

Rainwater Management at River Basin Level: A Case Study in Nansihu River Basin, China

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Abstract

Global climate change and rapid urbanization have altered natural hydrological processes, causing cities to face increasingly severe water-related challenges, including flooding, water scarcity, water quality degradation, and the deterioration of water bodies into black and odorous environments. Urban flooding has become a widespread problem in China: approximately 12% of Chinese cities experience minor flooding, while 50% experience severe flooding. However, many rainwater management projects focus primarily on protecting individual cities or smaller urban areas. Rather than addressing the underlying water-related problems caused by urbanization, these interventions often transfer them downstream or to adjacent watersheds. In this study, we use the term "rainwater management" to refer to the management of urban stormwater runoff.

To address the limitations of previous studies, this research proposes a watershed-scale approach to rainwater management that accounts for the effects of urbanization on hydrological processes, ecosystem services, and water security. The Nansihu River Basin (NRB), a rapidly urbanizing watershed in China, was selected as the case study area.

The study combined land-use change analysis, hydrological time-series analysis, hydrological assessment methods, and a spatially explicit water security assessment.

The results revealed increasing levels of population urbanization, continued urban expansion, a restructuring of the economy toward the secondary and tertiary sectors, and the progressive conversion of cropland into impervious surfaces, collectively indicating rapid urbanization in the NRB. Precipitation showed an overall increasing trend, whereas surface runoff and evaporation decreased. All three hydrological variables exhibited periodic fluctuations at multiple temporal scales and pronounced intra-annual variability. A comparison of urban and non-urban areas further demonstrated that precipitation during the flood season was generally higher in urban areas. This finding suggests that urbanization influenced local precipitation patterns and contributed to the development of an urban rainfall-island effect.

The ecosystem service assessment showed that water yield, carbon storage, and habitat quality all declined between 2000 and 2022. These declines were primarily associated with the conversion of natural land into built-up and other intensively used land during urbanization. The water security assessment identified priority water-source protection zones and areas of relatively high flood-inundation risk around Nansihu Lake. Water quality also remained a significant concern, with only approximately 20% of the monitoring stations classified as having good water quality.

Based on these findings, a watershed-scale rainwater management plan was developed for the NRB to restore the fundamental functions of the natural hydrological cycle. The proposed strategy integrates floodwater storage functions throughout the watershed, promotes decentralized small-scale facilities, protects rivers, forests, and other ecologically sensitive areas, and advances the separation of rainwater and wastewater systems to facilitate the restoration of natural hydrological processes. Furthermore, a watershed management authority operating across administrative boundaries should be established to coordinate water resources management, aquatic environmental protection, and rainwater management throughout the basin.

This study shifts rainwater management from a site-specific, city-centered, and drainage-oriented perspective toward a watershed-scale approach that treats the watershed as an interconnected hydrological and ecological functional unit. It provides a transferable framework for rainwater management in small- and medium-sized watersheds undergoing rapid urbanization, while allowing management strategies to be adapted to local environmental and socioeconomic conditions.

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List of abbreviations

BMPs	Best Stormwater Management Practices
CA	Cellular Automata
C _d	Concentration Period
CO ₂	Carbon Dioxide
COD _{Mn}	Chemical Oxygen Demand
CPI	Comprehensive Pollution Index
C _r	Regulation Coefficient
C _v	Variation Coefficient
D	Concentration Degree
DEM	Digital Elevation Model
GB3838-2002	Chinese Environmental Quality Standards for Surface Water GB3838-2002
GDP	Gross Domestic Product
GIS	Geographic Information System
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
LID	Low Impact Development
LULC	Land Use and Land Cover
MK	Mann-Kendall
NH ₃ -N	Ammonia Nitrogen
NRB	Nansihu River Basin
PAWC	Plant Available Water Content
RBMP	River Basin Management Plan
RRLD	Root Restricting Layer Depth
SCS-CN	Soil Conservation Service Curve Number
SNWT	South-To-North Water Transfer
SPI	Single Pollution Index
TN	Total Nitrogen
TP	Total Phosphorus
UNESCO	The United Nations Educational, Scientific and Cultural Organization

1 Introduction

1.1 Background

With global climate change and rapid urbanization, the natural hydrological cycle process has been changed, and cities are facing increasingly prominent water problems such as flooding, water scarcity, black odorous water bodies, and ecosystem degradation (Allan et al., 2020; Kundzewicz, 2008). Urban flooding causes huge socio-economic losses (Allaire, 2018). Limited urban land use, over-expansion of building scale, excessive hard paving and many other problems have resulted in hardening of urban surface (Atharinafi & Wijaya, 2021), and there is no place to discharge the rainwater that should have infiltrated into the ground, which increases surface runoff. This leads to an increase in the peak flow rate when heavy rain pours into the city, and the probability of waterlogging is greatly increased.

The development of China's urban drainage systems has not kept pace with the urbanization. Many urban drainage systems suffer from insufficient long-term investment, unreasonable drainage channel and pipe network design, and inadequately planned drainage infrastructure. A lack of foresight has resulted in undersized systems, delayed maintenance and management, and numerous other problems (Xia et al., 2017), but also led to the frequent occurrence of floods, the life of urban residents and personal safety has caused great impact (J. Wu et al., 2018). With socio-economic development, urban development is facing the trend of urban regionalization and regional urbanization, and the hydrological effects of urbanization and urban water safety problems will be more prominent at the level of the whole region (or river basin) (Du et al., 2012; Shukla & Gedam, 2018).

Urbanization is a process with strong externalities, and hydrological effects are one of the manifestations of those externalities. The root cause of the water problems caused by urbanization is that the disturbance of the hydrological cycle exceeds the natural capacity (Milly & Dunne, 1994; D. Yang et al., 2021), and its fundamental solution must be placed in the watershed where it is located, starting from the perspective of compensation and restoration of the hydroecology of the watershed, so as to ensure that the watershed where it is located in the hydrological cycle is smooth (Booth & Loheide II, 2012; Palmer et al., 2008).

Consequently, research on the hydrological effects of urbanization at larger spatial scales has become increasingly important, with watersheds widely regarded as the most appropriate units for hydrological analysis (Arora & Boer, 2001; Christensen et al., 2004; H. Li et al., 2017). However, most of the current research on urbanized water problems is on cities, solving problems from the perspective of cities themselves. The solution measures are mainly reflected in the construction of three major projects. That is, water supply projects (including new and expanded water storage and diversion projects within the city, urban water supply projects within the watershed and water conservation projects, etc.), water environment purification projects (including accelerating the construction of water treatment projects, improving purification equipment, etc.), disaster prevention and mitigation projects (including the expansion of urban watersheds, green space, increasing the laying of infrastructure such as drainage pipe networks and improving drainage methods, etc.). And most of these projects took

the city as an isolated point in the watershed, considering the interests of individual cities rather than the basic function of maintaining the hydrological cycle system of the watershed.

In order to meet the water supply, cities had to seriously over-exploit groundwater or built longