering water. Urban water consumption and wastewater emissions increase dramatically so that there is a need to figure out the more severe area of water security problem and the main factors influencing the urban water security. In order to provide a scientific basis for decision makers and managers, how to ensure the coordinated development of the social economy and the water ecological environment is a crucial task in Guizhou province.

Japan has a total of 6,852 islands extending along the Pacific coast of East Asia. The country, including all of the islands it controls, lies between latitudes 24° and 46°N, and longitudes 122° and 146°E. Japan’s annual total precipitation is about 1,700 mm, which is about twice the global average of 970 mm, while the annual precipitation per capita is approximately 5,100 m^3, roughly 1/3 of the world average of 16,800 m^3 [1]. Japan appears to be a water abundant area with high rainfall. However, Japan has a small land area and a high population density. Thus, in order to estimate the amount of water in a person, it cannot be concluded that Japan is rich in water. In addition, Japan is at a disadvantage when using water resources: the rainfall centers on the rainy, typhoon, and snowfall seasons and is significantly dependent on the weather. Besides, the country is so steep that most rainfall quickly runs off into the sea. Japan has made various efforts to ensure water resources under such conditions and built life's rich foundations.

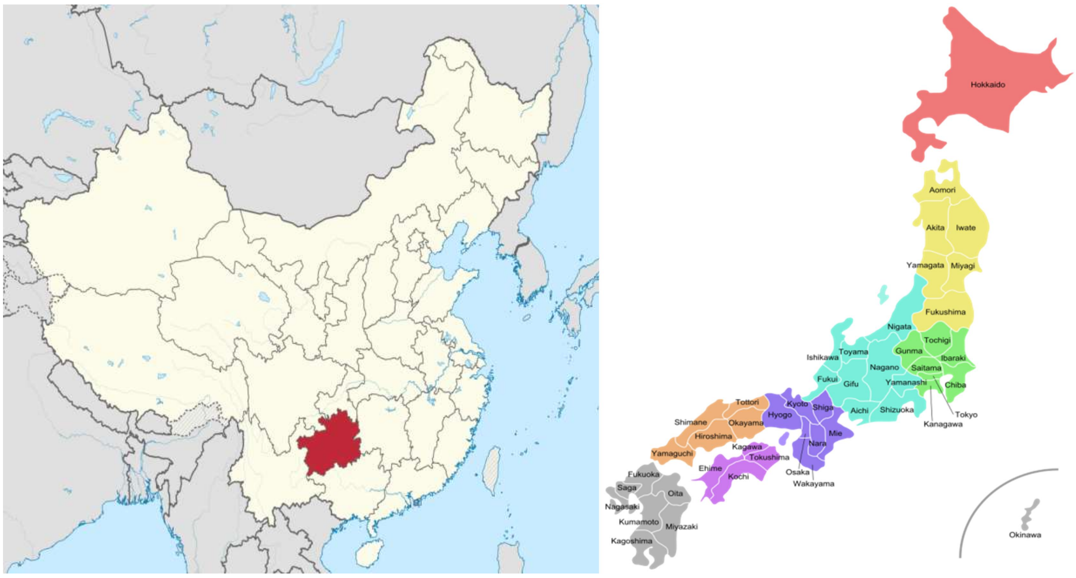


Fig.6-1 Location of Guizhou province in China and prefectures of Japan

6.1.2 Data sources

Data for the evaluation of Guizhou province are obtained from Water Resources Bulletin [2] and Guizhou Statistics Yearbook [3].

Data for the evaluation of Japan are all obtained from the statistical handbook [4]. For water-related data, the water demand and total water resources, the sector account's water consumption, and the precipitation are derived from the report of the current status of water resources in Japan [5]. The wastewater effluents are derived from the Comprehensive Survey on Water Pollutant Discharge [6].

6.2 Establishment of water security index system

The establishment of a scientific and reasonable index system would help to provide a basis for the accurate assessment of water security. Water security is a large complex system with many factors. But, there is no a uniform standard index system at present. The traditional pressure-state-response (PSR) framework is more used to establish the evaluation index in academia. PSR model can reflect the relation among nature, economy and social factors, providing a logical basis for water security index. So we adopt this framework from three aspects of water security to establish the evaluation indicators system.

6.2.1 Water resource security aspect

On one hand, Pressure index (P) mainly reflects the trend of the social and economic development and the contradiction between supply and demand of water resources, the study chose population, natural population growth, urbanization rate, total water resources or water availability, and water withdrawal or water demand (production, life and ecology) as the indexes to represent the pressure of water resources; State index (S) illuminates the maximum population and socio-economic scale that can be sustained by the local water resources, we select water consumption per 10,000 RMB and water resources per capita as indicators to replace the regional water resources carrying condition; Response index (R) mainly expounds how humanity take measures to solve the influence. So water use efficiency, investment in fixed assets and forest coverage rate are chosen. On the other hand, examples from academic always focused on water scarcity as a proxy for water resources [7]. The water stress indicator, which is the ration of current regional water withdrawal to water availability, is used to estimate apparent scarcity based on regional demand-driven use.

6.2.2 Water environment security aspect

Based on the basic principle of water security system, the pressure (P) index mainly reflects the potential cause of the change of the water environment, reflecting the socio-economic development has an impact on the water environment state, so total waste water including industrial emissions and life emissions is selected. The state (S) index mainly explains water environment quality conditions and current state of water quality and impact on socio-economic development. This study selects chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) to reflect organic pollution and eutrophication of water bodies. In addition, target rate of water function zone and water pollution accident are selected to perform. Response index (R) mainly refers to the socio-economic impact on water environment change, human has taken active measures to respond to water environment changes. So the selections are the standard-reaching rate for industrial wastewater discharge and treatment rate of city waste water in order to express the response of humanity to water environment changes. Moreover, the necessity and importance of dealing with water pollution incident must be considered. As a result, the indicator of water pollution incident is selected in order to express the response of humanity to the water environment emergency.

6.2.3 Water disaster security aspect

Water disaster refers to flood hazard in our study. The proxy indicators are selected after a literature review on vulnerability and water resources management, in order to identify the most widely used and accepted indicators and indices [8-12]. Annual precipitation, eroded area, and flood frequency are selected as the exposure indicators. Per capita water availability and population density are selected as the sensitivity indicators. Adaptive capacity expresses the potential of systems to effectively cope with the impacts and associated risks and is negatively associated with vulnerability. Adaptive capacity is developed into two parts, including early-warning capability and self-restoring capacity. Number of water departments is selected as the indicator to represent the early-warning capability. Per capita GDP and water conservancy construction investment are regarded as the self-restoring capability indicator.

6.3 Set pair analysis model

6.3.1 Modeling process

This study used a set pair analysis method to establish an evaluation model for WSS condition. The principle of SPA assumes that set A1 and set A2 are relative and constructs a set pair H = (A1, A2); N terms in A1 = (a1, a2… an) and in A2 = (b1, b2, …, bn) are used to show the characteristics of set A1 and set A2, respectively. S is the number of identical terms in a given characteristic, P is the number of contradictory terms in the characteristic, and F = N – S – P is the number of discrepant terms in the characteristic [13].

In this study, the SPA method is applied to assess the water resources, water environment, and water disasters objects. SPA can be summarized in a series of steps and the following steps are explained taking one object as an example. Evaluation indicators are set as A and evaluation standards are set as B. If the value of the evaluation index belongs to the range of standard, the feature is S, if the value of the evaluation index is next to the standard, the feature is F, if the value of the evaluated index is separated by another standard, the feature is P. The steps are below [14]:

Step 1 Establish the evaluation indicator set

According to the original data, the number of evaluation objects is denoted as *n*, which, at Japan's regions scale, is equal to 8 corresponding to the 8 regions under evaluation. Meanwhile, the number of evaluation indicators is denoted by *m*.

$$A=(x_{ij})_{m\times n}=\left\{\begin{matrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{matrix}\right\}(i=1,2,\ldots,m;j=1,2,\ldots n) \tag{6.1}$$

Step 2 Establish comment set:

According to the Yasmin's book "Health in sustainable development planning: the role of indicators” published by World Health Organization (WHO) and the reference Xuan et al., [15], the evaluation set is distinguished as five degrees, corresponding to the levels of excellent, good, medium, poor, very poor, respectively.

$$B = \begin{Bmatrix} s_{11}, & s_{12}, \ldots, s_{15} \\ s_{21}, & s_{22}, \ldots, s_{25} \\ \vdots \;\; \vdots & \vdots \;\; \vdots \\ s_{m1}, & s_{2}, \ldots, s_{m5} \end{Bmatrix} \tag{6.2}$$

Where s_{m1}, s_{m2}, s_{m3}, s_{m4}, s_{m5} are the values of representative criteria of m indicator, corresponding to the 5 grades: excellent, good, medium, poor, and very poor.

Step 3 Construct the connection degree formula:

$$\mu_{A-B} = \frac{S}{N} + \frac{F}{N} i + \frac{P}{N} j \tag{6.3}$$

Note that $a = S/N$, $b = F/N$, $c = P/N$, and thus Eq. (3) can be written as

$$\mu_{A-B} = a + bi + cj \tag{6.4}$$

$$\mu_{A-B} = \frac{S}{N} + \frac{F_1}{N} i_1 + \frac{F_2}{N} i_2 + \ldots + \frac{F_{n-2}}{N} i_{n-2} + \frac{p}{N} j \tag{6.5}$$

Aliased as：

$$\mu_{A-B} = a + b_1 i_1 + b_2 i_2 + \ldots + b_{n-2} i_{n-2} + cj \tag{6.6}$$

Where μ_{A-B} is connection degree, a、b、c are components of connection degree, $a, b, c \in [0, 1]$, a stands for the same degree; b refers to the degree of difference; c refers to the degree of opposite; they meet the demand of $a + b + c = 1$; i is discrepancy coefficient, reflecting the change between certainty and uncertainty, $i \in [-1, 1]$; j is opposite coefficient, its value is -1, meaning that $\frac{P}{N}$ and $\frac{S}{N}$ are opposite.

Step 4 Evaluation result processing

In the previous studies, the maximum connection degree method is widely used to process the evaluation result.

$$u = \max\left(\mu_{(A-B)1}, \mu_{(A-B)2}, \mu_{(A-B)3}, \mu_{(A-B)4}, \mu_{(A-B)5}\right) \qquad (6.7)$$

Where u is the final SPA evaluation result of the evaluated object.

6.3.2 Case study in Guizhou province

The evaluation of water security using set pair analysis theory utilizes a set pair constructed using index values and the standard grades of various indices. The set pair is calculated and analyzed using the identity, discrepancy and contradistinction degree. The water security evaluation indexes system is shown in Table 6-1. The paper defines the assessment standard complying with the requirements of international healthy and ecological cities. Accordingly, the assessment standard is divided into five ranks: Crisis, Insecurity, Basic security, Security, and Very security. The paper adopts the commonly suggested value of healthy ecological city as a value of the very security [16-17] and the international minimum value as the limitation value of Crisis state. Values of trisection points between the two standard values of Very security and Crisis are the standard values of Insecurity, Basic security and Security grades. Table 6-2 gives the specific grading standard.

Table 6-1 Index system of water security in Guizhou province

Object hierarchy	Sub-object hierarchy	Index hierarchy
The Evaluation Index System for Water Security in Guizhou	Water Resource	Natural Growth Rate of Population Urbanization Rate Total Water Resources Ten Thousand Yuan GDP Water Consumption Per Capita Water Resources Investment in Fixed Assets Rate of Forest Covered Water Use Efficiency
	Water Environment	Total Volume of Waste Water Discharged Target Rate of Water Function Zone Water Pollution Accident Up-to-standard Rate of Industrial Sewage Discharge Treatment Rate of City Waste Water
	Water Disaster	Water and Soil Loss Annual Precipitation Flood Disaster loss Investment of Water Resources Construction The Rate Soil Erosion Area The Flood Frequency

Table 6-2 Urban Water Security assessment grading standards in Guizhou province

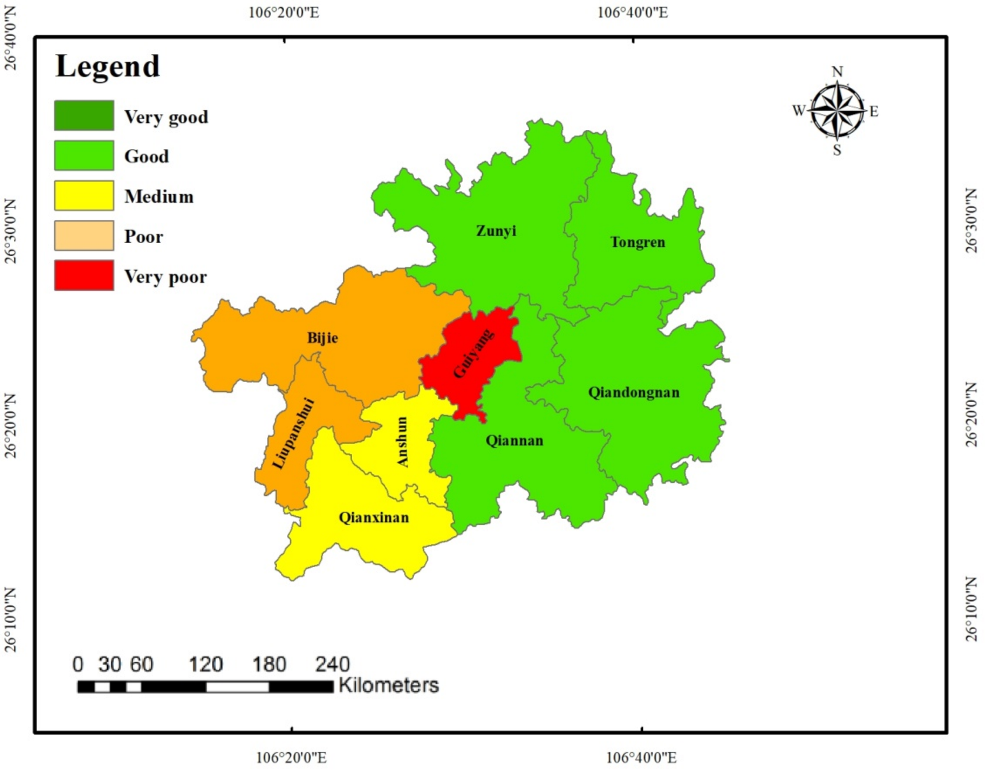
	Indices	Very security	Security	Basic security	Insecurity	Crisis
Water resources	Natural Growth Rate of population（‰）	< 6.20	[6.20, 7.10]	[7.11, 7.99]	[8.00, 8.88]	> 8.88
	Urbanization Rate（%）	<32.44	[32.44,43.22]	[43.23,54.20]	[54.21,65.09]	>65.09
	Total Water Resources (100 million cum)	>149.23	[114.69,149.23]	[80.14,114.68]	[45.58,80.13]	<45.58
	Per Capita Water Resources (cum /person)	>3703.38	[2862.14,3703.38]	[2020.89,2862.13]	[1179.63,2020.88]	<1179.63
	Rate of Forest Covered（%）	>60.1	[53.6,60.1]	[47.0,53.5]	[40.3,46.9]	<40.3
Water environment	Up-to-standard Rate of Industrial Sewage Discharge（%）(1)	>94.18	[85.54,94.18]	[76.89,85.53]	[68.23,76.88]	<68.23
	Treatment Rate of City Waste Water（%）(1)	>77.12	[64.01,77.12]	[50.89,64.00]	[37.76,50.88]	<37.76
Water disaster	Water and soil loss（%）	<31.63	[31.63,39.42]	[39.43,47.21]	[47.22,55.00]	>55.00
	Annual precipitation (100 million cum)	<110.13	[110.13,172.78]	[172.79,235.43]	[235.44,298.08]	>298.08
	The rate Soil erosion area mired (%)	<45.01	[45.01,52.80]	[52.81,60.59]	[60.60,68.38]	>68.38
	Mild (%)	<18.33	[18.33,21.82]	[21.83,25.31]	[25.32,28.79]	>28.79
	Moderate (%)	<8.21	[8.21,13.23]	[13.24,18.25]	[18.26,23.28]	>23.28
	Strength (%)	<2.26	[2.26,4.54]	[4.55,6.82]	[6.83,9.11]	>9.11
	Severe (%)	<0.31	[0.31,0.93]	[0.94,1.55]	[1.56,2.18]	>2.18

Note: (1) the standard data come from the standard of surface water quality in China (GB3838)

Based on the assessment results of SPA model about water security in cities of Guizhou province above, we input the assessment results into GIS software and it is clear to see the ranked distribution. Fig. 6-2 (a) shows the spatial distribution of water resources security subsystem under the evaluation of SPA model. The security of water resources subsystem in Guiyang city is critical because water resource per capita in Guiyang is lower than other cities. The state of Zunyi, Tongren, Qiandongnan, and Qiannan is security; it also confirms that the water supply is greater than the actual demand. Anshun and Qianxinan rank the basic security; supply and demand for water are balanced. Bijie and Liupanshui are at insecurity state and water supply cannot meet water demand.

The security of water environment subsystem is secure in Guiyang and Zunyi. The state of Bijie, Anshun, Qiandongnan, and Qiannan is basic security and water quality level can just reach the standard; Liupanshui and Qianxinan are insecurity, the water environment is vulnerable and it is easy to be damaged in Fig. 6-2 (b).

Fig. 6-2 (c) shows the security of water disaster subsystem. The state of Qiandongnan is very secure. Guiyang, Anshun, Qiannan, and Qianxinan are secure as well. The security of water disaster in Zunyi is basic secure; Tongren, Liupanshui are insecure; Bijie is in a state of crisis. Fig. 6-2 (d) shows the composed state of all subsystems. It comprehensively reflects the conditions of water resources, water quality, and water disaster. Guiyang, Qiandongnan, and Qiannan are secure; the composed state of Zunyi, Tongren, Anshun, and Qianxinan is basic secure; Bijie and Liupanshui are at a state of insecurity.



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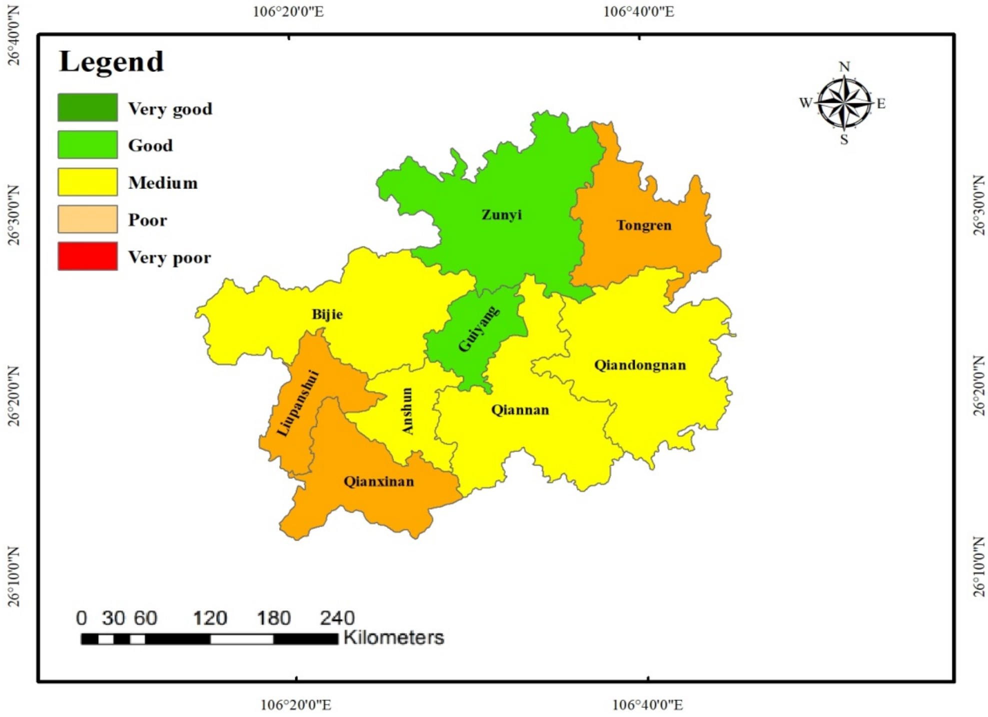
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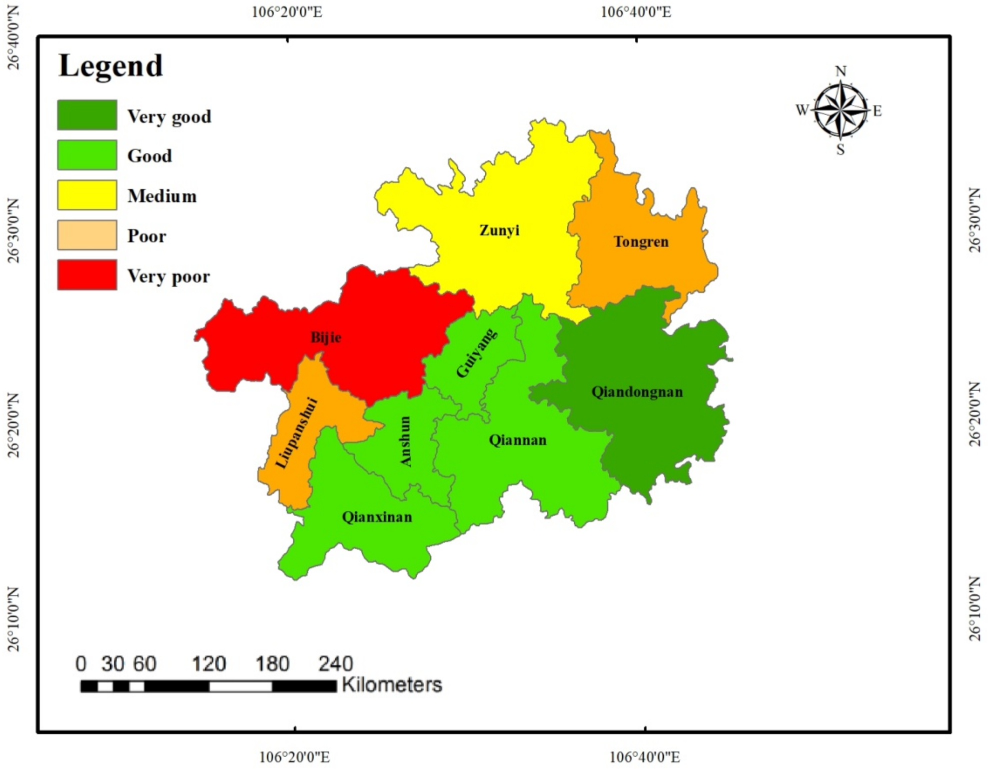
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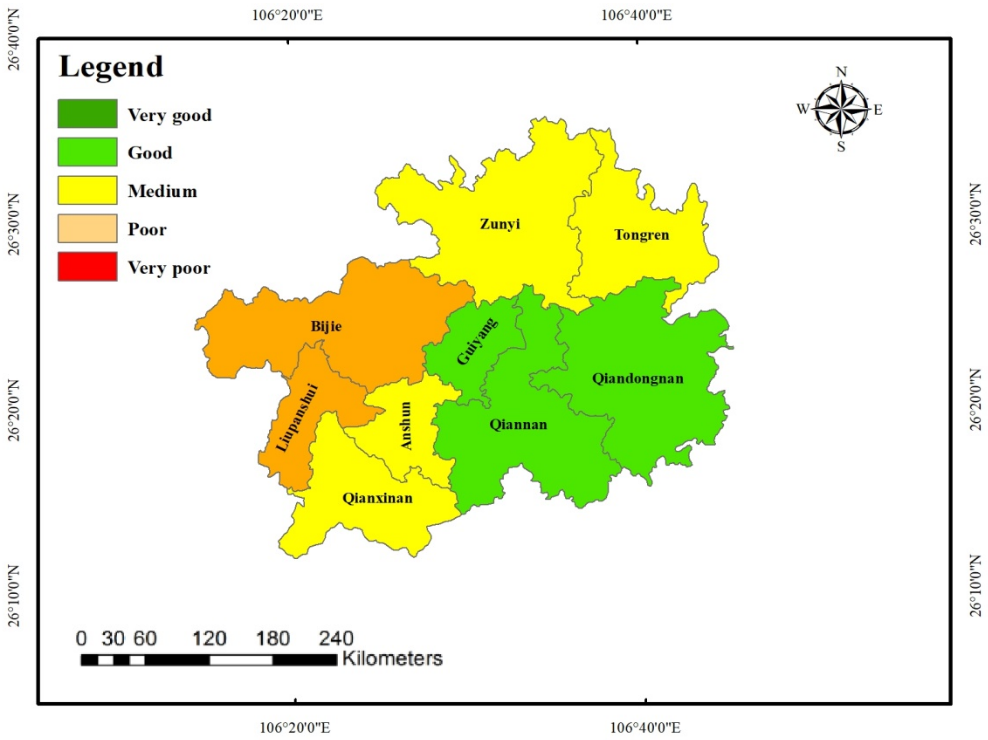


(d)

Fig. 6-2 Spatial distribution of different water subsystems: (a) Water resources subsystem; (b) Water environmental subsystem; (c) Water disaster subsystem; (d) Water security system.

6.3.3 Case study in Japan

The establishment of a scientific and reasonable index system would help to provide a basis for the accurate assessment of regional water security. Water security system is a large complex system with many influenced factors. To date, there is no uniform standard index system. In this work, we establish the index system from the three pillars of Water security system. The specific assessment indicators of water security system are shown in Table 6-3. Table 6-4 shows the concrete grades standards.

Table 6-3 Index system of water security in Japan

Object hierarchy (A)	Sub-object hierarchy (B)	Index hierarchy (C)	Definition	Reasons
Water security condition in Japan	B_1: Water resource subsystem	C_{11}: Population (k)	Resident population statistics by census	Reflection of water resources conditions on which human depends
		C_{12}: Water withdrawals ($10^8m^3/y$)	Freshwater taken from ground or surface water sources, and conveyed to a place of use	
		C_{13}: Water availability ($10^8m^3/y$)	The quantity of water that can be used for human purposes without significant harm to ecosystems or other users	
	B_2: Water environment subsystem	C_{21}: Water Pollution Incidents (number of times)	Sudden event of water pollution	Relevance to water environmental quality on which human depends
		C_{22}:Total nitrogen (TN) (t/y)	The sum of nitrate (NO3), nitrite (NO2), organic nitrogen and ammonia (all expressed as N).	
		C_{23}:Chemical oxygen demand (COD) (t/y)	An indicative measure of the amount of oxygen that can be consumed by reactions in a measured solution	
		C_{24}:Total phosphorus (TP) (t/y)	The sum of all phosphorus compounds that occur in various forms	
	B_3: Water disasters subsystem	C_{31}: Annual Precipitation (mm)	The average amount of total rain that a place generally receives	Demonstrate the exposure of vulnerability
		C_{32}: Eroded area (ha)	Soil erosion area	
		C_{33}: Flood Frequency (number of times)	Caused by rainfall overwhelming the capacity of urban drainage systems	
		C_{34}: population density (Person/km^2)	The ratio of population to area	Demonstrate the sensitivity of vulnerability
		C_{35}: Per capita water availability ($10^3m^3/y$)	The ratio of water availability to population	
		C_{36}: Number of water departments (number)	Management of water supply and wastewater treatment sectors	Demonstrate the adaptive capacity of vulnerability
		C_{37}: Per capita GDP ($)	The ratio of GDP to population	

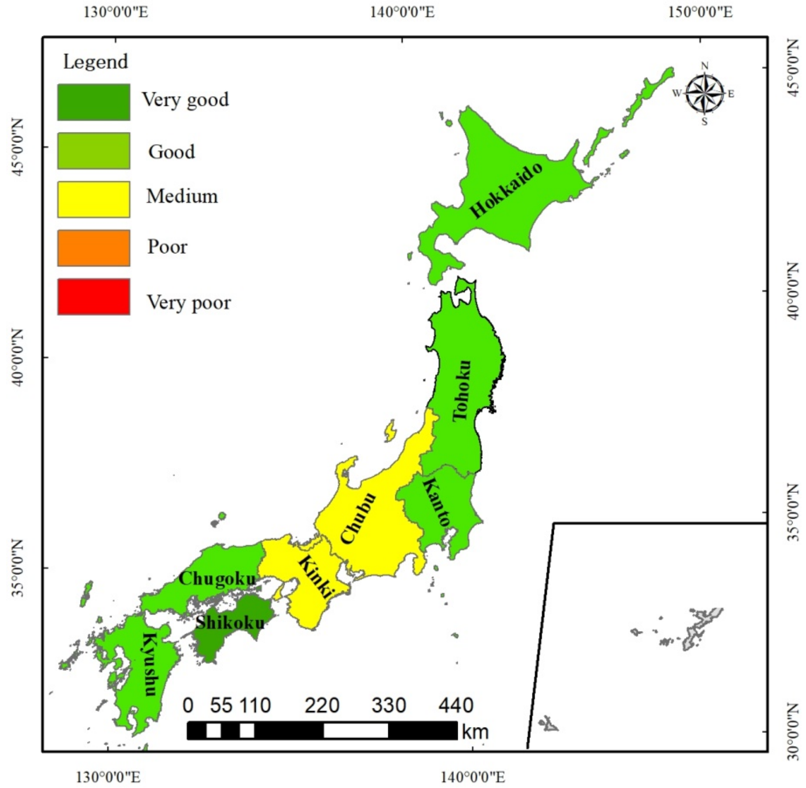
Table 6-4 Evaluation grades standards in Japan

Index	Grade 1 (excellent)	Grade 2 (good)	Grade 3 (medium)	Grade 4 (poor)	Grade 5 (very poor)
C_{11}	<9558	[9558, 19078)	[19078, 28598)	[28598, 38118)	≥38118
C_{12}	≥783.6	[642.9, 783.6)	[502.1, 642.9)	[361.4, 502.1)	<361.4
C_{13}	<53.8	[53.8, 88.9)	[88.9, 124.0)	[124.0, 159.1)	≥159.1
C_{21}	<514	[514, 1150)	[1150, 1786)	[1786, 2422)	≥2422
C_{22}	<54387.1	[54387.1, 82583.5)	[82583.5, 110779.9)	[110779.9, 138976.3)	≥138976.3
C_{23}	<40889.7	[40889.7, 65703.6)	[65703.6, 90517.5)	[90517.5, 115331.4)	≥115331.4
C_{24}	<2475.3	[2475.3, 4054.8)	[4054.8, 5634.4)	[5634.4, 7213.9)	≥7213.9
C_{31}	<1298.6	[1298.6, 1549.5)	[1549.5, 1800.5)	[1800.5, 2051.4)	≥2051.4
C_{32}	<372.1	[372.1, 802.4)	[802.4, 1232.6)	[1232.6, 1662.9)	≥1662.9
C_{33}	<4	[4, 5)	[5, 7)	[7, 8)	≥8
C_{34}	<241	[241, 535.17)	[535.17, 829.33)	[829.33, 1123.50)	≥1123.50
C_{35}	≥9.09	[6.82, 9.09)	[4.54, 6.82)	[2.26, 4.54)	<2.26
C_{36}	≥7	[5, 7)	[3, 5)	[1, 3)	<1
C_{37}	≥55430.50	[47814.65, 55430.50)	[40198.81, 47814.65)	[32582.97, 40198.81)	<32582.97

Based on the assessment results of the SPA model about water security in different regions of Japan above, we input the assessment results into GIS software and it is clear to see the ranked distribution. Fig. 6-3 (a) shows the current situation of water resources subsystem in Shikoku has a grade of 1. Although Shikoku has the smallest and least populous of the four main islands of Japan, located south of Honshu and east of the island of Kyushu, it has relatively limited local water resources. The condition of the development and utilization of water resources is classified as grade 1, which means that Shikoku's water resources meet the water resource demands of all of its departments. Fig. 6-3 (b) shows the water environment condition in Shikoku also has a grade of 1, meaning that the current water environment exhibits some strength. While the current situation of water disasters subsystem is classified as grade 4 in Fig. 6-3 (c), which indicates that the potential risks are more severe for Shikoku. In other words, the water resources and water environment conditions have a grade of 1, which implied that the Shikoku's sustainable use of water resources is at a relatively good level and meets the requirements of sustainable development. At the same time, more attention should be paid to the preparation for the prevention of water disaster and mitigation in the future.

The current situation of Chubu and Kinki all has a grade of 3, no matter in water resources, water environment, or water disasters. It means that the current performance of water security system is normal, but the WSS faces a slight load. Overall, these results are consistent with the actual situation in Chubu and Kinki. However, certain measures must be taken to improve the sustainable development of WSS and maintain a long-lasting and positive cycle. The current conditions of water resources, water environment, and water disasters in other regions are classified as grade 1 or 2, which indicates that the current states in these regions are in an optimal or suboptimal state and requires keeping the good momentum.

From Fig. 6-3 (d), the synthesized situation of water security indicates that Hokkaido, Tohoku, Kanto, Chugoku, and Kyushu are in a grade of 2. Chubu, Kinki and Shikoku have a grade of 3. In other words, the overall condition of water security in Japan is moderate, but it needs external policy supporting the water sustainable development. Without appropriate intervention, it will be change to bad situation.



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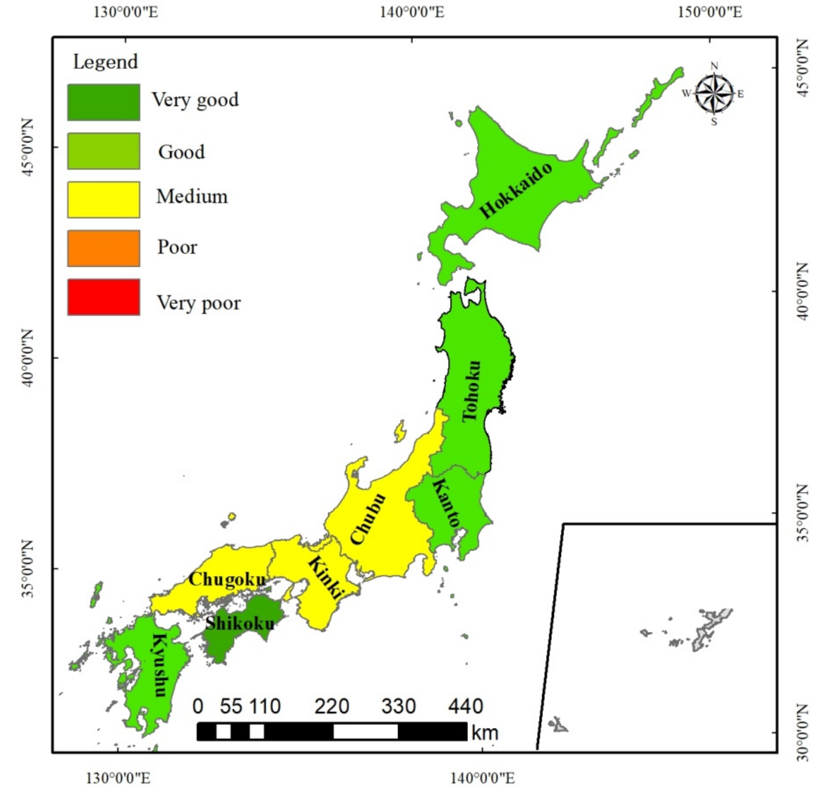
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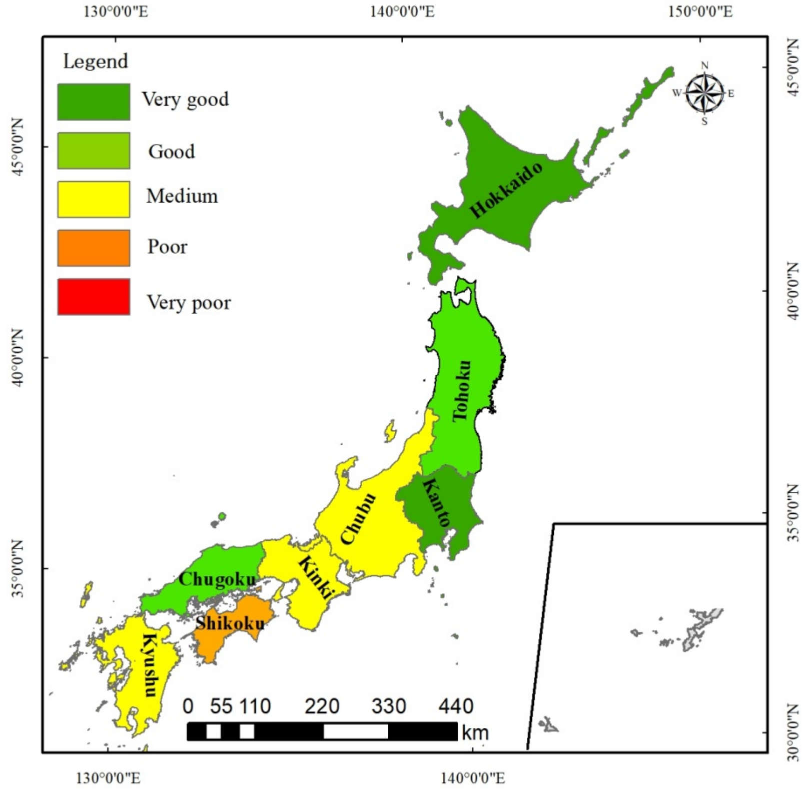
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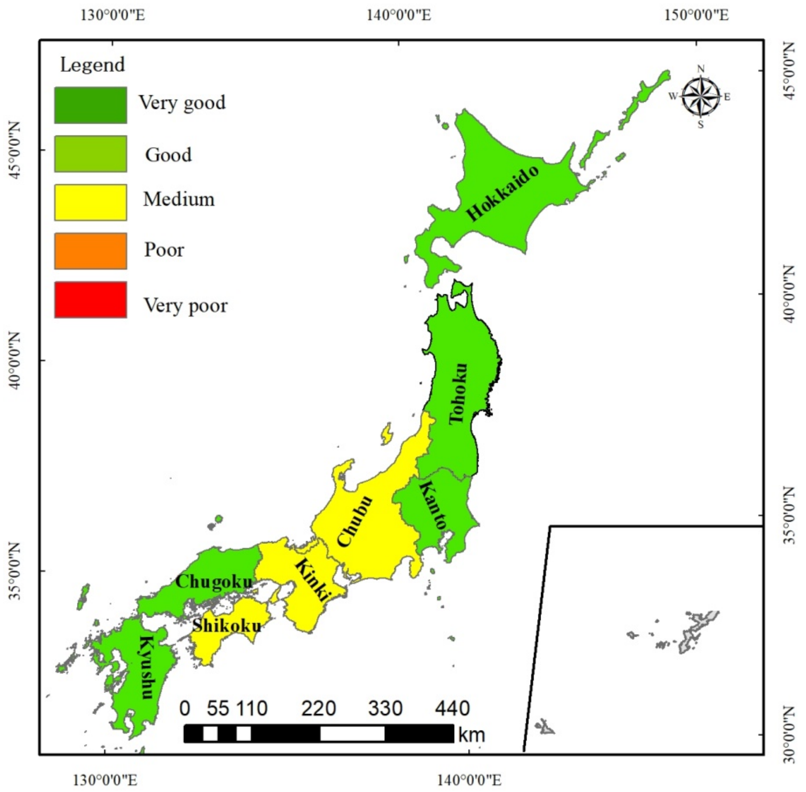

(d)

Fig. 6-3 (a) Description of water resources subsystem; (b) Description of water environment subsystem; (c) Description of water disasters subsystem; (d) Description of water security system.

6.4 Summary

In recent years, many scholars have focused on the issue of limited freshwater availability in the city. They paid much attention mainly to water volume, but it is not enough to only account for water volume in policy-making and local governed view. For the urban governors, they need to take into consideration economic, society, technology and environment. An integrated and acceptable methodology is desired to maintain the sustainability of water security. First, we used "PSR" framework to establish integrated indicators from water resources, water environment, and water disaster. Second, we develop an integrated evaluation model-SPA to do a comparison study between Guizhou province in China and Japan. According to the classification criterion, the evaluation results showed that:

(1) There are three cities were at a secure state, four cities at the basic secure state, and two cities in an insecure condition. Then we presented the spatial security level information of water resources, water environment and water disaster with the GIS software. The significance of our method is that we can clearly acquaint where water scarce is, where water seriously polluted is and where water hazards occur.

(2) The current situation of water security system in Japan is as follows: for the water resources subsystem, the current situation of the total eight administrative divisions are one excellent, five good, and the rest two medium; for the water environment subsystem, all administrative divisions have grades of medium or above level; for the water disasters subsystem, except Shikoku is very poor, the rest medium or above.

(3) According to comparison, we found that Japan and Guizhou province with similar geographical conditions have significant differences between water resources, water environment, and water disaster subsystems. Moreover, in terms of overall water security, the overall water security in Guizhou Province is poor, and overall water security in Japan is good. That is to say, Japan, which is economically and socially developed, has a stronger ability to regulate water resources, water environment, and water disasters than Guizhou, which has a poor economic and social development level.

Based on the current status evaluation of water security in Guizhou province and Japan, we have an overall understanding of the current state of water security in Japan and Guizhou Province. In addition, water security is also closely related to social and economic conditions. In order to better understand the relationship between water security system and socio-economic system, we will use the system dynamics model to simulate in the next chapter. The problem we want to solve next is to do quantification research on the key variables which affect the water subsystems, to study the interactions between water resources, water environment, water disasters subsystems, and economy and population subsystems.

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Chapter 7

SCENARIOS SIMULATION AND COMPARISON OF WATER SECURITY SYSTEM

CHAPTER 7: SCENARIOS SIMULATION AND COMPARISON OF WATER SECURITY SYSTEM

CHAPTER 7: INTEGRATED ASSESSMENT AND COMPARISON OF WATER SECURITY

7.1 Introduction

Nowadays, human society is facing serious water challenges such as water scarcity, water pollution, and especially water damage caused by flood [1]. In order to solve these issues, policy-makers have formulated surface water management and groundwater management policies, respectively. These traditional water management policies do not account for the interactions of the water issues. Therefore, integrated water management approach integrates water supply and water demand, water quantity and water quality, surface water and groundwater, and water-related institutions at national, regional, municipal and local levels [2]. However, integrated water management has been narrowly construed as a prescriptive way of knowing water based largely on technical–scientific knowledge, while water security represents a discursive way of knowing water with a greater consideration of human values, ethics and power [3]. This decision-making process requires well understanding of the significant contributors to regional water problems and of the way that the water management system will react to particular policies. During this process, it’s essential to understand the interactions among a number of related social, economic, environmental, managerial, regulatory, and lifestyle factors. These interactions are complicated not only because they simultaneously involve various system components but because they dynamically change over time. As a consequence, system dynamics (SD) was considered to be an appropriate approach for predicting dynamic results of the interactions and analyzing implications of different policies given such complexes.

Langsdale et al. [4] have established the water supply-demand modeling to study the impact of climate change on the water resources futures, and some scholarchs have simulated the treatment efficiency of wastewater using system dynamics model [5, 6]. Other scholarchs have proposed an aquifer modeling of system dynamics [7-9], and hydro-power generation modeling of system dynamics [10, 11]. However, most of these studies focused on basins, not on the water resources management of administrative regions. Moreover, the above researches on the sustainable utilization of water resources are all about how to establish a water resource optimization model and propose corresponding countermeasures based on the optimization model. No in-depth research has investigated the interaction among water security, society, and the economy through the SD method. Meanwhile, a water security system includes the subsystems of water resource security, water environment security, and water disaster security. All the subsystems interact with and restrain each other. To the best of our knowledge, few literature studies identifying the key variables that affect systemic change and studies the interactions between subsystems. Thus this study is to fill the gap. The main innovativeness of the study lies mainly in the following points:

(1) This study conducts an empirical analysis using the data of administrative regions in Japan and Guizhou province to provide policy advice.

(2) Quantitative research is conducted on the key variables which affect the subsystems.

(3) The impact of water resources, water environment, and water disasters subsystems on the economy and population subsystems is analyzed.

7.2 Methodology

SD model is a powerful and simple method that uses causal-loop and stock-flow diagrams to describe some interrelated systems. The purpose of a system dynamic study is to understand how and why the dynamics of a subject are generated and to search for administrative policies to improve its current situation. This study applies SD model software Vensim to simulate water resources, water environment, water disasters, and future changes from 1995 to 2025 from the temporal dimension. First step is to determine research objective and analyze restriction condition, structure and function. Second step is to establish stock-flow diagrams of subsystems and achieve model programs. Then, sensitivity degree analysis and data validation are carried out for testing reasonability and feasibility of model. Third step is to conduct design and simulation of scenarios. An optimal scenario is selected according to simulation results. Final step is to perform an integrated analysis towards the optimized scenario.

7.2.1 Model description

SD model established in this chapter studies the sustainability of water security system (WSS) according to cybernetics, system theory and information theory. It can elucidate interaction and relationship among various influencing factors to perform a dynamic simulating test, as is an outstanding feature of the SD model. The purpose of this test is to investigate changing behaviors and tendencies of WSS in alternative scenarios (parameters or strategies) for supporting the corresponding policies and managements.

Process of system dynamics model includes six steps. First step is to establish stock and flow diagrams of SD model (shown in Fig.7-1). Second step is to establish equation of all variables in the model (shown in Fig.7-2). Third step is to change parameter value in the model (shown in Fig.7-3). Fourth step is to carry out model test. Fifth step is to set graph of simulation results. Sixth step is to carry out different scenarios simulation.

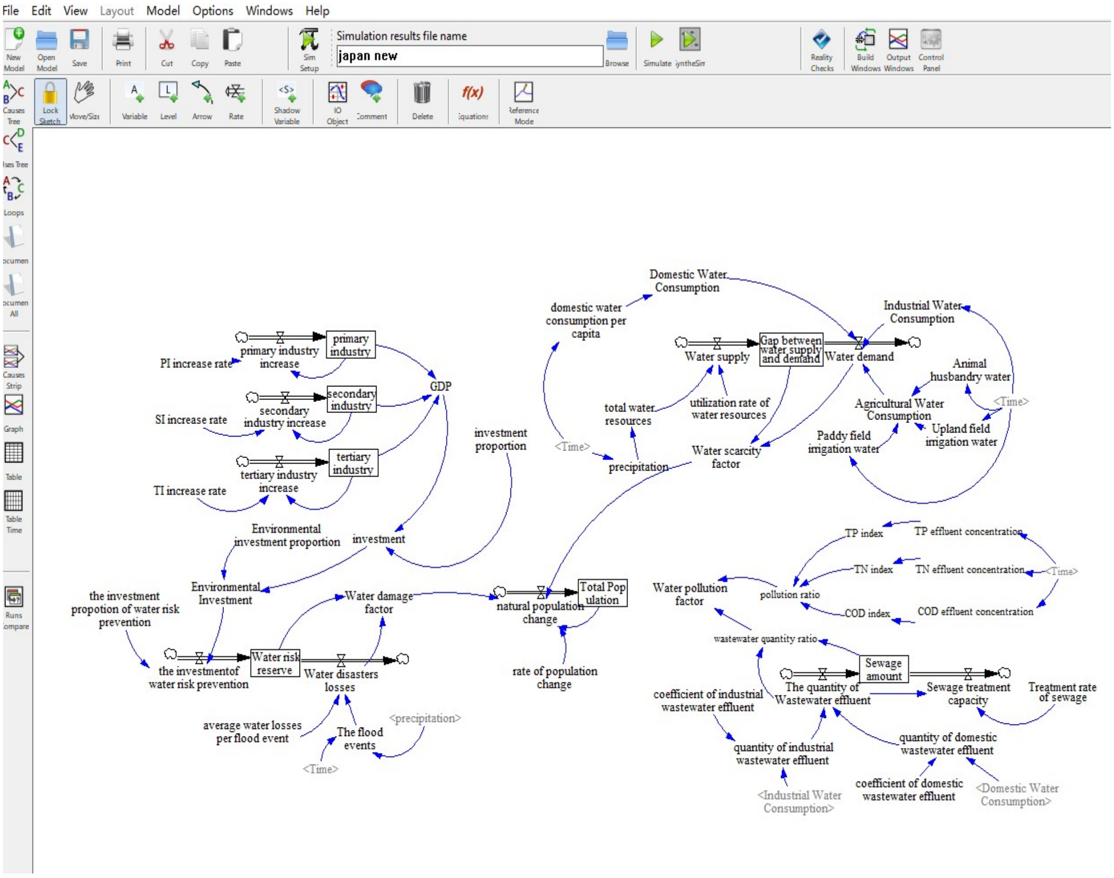
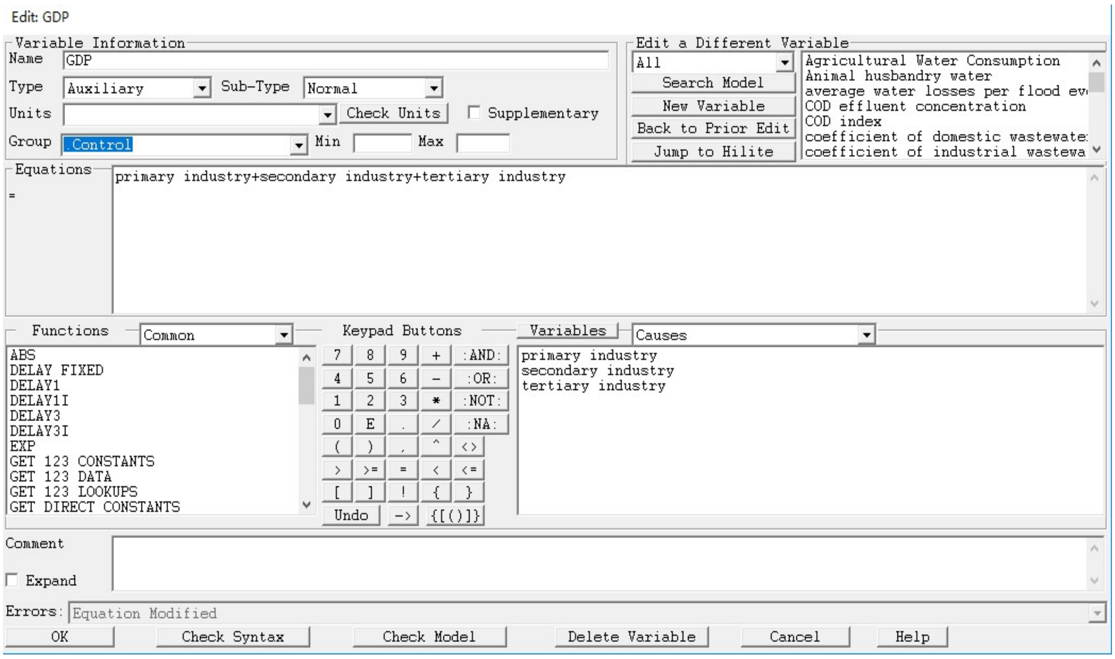


Fig.7-1 Establishment of stock and flow diagrams of system dynamics model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Variable Information

Name: GDP

Type: Auxiliary

Sub-Type: Normal

Units:

☐ Supplementary

Group: Control

Min:

Max:

Equations

= primary industry+secondary industry+tertiary industry

Edit a Different Variable: All

Agricultural Water Consumption
Animal husbandry water
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COD effluent concentration
COD index
coefficient of domestic wastewate
coefficient of industrial wastewa

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GET DIRECT CONSTANTS

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primary industry
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Fig.7-2 Equation establishment of all variables in the model

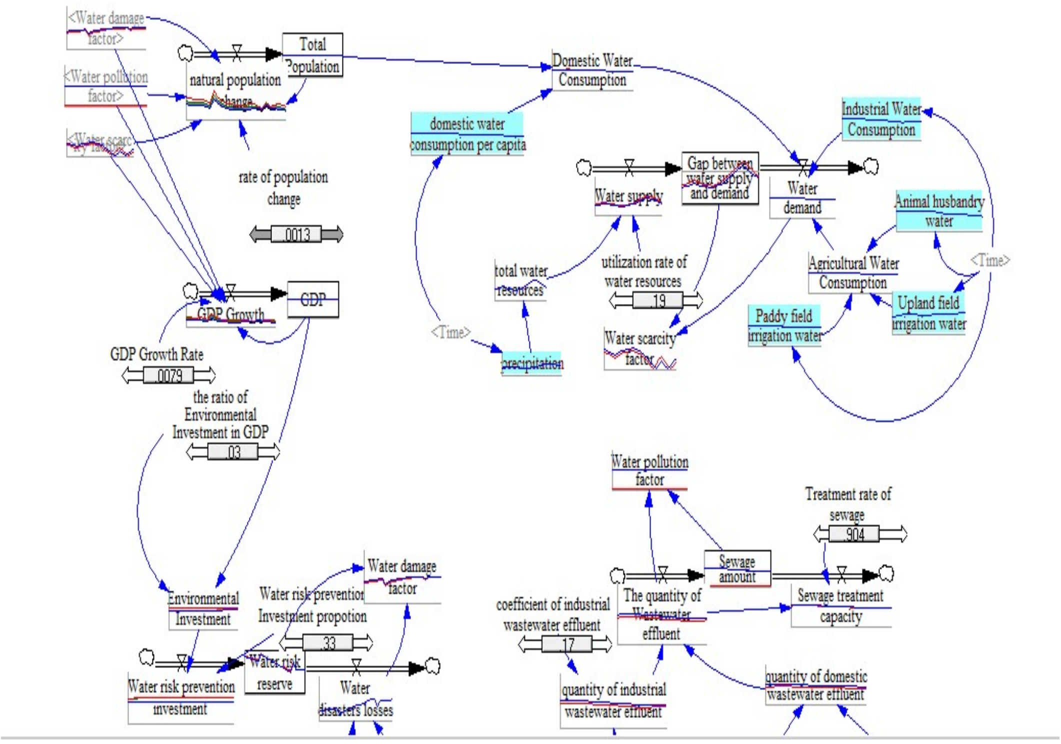


Fig.7-3 Parameter setting of system dynamics model

7.2.2 Model structure

This study chooses WSS as the research object and the period 1995-2025 as the research period, with a time step of 1 year. Five subsystems are then used to analyze the impact on the WSS, namely economy, population, water resources, water environment, and water disasters, as described more in detail below.

7.2.2.1 Population subsystem

In population subsystem, we select the total population, natural population change, and rate of population change. Natural population change is the rate variable that leads the total population stock to change. The natural population change is influenced by the rate of population change, water scarcity factor, water pollution factor, and water damage factor. This means that besides the rate of population change, the total population can also be affected by water shortages, water damage, and water pollution. Obviously, these variables have a negative influence on the total population. Fig.7-4 presents the stock-flow diagram of population subsystem. Fig.7-5 presents the cause tree diagram of population subsystem.

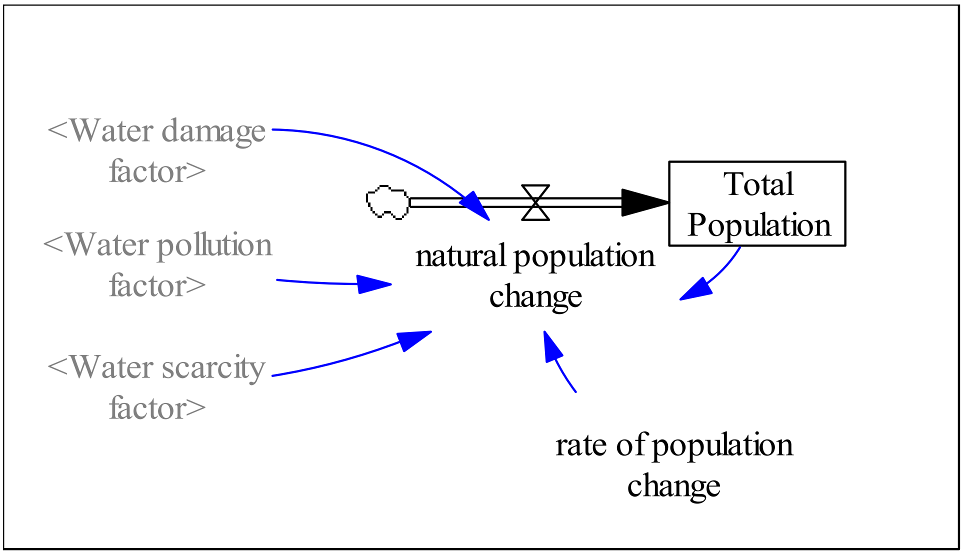


Fig.7-4 Stock-flow diagram of population subsystem

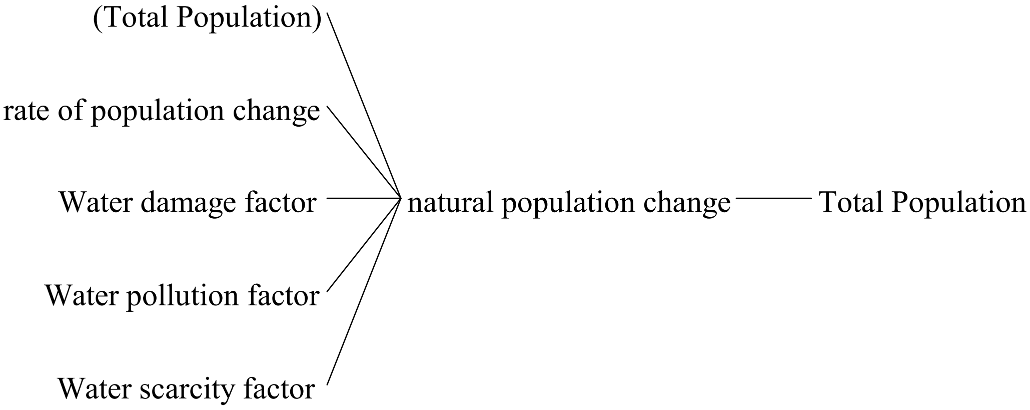


Fig.7-5 The cause tree diagram of population subsystem

7.2.2.2 Economic subsystem

One classical breakdown of economic activity distinguishes three sectors: [12] primary: involves the retrieval and production of raw materials, such as corn, coal, wood and iron. (A coal miner, farmer or fisherman would be workers in the primary sector.) Secondary: involves the transformation of raw or intermediate materials into goods e.g. manufacturing steel into cars, or textiles into clothing. (A builder and a dressmaker would be workers in the secondary sector.) Tertiary: involves the supplying of services to consumers and businesses, such as baby-sitting, cinema and banking. (A shopkeeper and an accountant would be workers in the tertiary sector.) The selection of economic subsystem variables is mainly considered from two aspects: On the one hand, the main focus of an economy's activity shifts from the primary, through the secondary and finally to the tertiary sector. The selection of these variables i.e. primary industry, primary industry increase, primary industry increase rate, secondary industry, secondary industry increase, secondary industry increase rate, tertiary industry, tertiary industry increase, tertiary industry increase rate, and GDP is to reflect the different demand for water in different economic sectors. The relationship between the economic subsystem and the water resources subsystem is established. On the other hand, the variables of investment, investment proportion, environmental investment, and environmental investment proportion are selected to establish links between the economic subsystem and the water disaster subsystem. Meanwhile, with the help of expert consultation and literature investigation [13], the variables (i.e. fourteen indicators) of the economic subsystem are determined. Fig.7-6 presents the stock-flow diagram of economy subsystem. The cause tree diagram of economy subsystem is shown in Fig.7-7.

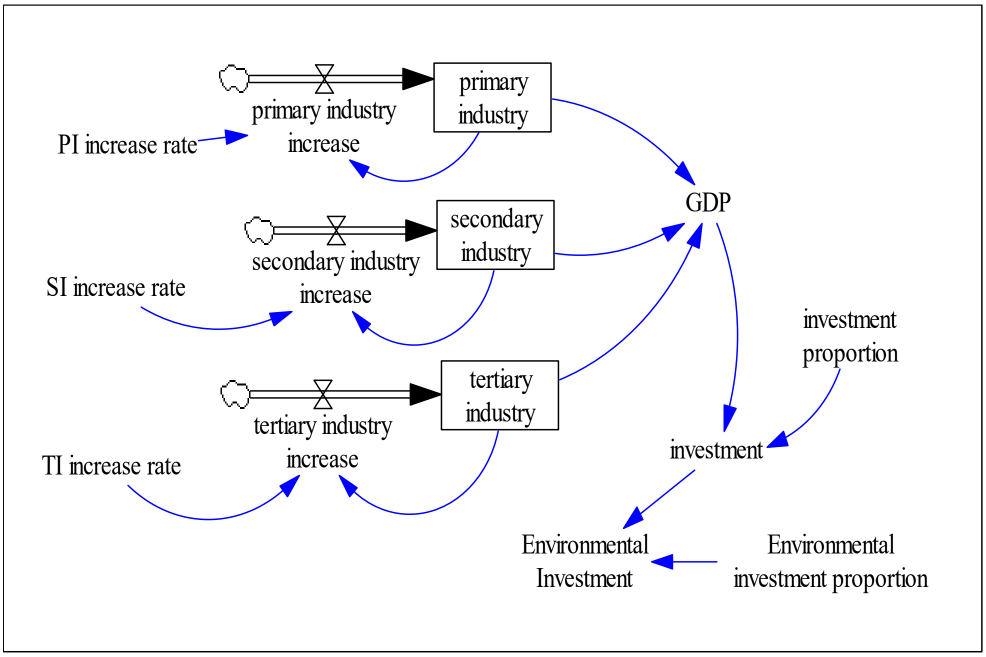


Fig.7-6 Stock-flow diagram of economic subsystem

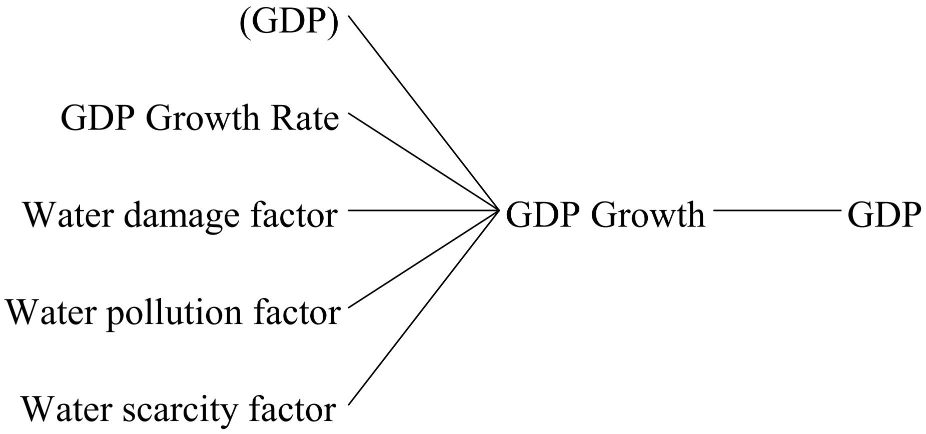


Fig.7-7 The cause tree diagram of economy subsystem

7.2.2.3 Water resources subsystem

This subsystem reflects the variations between water supply and water demand, namely the gap between water supply and demand. Here, water demand is counted from the actual use of water resources in Japan. The water use accounts in Japan are domestic water consumption, industry water consumption, and agricultural water consumption. Among them, agricultural water consumption is divided into paddy field irrigation water, upland field irrigation water, and animal husbandry water. Water supply is estimated based on total water resources and the utilization rate of water resources. The total water resources are changed with the annual precipitation. Water scarcity factor is a core variable in the subsystem, which is simulated by both the total water demand and the gap between water supply and water demand. Fig.7-8 presents the stock-flow diagram of water resources subsystem. The cause tree diagram of water resources subsystem is shown in Fig.7-9.

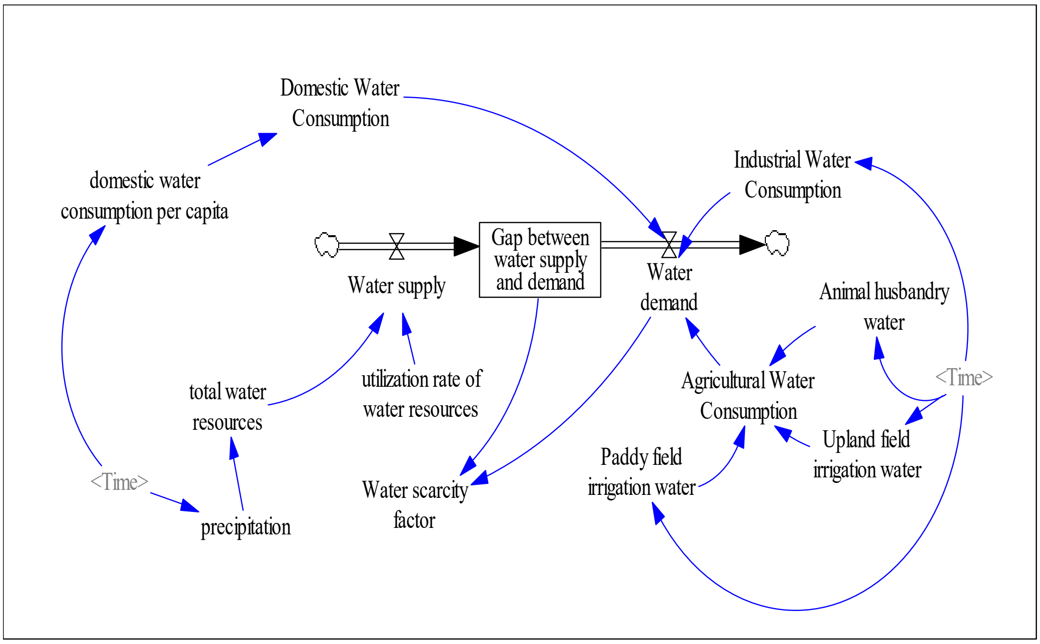


Fig.7-8 Stock-flow diagram of water resources subsystem

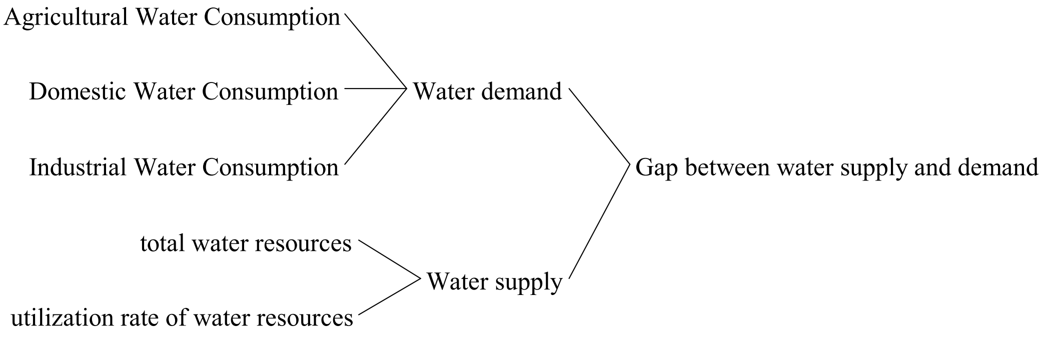


Fig.7-9 The cause tree diagram of water resources subsystem

7.2.2.4 Water environment subsystem

In order to present water environment state not only in quantity but quality, we added the auxiliary variable pollution ratio which is the characterization of the pollution levels. It is represented by the maximum value of contaminants TP, TN, and COD. The TP index, TN index, and COD index variables stand for if the effluent concentration of TP, TN, and COD is larger than the “Uniform National Effluent Standards” in Japan, the impact value is 1 otherwise 0. In this study, the effluent concentrations of TP, TN, and COD are a nonlinear function of time. Lookup function in Vensim software is used to build an equation to describe the nonlinear relationship. The variable of water pollution factor is calculated by both pollution ratio and wastewater quantity ratio. Wastewater quantity ratio is derived by sewage amount and the quantity of wastewater effluent. The quantity of wastewater effluent is the sum of the quantity of industry wastewater effluent and the quantity of domestic wastewater effluent. Sewage treatment capacity is the product of the quantity of wastewater effluent and treatment rate of sewage. The quantity of wastewater effluent and the sewage treatment capacity are all rate variables [14]. Besides these variables, the coefficient of industrial wastewater effluent, the coefficient of domestic wastewater effluent, and treatment rate of sewage are constants in this subsystem. Fig.7-10 presents the stock-flow diagram of water environment subsystem. The cause tree diagram of water environment subsystem is shown in Fig.7-11.

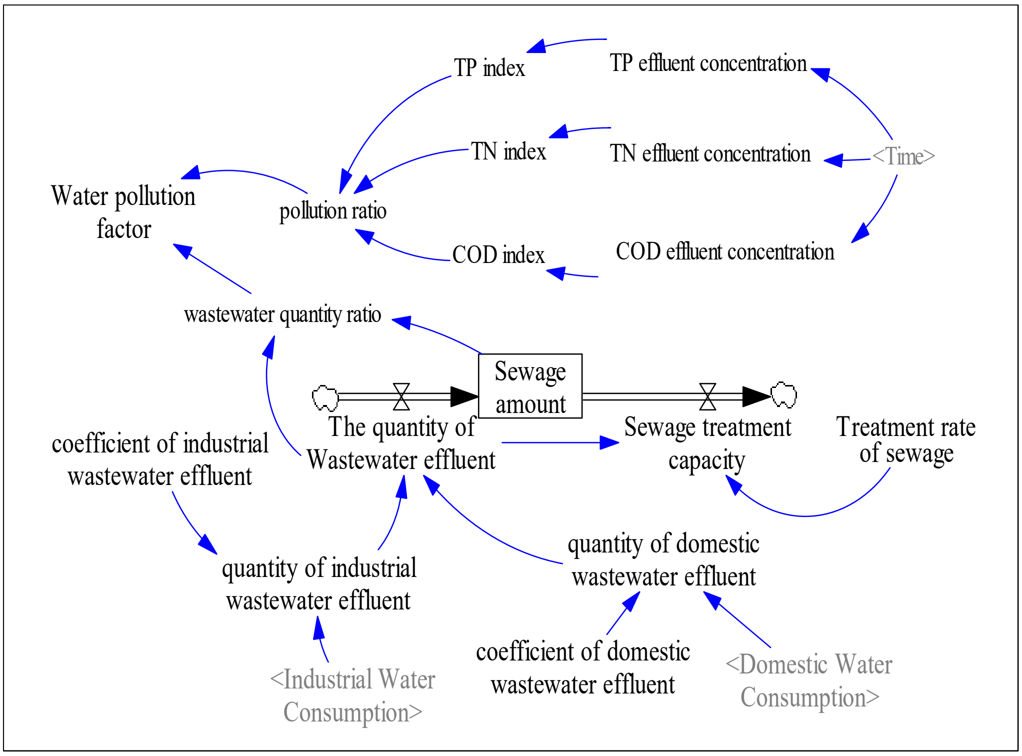


Fig.7-10 Stock-flow diagram of water environment subsystem

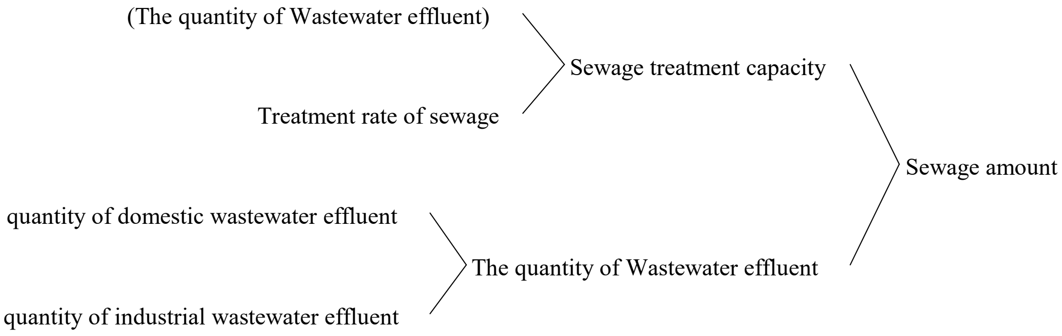


Fig.7-11 The cause tree diagram of water environment subsystem

7.2.2.5 Water disaster subsystem

At present, there is no standard of water disasters assessment system. The study adopts the losses caused by water disasters and the reserve funds invested in preventing and controlling water disasters to reflect the water damage factor. Water disasters losses are estimated based on the average water losses per flood event and the frequency of the flood events. The flood event is a lookup function with precipitation. Water risk reserve is stock variable, and the investment of water risk prevention and the water disasters losses are rate variables. Fig.7-12 presents the stock-flow diagram of water disaster subsystem. The cause tree diagram of water disaster subsystem is shown in Fig.7-13.

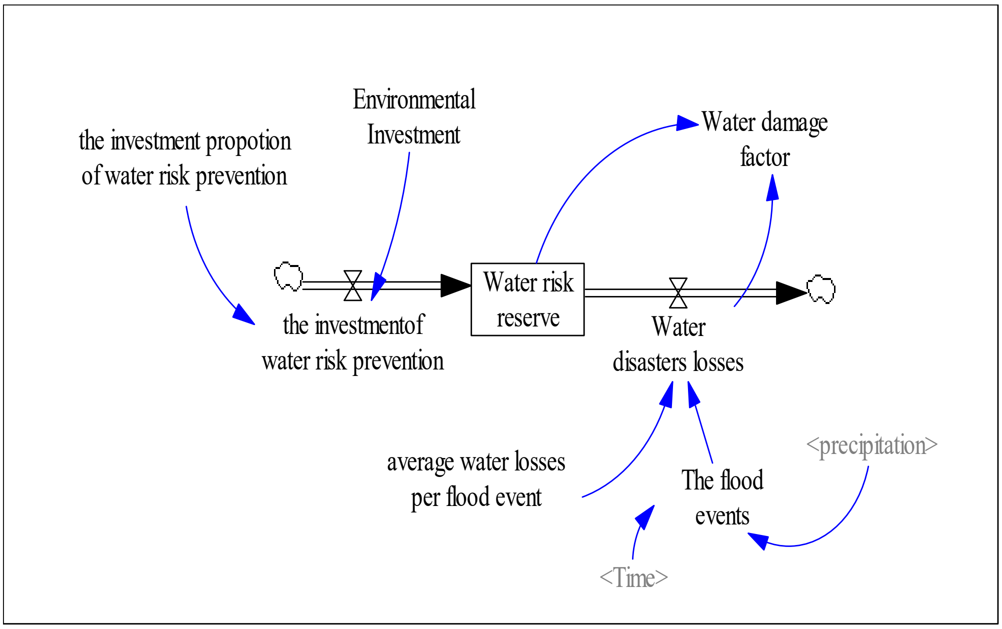


Fig.7-12 Stock-flow diagram of water disaster subsystem

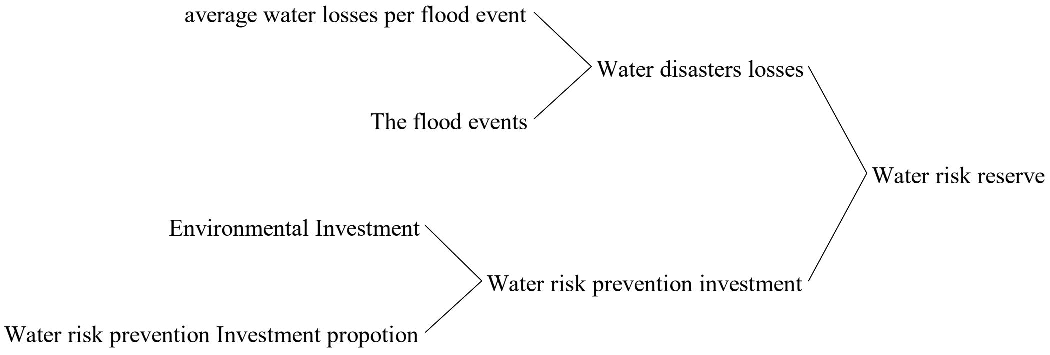


Fig.7-13 The cause tree diagram of water disaster subsystem

7.2.3 Model test

7.2.3.1 Verification of historical data

It is important to empirically calibrate the SD model for testing reasonability and feasibility of simulation results. On one hand, this can be fulfilled by a matching test of historical behavior in the current scenario. On the other hand, this can be tested by sensitivity analysis. The two methods are important ways to validate the effectiveness of the SD model. We chose total population and GDP variables with available values for validation. To validate the SD model, we compared the real data with the simulated value from 2005 to 2010, respectively. The model testing results are shown in Fig. 7-14. It is evident that the simulated values of variables are closer to the real values from 2005 to 2010. This suggests the reasonability of the model. The simulated values of variables have the low relative errors of ±10% against the real values from 2005 to 2010. This indicates the validity of the model.

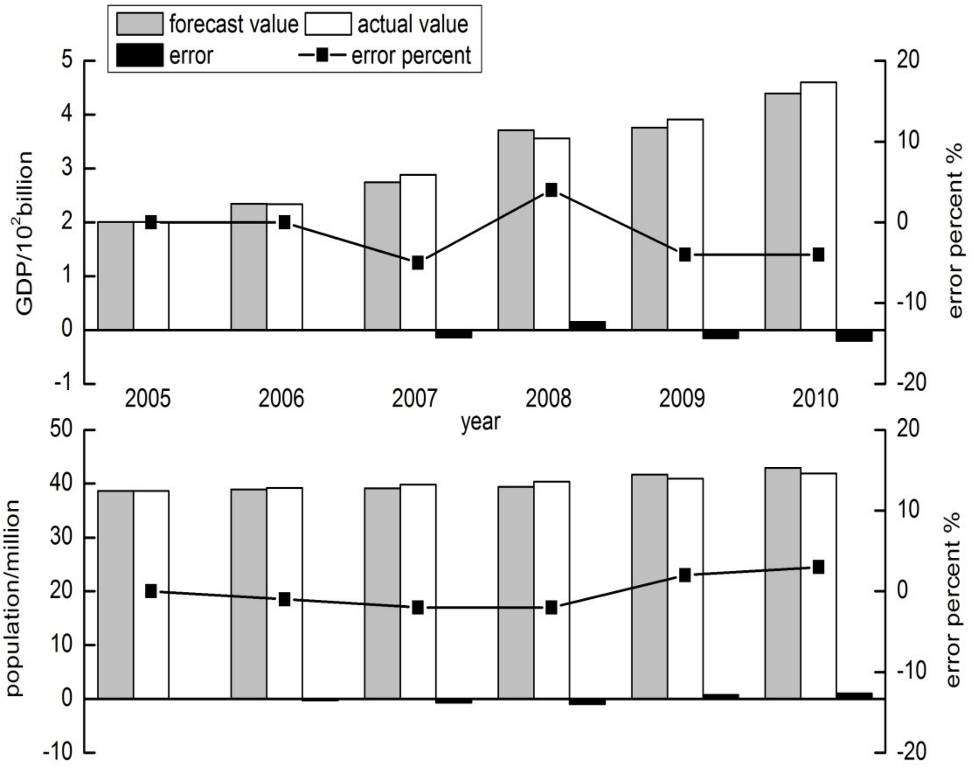


Fig. 7-14 The error statistics of model GDP and total population simulation results

Table 7-1 lists the relative error between the actual and simulation values of GDP, total population, agricultural water consumption, industrial water consumption, and domestic water consumption. When using system dynamics model to simulate economic data, if the error rate between the true and simulation values is in the interval -10% to 10%, the results should be strong. As shown in Table 7-1, all of the relative errors for all of the variables were less than 10% with only one exception GDP. The reason is that this paper establishes the system dynamics of WSS, mainly focusing on water resources system variables rather than economic system variables. Therefore, when establishing the feedback loop of the economic system, only the effects of water scarcity, water pollution and water disaster on GDP are considered, and the influence of other factors on GDP is ignored. The relative error of GDP between the simulation results and the actual values were large. Compared with another research case with system dynamics model [13, 15, 16], the model still meets the requirements of model accuracy and can be used for further analysis.

Table 7-1 Relative error between the true and simulation values

		GDP	Total population	Agricultural Water Consumption	Domestic Water Consumption	Industrial Water Consumption
1995	Actual value	54490	1.27768	585	65.8	540.5
	Simulation value	54490	1.27768	585	65.8	540.5
	Relative error	0	0	0	0	0
1996	Actual value	48340	1.258	590	63.6	541
	Simulation value	54551.4	1.27797	588	64.1	543.5
	Relative error	12.85	1.59	-0.34	0.79	0.46
1997	Actual value	46150	1.261	588	64.8	552.9
	Simulation value	54610.9	1.27823	581	66.4	546.4
	Relative error	18.33	1.37	-1.19	2.47	-1.18
1998	Actual value	44330	1.264	587	64.2	549.6
	Simulation value	54668.8	1.27848	578	66.2	545.4
	Relative error	23.32	1.15	-1.53	3.12	-0.76
1999	Actual value	45620	1.266	580	63.7	545.9
	Simulation value	54726.7	1.27872	576	66	542.3
	Relative error	19.96	1.00	-0.69	3.61	-0.66
2000	Actual value	48880	1.269	574	63.7	555.3
	Simulation value	54784.6	1.27895	574	64.3	555.3
	Relative error	12.08	0.78	0.00	0.94	0.00

7.2.3.2 Analysis of sensitivity degree

In order to observe the response of composite index variable of water security, we chose 14 major parameters of water security system. The values of parameters are ranked at 3%, 2%, 1%, -3%, -2%, -1%, respectively. The analysis in Table 7-2 shows that the changing range of water security composite index in 2025 is reasonable less than ± 10%. So, the developed SD model is reliable to elucidate the causal feedback relationship and predict the dynamic change of water security system. We can see from Table 7-2 that the sensitivity slopes of the eight parameters, including the natural population growth rate, GDP growth rate, water quota of farmland irrigation, water quota of woodland and livestock, urban domestic water demand, urbanization level, water and soil loss, the rate soil erosion area, are positive. But the sensitivity slopes of the six parameters including water use efficiency, ratio up to the standard of water quality, the rate of treated industrial wastewater, the rate of treated domestic wastewater, the rate of environment investment and the rate of water resources investment, are negative. Sensitivity slopes were applied to describe how water security composite index was verified with parameters variation. For example, the sensitivity slope of natural growth rate of population was calculated by the two points at (3%, 0.0001) and (–3%, – 0.000072); the sensitivity slopes of GDP Growth Rate were calculated by the two points at (3%, 0.0095) and (–3%, – 0.0094); other parameters are the same. As shown in Table 3, we found that the larger the absolute value of sensitivity slope is, the more sensitive the water security composite index was, that is, the value of water security composite index changed to a larger extent. The positive sensitivity slope will cause the rising of the water security composite index in 2025, while the negative slope will cause the opposite result. The water security composite index reflects the driving force index, pressure index, state index, influence index, and response index. When its value is zero, it means that water security system is balanced. If the composite index value is more than zero, the WSS is unsafe. If the composite index value is less than zero, the WSS is safe. In this case, if we increased or reduced the largest absolute value of sensitivity slopes, we would achieve the goal of reducing water security composite index and make the urban water security comprehensive state more and more secure. Instead, the water security state of the city will become more and more insecure. So, the ways to improve the water security state of the city are summarized as follows: we should reduce agricultural water consumption, urban domestic water demand; at the same time improve the impact factor ratio up to the standard of water quality, the rate of environment investment.

Table 7- 2 The changes of water security composite index under different impact factors in 2025

Parameters	Rate of Change						Sensitivity Slopes
	3%	2%	1%	-1%	-2%	-3%	
Natural growth rate of population	0.000 1	0.000 1	0.000 0	-0.000 0	-0.000 1	-0.000 1	0.002 9
GDP Growth Rate	0.009 5	0.005 3	0.003 1	-0.003 1	-0.006 3	-0.009 4	0.313 7
Water quota of farmland irrigation	0.016 1	0.010 7	0.005 4	-0.005 4	-0.010 7	-0.016 1	0.536 2
Water quota of woodland and livestock	0.001 1	0.000 7	0.000 4	-0.000 4	-0.000 7	-0.001 1	0.036 6
Urban domestic water demand	0.002 8	0.001 8	0.000 9	-0.000 9	-0.001 8	-0.002 8	0.092 1
Urbanization level	0.001 5	0.001 0	0.000 5	-0.000 6	-0.001 0	-0.001 5	0.049 6
Water use efficiency	-0.003 0	-0.001 9	-0.001 0	0.001 0	0.001 9	0.003 0	-0.097 2
Ratio up to the standard of water quality	-0.014 0	-0.009 3	-0.004 7	0.004 7	0.009 3	0.014 0	-0.466 0

Sensitivity analysis also can be expressed in an important equation to verify the validity of the model. A stable and effective model should have low sensitivity. Sensitivity analysis analyzes the effects of parameter changes on the output of model variables by adjusting the parameters in the model. In this study, the sensitivity model is used to analyze the sensitivity of the system. The formula is as follows [17]:

$$S_Q = \left| \frac{\Delta Q_{(t)} X_{(t)}}{Q_{(t)} \Delta X_{(t)}} \right| \tag{7.1}$$

Where S_Q is the sensitivity of stock variable to constant X; $Q_{(t)}$ and $X_{(t)}$ are the values of stock variable Q and constant variable X at time t. $\Delta Q_{(t)}$ and $\Delta X_{(t)}$ are the added values of Q and X at time t.

When there are n stock variables, for the constant X, the average sensitivity is

$$S = \frac{1}{n} \sum_{i=1}^{n} S_{Qi} \tag{7.2}$$

Where S_{Qi} is the sensitivity of stock variable Qi to constant; S is the average sensitivity; n is the number of stock variables.

Because more constant variables are involved in the WSS, only the four constant variables and five stock variables that are more representative in the system are selected. The analysis was based on the data during 1995-2000. In one trial, change one of the constant variables (change by 10%) and analyze its effect on the five stock variables. The sensitivity analysis results are shown in Table 7-3. It can be seen from Table 7-3 that the sensitivity of the environmental investment proportion to the system reaches 6.05%, which is the highest. The sensitivity of all constants to the system is less than 10%, indicating that the system has low sensitivity to constant variables and strong stability.

Table 7-3 Results of sensitivity analysis

Constant Stock	GDP growth rate	Coefficient domestic wastewater effluent	Environmental investment proportion	Rate of population change
Total population	0.00017	0.00009	0.00112	0.00112
GDP	0.00594	0.00002	0.00594	0.00000
Gap between water supply and demand	0.00000	0.00002	0.00015	0.00015
Sewage amount	0.00009	0.26922	0.00027	0.00027
Water risk reserve	0.00153	0.00005	0.29510	0.00000
S	0.00155	0.05387	0.06052	0.00031

7.3 Simulation of water security system in Guizhou province

7.3.1 Description of different scenarios

The purpose of building a system dynamics model is to test a variety of potential policies for improving system performance. For the different planning objectives, many simulative alternatives are attained through adjusting variables and parameters. In Guizhou province, according to the SPA evaluated results in chapter 6, it is accessible to know the water security state of every city. But that is not enough. We also need to illustrate the impact factors of water security and the future dynamic changing tendency of water security indicators. For different developing purposes in the water security system, some simulation scenarios can be assumed through adjusting variables and parameters. In order to represent other water security state of the city, we selected three typical cities (Guiyang city, Zunyi city, Bijie city) to represent Guiyang scenario, Zunyi scenario, and Bijie scenario in Guizhou province based on the actual values of specifically related parameters. The concerted scenario is the optimal combination of the other three scenarios. The parameters values in the concerted scenario are derived from increasing or decreasing ten percent according to the best parameter value in the three scenarios. These scenarios can reflect and predict the system's performance and tendency with the established SD model. The detailed settings of parameters in typical cities scenarios and concerted scenario were compared in Table 7-4.

Table 7-4 Parameter setting of different cities scenarios simulation

Parameters	Developed model			
	Guiyang scenario	Zunyi scenario	Bijie scenario	concerted scenario
Water quota of farmland irrigation (10^8 m^3)	49.34	29.64	35.58	26.676
Urban domestic water demand (m^3)	62.78	32.65	46	29.385
Ratio up to the standard of water quality (%)	87.5	81	69.2	96.25
The rate of environment investment (%)	6.5	4	2.5	7.15
Water and soil loss (%)	32.6	41.7	58.9	29.34
The rate of treated industrial wastewater (%)	97.2	89.5	80.6	99.14

7.3.2 Simulation results of different modes

Water demand stands for the security status of water resources subsystem. From Fig. 7-15 (A), we can get that in Guiyang scenario from 2005 to 2017, the gap of water resources is negative. It means that water supply is lower than water demand and water resources are short. But the gap is small. However, the gap of water resources increases faster and faster since 2017. The gap of water resources will reach 102 hundred million cubic meters by 2025; In Zunyi scenario (Fig. 7-15 (B)) and Bijie scenario (Fig. 7-15 (C)) from 2005 to 2017, the gap of water resources is positive. It says that water supply is higher than water demand and water resources are surplus. But the gap of water resources turns negative and gradually increases since 2020; in Bijie scenario, the gap of water resources becomes negative and increases slowly since 2019; in concerted scenario (Fig.7-15 (D)), we deduce the value of water quota of farmland irrigation and urban domestic water demand by 10%, respectively. The gap of water resources in the concerted scenario is 30% higher than that in Guiyang scenario, 4% higher than that in Zunyi scenario, and 15% higher than that in Bijie scenario by 2025. At the same time, the gap is the lowest in the concerted scenario.

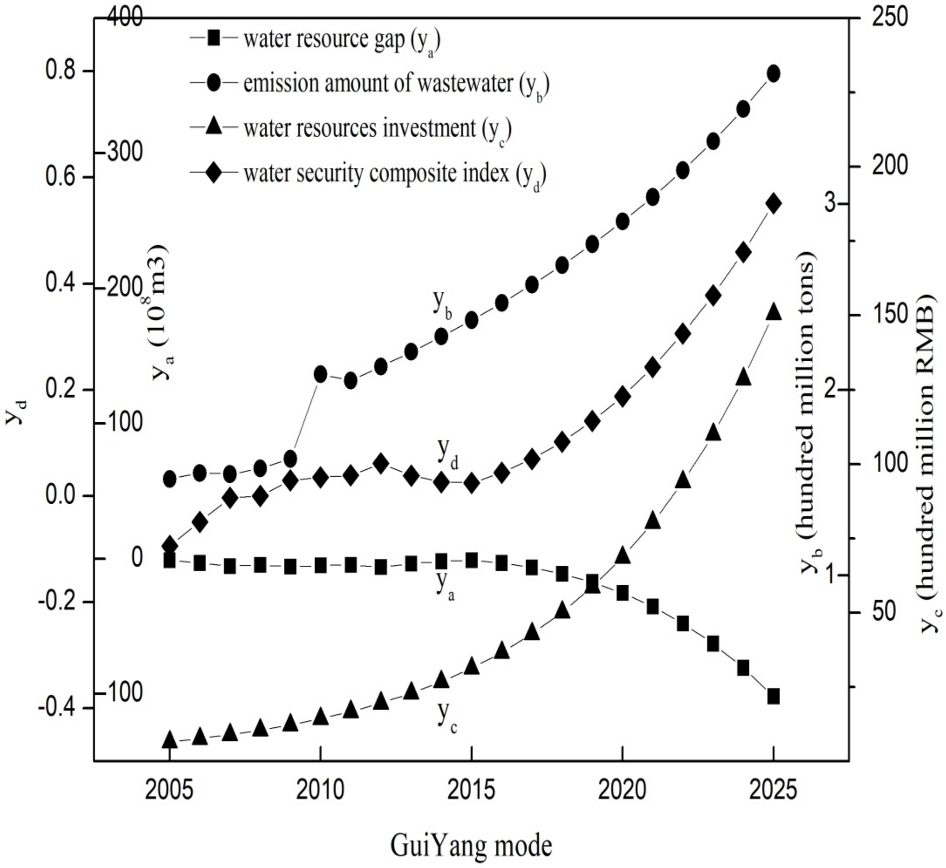
Emission amount of wastewater represents the safety status of water environment subsystem. It can be seen from Fig. 5A; the emission amount of wastewater is increasing gradually starting from 2011. It is the highest increasing amount in Bijie scenario (Fig. 7-15 (C)), which will reach 9.9 hundred million tons by 2025. It is the second amount of wastewater in Zunyi scenario (Fig.7-15 (B)), which will be 6.6 hundred million tons and then the lowest in Guiyang scenario (Fig. 7-15 (A)) may be 3.7 hundred million tons by 2025. Under concerted scenario (Fig. 7-15 (D)), we improve ratio up to the standard of water quality by 2%, the emission amount of wastewater is 3.0 hundred million tons. The amount of wastewater in the concerted scenario is 18.9% lower than that in Guiyang scenario, 54.5% lower than that in Zunyi scenario, and 69.7% lower than that in Bijie scenario by 2025. It conforms to the standard of environment-friendly development pattern.

The investment of water resources conservancy is used to reflect the safety status of water disaster subsystem. The investment all kept at a low level in Guiyang, Zunyi and Bijie scenarios. Starting from 2015, the investment began to increase in all scenarios. In concerted scenario (Fig. 7-15 (D)), the study deduces the value 10% of water and soil loss area and improves the rate 10% of environment investment respectively. The investment of water resources conservancy in the concerted scenario is 10% higher than that in Guiyang scenario, 78.7% higher than that in Zunyi scenario, and 186.2% higher than that in Bijie scenario by 2025.

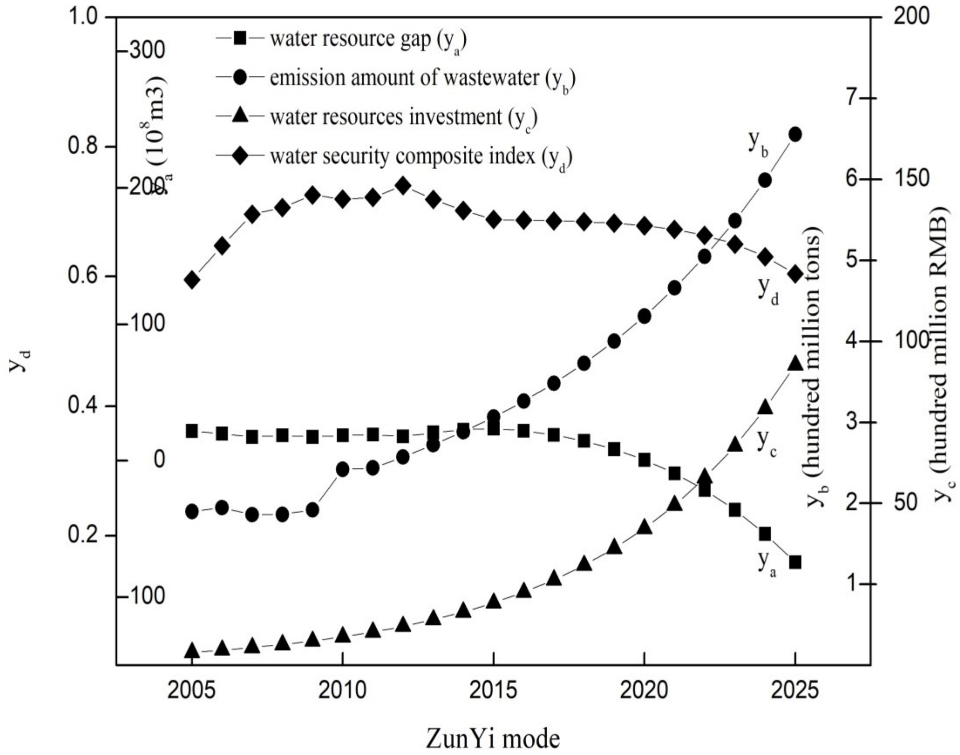
The water security composite index represents the comprehensive safety status of the water security system. It is the feedback relations of water resources subsystems, water environment subsystem, and water disaster subsystem. As mentioned above, the composite index value is more than zero, WSS is unsafe. If the composite index value is less than zero, WSS is safe. We can conclude from Fig. 7-15 (A) that the composite index is less than zero. It means the system is secure in Guiyang scenario from 2005 to 2008. But by 2008, the composite index becomes greater than zero, the system turns insecure. Furthermore, the trend of the composite index value will increase from –0.1 in 2005 to 0.58 in 2025. It implies that the comprehensive safety status will be more and more insecure.

In Fig. 7-15 (B), the composite index value was 0.59 in 2005. It kept increasing till 2012; the value was the largest 0.75. Then the composite index experienced a decline after rising, by 2025 the value will be 0.6. So the level of WSS is lower in Zunyi scenario than that in Guiyang scenario from 2005 to 2025. And the composite index is more than zero and is rising continually during a period of 2005–2025, the value changed from 0.7 to 1.52 (Fig. 7-15 (C)). The level of WSS is the lowest in Bijie scenario than that in previous two scenarios.

Under the concerted scenario, we reduced agricultural water consumption, urban domestic water demand, and improved the impact factor water and soil loss area, ratio up to the standard of water quality and the rate of environment investment by 10% respectively. The composite index value was –0.4 in 2005 and it will be 0.3 in 2025. The composite index in the concerted scenario is 45.5% lower than that in Guiyang scenario, 50% lower than that in Zunyi scenario, and 80.3% lower than that in Bijie scenario by 2025. The composite index is the lowest in four scenarios and the level of WSS is the highest.



A


water resource gap (y_a)
emission amount of wastewater (y_b)
water resources investment (y_c)
water security composite index (y_d)
y_d
y_a (10^8 m3)
y_b (hundred million tons)
y_c (hundred million RMB)
1.0
0.8
0.6
0.4
0.2
300
200
100
0
-100
7
6
5
4
3
2
1
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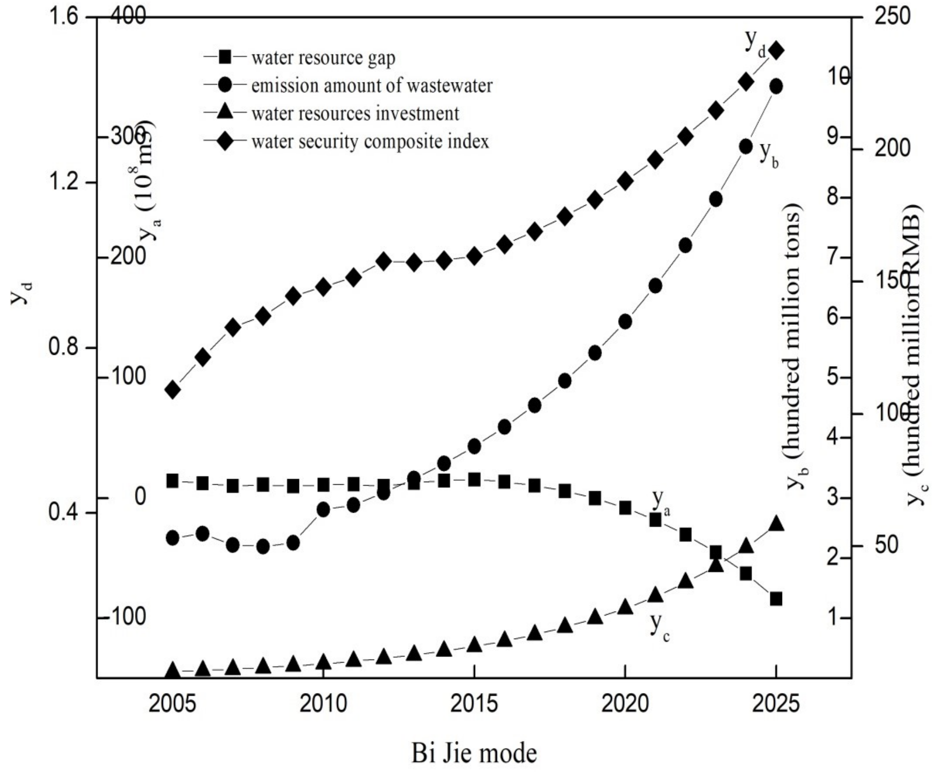
150
100
50
y_b
y_d
y_c
y_a
2005
2010
2015
2020
2025
ZunYi mode

B


water resource gap
emission amount of wastewater
water resources investment
water security composite index
y_d
y_a (10^8 m3)
y_b (hundred million tons)
y_c (hundred million RMB)
1.6
1.2
0.8
0.4
400
300
200
100
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-100
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9
8
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250
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2005
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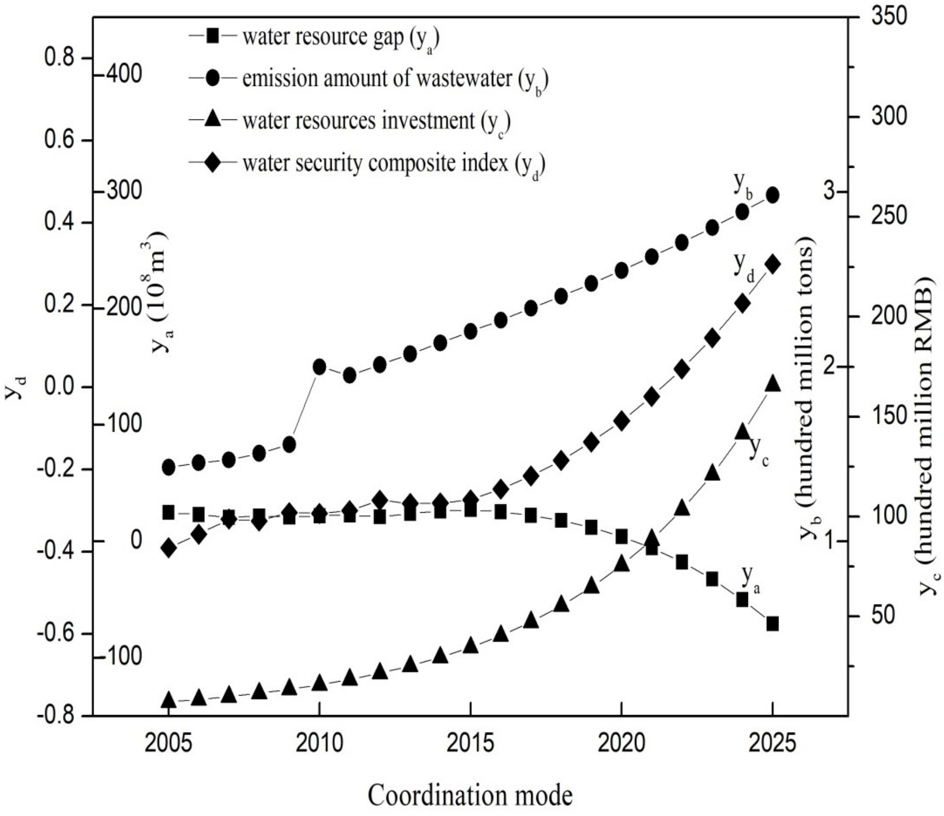
2025
Bi Jie mode

C



D

Fig. 7-15 The changes of water security indexes in different modes: A. Guiyang mode; B. Zunyi mode; C. Bijie mode; D. Coordination mode

7.3.3 Scenario selection

The evolution of driving factors of water resources subsystem is mainly embodied by two aspects: on one hand, there are two constraints including the fragile ecosystem and special karst landform features. Because karst soil rocky desertification is not only a geo-ecological disaster induced by Karst geomorphic but also a critical factor restraining the social and economic development of Southwest China; on the other hand, it is mainly caused by water quota of farmland irrigation and urban domestic water demand. The gap of water resources continues to increase in all scenarios before 2025 and it will keep the evolution trend. Karst depression is the main landscape in Guizhou province. Multi-year average precipitation is 900—1300 mm. Water resources are rich and water resource per capita is 2829 m^3. The water resource per capita in Guizhou is 1.26 times larger than it in the nation. But high mountains and low rivers are distributed in these regions, the difference of elevation between plateau surface and river is so great and the value is 200-800 m. It is hard to pump surface water to the plateau and economic benefit is poor. The driving factor of water environment subsystem is mainly caused by the factor of ratio up to the standard of water quality. The emission of wastewater will continue to increase and the trend will not change in recent years before 2025 in Guiyang, Zunyi and Bijie scenarios. In the scenario of coordination, the emission of industrial wastewater reduces significantly when the factor of ratio up to the standard of water quality only improves by 2%. Some evidence suggests that the rate of treated industrial wastewater will be increased to 85% by 2020 in Bijie city, the emission of wastewater will reduce, and the ecological environment will be better and better. The evolution driving factors of the water disaster subsystem are mainly controlled by two reasons: one is that the precipitation is abnormal caused by climate change and extreme high temperature. The extremely weather also leads to flooding occurring frequently. Research has shown that flood disaster increased as precipitation decreased; another reason is that some adaptation countermeasures about water disasters caused by climate change are insufficient and water conservancy investment is also lacking. Water is one of the most sensitive sectors to climate change and it is significant to evaluate impacts of climate change on the water resource. The evolution of water disaster subsystem is uncertain, but with the protection of water conservancy facilities, the occurrence of water disaster will reduce.

Guiyang city is the center of politics, economy, and culture in Guizhou province. The level of social and economic development in Guiyang city is at the front rank of Guizhou. Based on the characteristics analysis of the water security system above, the adjustment strategies of Guiyang city are that: the most important of all is to improve the security level of water resources subsystem, followed by the focus on the water environment subsystem and water disaster subsystem. The government should put forward to a reasonable plan for water engineering. We suggest the inter-basin water transfers because it is an effective manner that can settle the uneven distribution of regional water resources to achieve the district-optimal allocation of water resources. In order to increase underground water storage capacity, the underground river and groundwater observation posts are suggested to be developed. These strategies match well with the proposed twelfth five-year water conservancy planning of Guizhou province about Guiyang city.

Zunyi city is located in the main area of the Yangtze River shelter-forest comprehensive development zone and it is one of the important towns in western China. Based on the characteristics analysis of the water security system above, the adjustment strategies of Zunyi city are that: it is urgent to strengthen the security level of water environment and water disaster subsystems. The proposal is that the investment funds of water conservancy facilities should be improved and the awareness of flood and drought control should be raised. These strategies are also in good agreement with the proposed twelfth five-year water conservancy planning of Guizhou province about Zunyi city.

Bijie has accelerated development since 1989 as the experimental area of “poverty relief and ecological construction”. But the economic development also caused the serious water pollution. Based on the characteristics analysis of the water security system above, the adjustment strategies of Bijie city are as follows: management measures should be strengthened in all aspects of the water security system. Especially, the ecological environment and water environment should be improved at the same time. Secondly, it needs to guarantee the water requirement of industrialization and urbanization. Thirdly, in order to harness the small and medium-sized rivers, local government should protect wetland ecological system as could as possible. These were also put forward in the twelfth five-year water conservancy planning of Guizhou province about Bijie city.

Coordination scenario is the optimal combination of water resources subsystem, water environment subsystem, and water disaster subsystem. Another scenario may refer to the coordination scenario for deliberate adjustment and control in order to achieve the best water security level.

7.4 Simulation of water security system in Japan

7.4.1 Description of different scenarios

Based on the above SPA evaluation, we have obtained that the current situation of water resource subsystem and water environment subsystem is in good condition, while the water disaster subsystem is in poor condition. In order to realize the balanced development of WSS and understand the interaction between the subsystems, we developed different priority models: water resources priority model A, water environment leading model B, water disasters leading model C, and balanced development model D. The corresponding parameters of these different models have been adjusted based on the base model (See Table 7-5).

Table 7-5 Comparison of the models

Parameter	Base model	Model A	Model B	Model C	Model D
Utilization rate of water resources	Constant	Raise by 10%	Constant	Constant	Raise by 10%
Treatment rate of sewage	Constant	Constant	Raise by 10%	Constant	Raise by 10%
Coefficient of industrial wastewater effluent	Constant	Constant	Drop by 10%	Constant	Drop by 10%
Coefficient of domestic wastewater effluent	Constant	Constant	Drop by 10%	Constant	Drop by 10%
The environmental investment proportion	Constant	Constant	Constant	Raise by 10%	Raise by 10%
Water risk prevention investment proportion	Constant	Constant	Constant	Raise by 10%	Raise by 10%

7.4.2 Simulation results of different modes

Table 7-6 shows that when the utilization rate of water resources improves 10% in model A, the gap between water supply and demand is reduced by 62.01%. Meanwhile, the water scarcity factor is reduced by 57.86%. In other words, compared with the base model, model A decreases by 15.22% and 16.86% in the reduction of the gap between water supply and demand and the water scarcity factor, respectively. It is an obvious promoted effect of improving water use efficiency to maintain water balance and water sustainable use. In terms of model B, we focus on the water environment subsystem. Compared with the base model, the treatment rate of sewage is raised by 10% and the coefficient of industrial wastewater effluent and domestic wastewater effluent are all dropped by 10%, which causes the sewage amount and water pollution factor to drop significantly. Therefore, it is implied that the two-pronged approach can effectively control water pollution by controlling the discharge of sewage sources and increasing the treatment capacity of sewage. Concerning model C, water disaster subsystem is dominate. The environmental investment proportion and water risk prevention investment proportion all improve 10% than the base model. However, compared to the base model, the water damage factor of model C is not dropped and the water risk reserve of model C increases by 8.63%. This finding means that although model C guarantees the growth rate of environmental investment and enlarges water risk prevention investment, it cannot solve the water damage issue. This also reveals that it is not enough to reduce the water disasters losses only by strengthening the investment in prevention. It is well known that there are some direct measures to avoid flood damage such as strengthening the construction of dikes and reservoirs, and river regulation. It can also minimize flood losses based on scientific predicting of flood and rational planning of flood detention areas. At last, it is the last measure to mitigate flood losses to establish an emergency response system for flood prevention and rescue. While from the perspective of fundamental problem solving, it is important to reduce the possibility of flood disasters. The long-term implementation of soil and water conservation can fundamentally reduce the chance of flood.

As we all know, Japan’s population has experienced negative growth in recent years. The reasons for the negative growth of the population are complex. In the paper, we found that the water disaster subsystem has the most significant impact on the population according to the analysis of water security subsystems. Compared with the base model, except model D, the growth rate of population in model C is the greatest (about 0.45%), whereas it is the lowest in model A (about 0.39%). It implies that the water damage factor has a larger effect on the population than the water scarcity factor and water pollution factor in Japan. Again, this effect is also found in the economic subsystem. The growth rate of GDP in model C is the greatest (about 2.77%) and it is the lowest in model A (about 2.42%). Therefore, water damage factor plays a critical role in the WSS of Japan. It is consistent with the evaluation results of the SPA model above, that is, the current situation of water disasters subsystem is severe in Japan than the water resources and water environment subsystems.

Model D integrates all the advantages of models A, B, and C. Total population growth rate and GDP growth rate are different in Models A, B, C, and D. Of these models, the growth rate in model D is the greatest, followed by that in model C, model B, and model A, which means the balanced scenario has the most efficient effect on economy and population, followed by the water disaster dominated scenario, the water environment leading scenario, and finally the water resources prioritized scenario. Meanwhile, the growth rate of the gap between water supply and demand is hardly influenced by models B and C, meaning that the gap between water supply and demand is mainly affected by utilization rate of water resources. Table 7-6 also shows that the models A and C have few significant differences in the growth rate of sewage amount, indicating that the treatment rate of sewage, the coefficient of industrial wastewater effluent, and the coefficient of domestic wastewater effluent are the main drivers.

Table7-6 Simulation values and the growth rate of the subsystems in all models

Subsystem	Variable	Year	Base model	Model A	Model B	Model C	Model D
Water resources subsystem	Gap between water supply and demand (10^8m^3)	1995	-522.955	-522.955	-522.955	-522.955	-522.955
		2015	181.176	305.47	181.158	181.137	305.404
		2025	-278.283	-198.676	-278.306	-278.33	-198.753
		Growth rate (%)	-46.79	-62.01	-46.78	-46.78	-61.99
	Water scarcity factor	1995	0.439	0.439	0.439	0.439	0.439
		2015	0.171	0.288	0.171	0.171	0.288
		2025	0.259	0.185	0.259	0.259	0.185
		Growth rate (%)	-41.00	-57.86	-41.00	-41.00	-57.86
Water environment subsystem	Sewage amount (10^8m^3)	1995	11.792	11.792	11.792	11.792	11.792
		2015	10.246	10.246	0.576	10.248	0.577
		2025	10.495	10.496	0.59	10.497	0.591
		Growth rate (%)	-11.00	-10.99	-95.00	-10.98	-94.99
	Water pollution factor	1995	0.096	0.096	0.096	0.096	0.096
		2015	0.1	0.096	0.006	0.095	0.006
		2025	0.1	0.1	0.006	0.1	0.006
		Growth rate (%)	4.17	4.17	-93.75	4.17	-93.75
Water disasters subsystem	Water risk reserve (10^8 USD)	1995	-1380.25	-1380.25	-1380.25	-1380.25	-1380.25
		2015	-2564.73	-2563.9	-2564.72	-2446.75	-2443.91
		2025	-4140.85	-4140.12	-4139.6	-4021.78	-4018.73
		Growth rate (%)	200.01	199.95	199.92	191.38	191.16
	Water damage factor	1995	0.719	0.719	0.719	0.719	0.719
		2015	0.824	0.823	0.823	0.786	0.785
		2025	0.882	0.882	0.882	0.857	0.856
		Growth rate (%)	22.67	22.67	22.67	19.19	19.05
Population	Total Population (10^8 people)	1995	1.2777	1.2777	1.2777	1.2777	1.2777
		2015	1.2816	1.2819	1.2819	1.2824	1.2833
		2025	1.2824	1.2827	1.2829	1.2834	1.2844
		Growth rate (%)	0.37	0.39	0.41	0.45	0.52
Economy	GDP (10^8 USD)	1995	54490	54490	54490	54490	54490
		2015	55500	55583.3	55602.5	55716.6	55953.8
		2025	55732.2	55806.2	55858.9	56000	56254.6
		Growth rate (%)	2.28	2.42	2.51	2.77	3.24

7.4.3 Scenario selection

From the national scale of Japan, the water disaster subsystem has a close relationship with the population and the economy subsystems, suggesting that exploring more advanced emergency response technologies of water hazards, seeking ways to prevent or minimize economic losses caused by water hazards is important. In addition, the countermeasures for water damage cannot be carried out in isolation. Public participation is equally important. Water damage education, supervision, and publicity of property loss should be carried out to improve water protection by the public. Water resources subsystem policy should broaden the utilization of water resources: Although controlling demand can relieve pressure on water resources temporarily, this study showed that improving the utilization of water resources is the key to ensure water resources balance. As the supply of water resources may reduce in the future due to climate change, it is urgent to amend the policy of water supply, to change the water use style, and to enhance the water-use efficiency. The balanced scenario is the optimal integration of water resources subsystem, water environment subsystem, and water disaster subsystem. Other scenarios only pay attention to certain one aspect. For the water security system of Japan, comprehensive control is necessary to achieve optimal condition.

7.5 Summary

In this chapter, According to theory and methodology of system dynamics, this study discusses the programming of economy - water - society, and develops an SD model by which several typical scenarios are proposed for comparative analysis. The optimal measurement is suggested in excellent coincidence with sustainable development of water security in Guizhou and Japan. The results show that:

(1) Based on the simulation of SD model, we found that current three scenarios of the water security in Guizhou exist in various degrees of impairment. Guiyang scenario mainly manifests in the aspect of water supply and demand; Zunyi scenario is embodied in the aspect of water environment and water disaster subsystems; Bijie scenario is showing the crisis in all subsystems. In order to efficiently improve the WSS, the main factor that influences water security composite index was researched.

(2) According to sensitivity analysis, in Guizhou province, water quota of farmland irrigation, urban domestic water demand, water and soil loss, ratio up to the standard of water quality and the rate of environment investment are the influencing factors of water security system. Thus special attention should be paid to these factors for policy-maker and local regulator. Next, we adjusted the impact factors and set concerted scenario from the administrator perspective. Comparing with other three scenarios, we realize that water supply can meet the needs of social and economic development, and the biggest economic benefits and environmental benefits could be obtained

before 2025 under the concerted scenario. Our results are highly anticipated to help promote the sustainable development of urban water security system of Guizhou province in southwest China.

(3) For Japan, the utilization rate of water resources is the key variable in water resources subsystem. The treatment rate of sewage, the coefficient of industrial wastewater effluent, and coefficient of domestic wastewater effluent are the important variables in water environment subsystem. In the WSS of Japan, the population and economy are most influenced by water disaster subsystem, not water resources and water environment subsystems. Water security problems cannot be solved only through adjustment in one aspect, which must be discarded. It is found that strengthening the comprehensive intervention of the balanced model will contribute to the whole WSS. A balanced model can achieve not only steady water supply and demand, protect the water environment, and mitigate water disasters, but also maximize the benefits for both the economy and population. This study provides a map for water management and achieving water security in the different administrative divisions of Japan.

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Appendix

The main equations of the system dynamics model

No.	Variables	Equations	Unit
1	Total GDP	primary industry + secondary industry + tertiary industry	10^8USD
2	Total Population	INTEG (natural population change, 1.27768)	10^8people
3	natural population change	Total Population*rate of population change*(1-Water pollution factor)*(1-Water scarcity factor)*(1-Water damage factor)	10^8people
4	Total water resources	3.36*precipitation-1521.43 R^2=0.62	10^8m^3
5	Water demand	Agricultural Water Consumption + Domestic Water Consumption + Industrial Water Consumption	10^8m^3
6	Agricultural Water Consumption	Paddy field irrigation water + Animal husbandry water + Upland field irrigation water	10^8m^3
7	Domestic Water Consumption	Total Population*domestic water consumption per capita	10^8m^3
8	Animal husbandry water	WITH LOOKUP (Time, ([(1995,0) (2050,10),(1995,5),(2000,5),(2005,5),(2010,4),(2014,4)],(1995 ,5),(2000,5),(2005,5),(2010,4),(2015,4),(2020,3.5)))	10^8m^3
9	Water scarcity factor	ABS(Gap between water supply and demand/Water demand)	Dmnl
10	quantity of domestic wastewater effluent	Domestic Water Consumption*coefficient of domestic wastewater effluent	10^8m^3
11	quantity of industrial wastewater effluent	Industrial Water Consumption*coefficient of industrial wastewater effluent	10^8m^3
12	Sewage treatment capacity	The quantity of Wastewater effluent*Treatment rate of sewage	10^8m^3
13	The quantity of Wastewater effluent	quantity of domestic wastewater effluent + quantity of industrial wastewater effluent	10^8m^3
14	Water risk prevention investment	Environmental Investment*Water risk prevention Investment proportion	10^8USD
15	Water pollution factor	pollution ratio + wastewater quantity ratio	Dmnl
16	Environmental Investment	GDP*the ratio of Environmental Investment in GDP	10^8USD
17	Water disasters losses	average water losses per flood event*The flood events	10^8USD
18	Water damage factor	ABS(Water risk reserve/Water disasters losses)	Dmnl
19	Pollution ratio	Max (TP index, TN index, COD index)	Dmnl
20	TP index	IF THEN ELSE (TP effluent concentration>16{1} {0})	Dmnl
21	TP effluent concentration	WITH LOOKUP (Time, ([(0,0)-(3000,20)],(1996,9.8),(1999,11.2),(2002,17.6),(2008,14),(2011,18.3),(2015,10.8),(2020,12)))	Mg/l

Chapter 8

CONCLUSIONS

Water security has emerged as a major framing template in environmental governance and resource management. The term and underlying concepts have attracted the attention of governmental and nongovernmental organizations, private industry, and the academy in policy and practice. Water security is considered as a concept that content is constantly enriched and evolved. The different requirements for water security depend on the secure development stages. The satisfied standard changes from the requirements for basic water quantity and quality to the requirements for health and recreation, which reflects the process of continuous improvement.

Regardless of how the concept of water security changing, the most basic security contents are constant. That is, water resources security, water environment security and water disaster security. However, most of the research only focuses on one aspect of security. There are few integrated studies. As the content of water security issues becomes more and more complex, and new water security issues continue to emerge, integration research is an inevitable trend. Therefore, after analyzing water resources security, water environment security and water disaster security, we have made a comprehensive simulation analysis of water security.

This thesis focuses on assessment and simulation of water security in terms of water resources, water environment and water disaster with the methodologies of ecological footprint model and system dynamics model and combines the three aspects scientifically and rationally for evaluating the complex water issues and contributing water management. On efficient basis of the investigation and theory analysis towards the present conditions, the application researches on several typical water security scenarios are executed.

The main works and results can be summarized as follows:

In chapter one, BACKGROUND AND PURPOSE, presents the multiple interpretations of water security, then it reviews and contrasts the development backgrounds and properties of three water management approaches, which are as methods to achieve water security, finally illustrates the motivation and purpose of this research.

In chapter two, MOTIVATION AND METHODOLOGY, firstly, the concepts and approaches for evaluation of water resources security, water environment security, and water disaster security is introduced respectively. Then the method for integrated assessment of water security is described. Finally, the scenarios simulation of water security is illustrated with system dynamics approach.

In chapter three, DYNAMIC ASSESSMENT AND FORECAST OF WATER RESOURCES SECURITY, based on the water ecological footprint model, the total water ecological footprint and water ecological capacity, the water ecological footprint per capital and the water ecological capacity per capital for Beijing, Shanghai, Tianjin, and Chongqing in 2004-2015 were analyzed, respectively. It gives us a holistic implication about the water utilization in different types of cities according to analyze the driving factors of the water ecological footprint and water ecological capacity.

In chapter four, SPATIO-TEMPORAL CHARACTERISTICS OF WATER RESOURCES SECURITY AND WATER ENVIRONMENT SECURITY, the chapter is arranged as follows: Firstly, the water ecological capacity of the whole Japan and different regional divisions were quantified and calculated respectively, with a yield factor and balance factor from the water supply side. Secondly, the water ecological footprint was analyzed from the temporal and spatial perspectives in Japan. And the characteristics of water ecological footprint in Japan were drawn from the water demand side. Then, the water sustainability indicators were applied to assess water sustainability and water efficiency. Finally, the countermeasures for water sustainability and policy implications were proposed.

In chapter five, ASSESSMENT OF WATER DISASTER SECURITY AND IDENTIFICATION OF ADAPTATION STRATEGIES, in this chapter, based on the concept of vulnerability and fuzzy synthetic evaluation method (FSE), Firstly, a vulnerability assessment framework of sponge city is proposed, which includes establishment of index system, assessment of exposure, sensitivity, adaptive capacity and comprehensive vulnerability. Secondly, geographical information system (GIS) is applied to reflect the spatial distribution relation between precipitation condition and urban vulnerability. Then, according to the analysis of relation between precipitation condition and vulnerability, the sponge cities are divided into 4 different categories. Finally, the appropriate and sustainable strategies are presented for different categories sponge cities.

In chapter six, INTEGRATED ASSESSMENT AND COMPARISON OF WATER SECURITY, An integrated and acceptable methodology is desired to maintain the sustainability of water security. First, we used “PSR” framework to establish integrated indicators from water resources, water environment, and water disaster. Second, we develop an integrated evaluation model-SPA to do a comparison study between Guizhou province in China and Japan.

In chapter seven, SCENARIOS SIMULATION AND COMPARISON OF WATER SECURITY SYSTEM, in this chapter, According to theory and methodology of system dynamics, this study discusses the programming of economy - water - society, and develops an SD model by which several typical scenarios are proposed for comparative analysis. The optimal measurement is suggested in excellent coincidence with sustainable development of water security in Guizhou province and Japan.

In chapter eight, CONCLUSIONS have been presented.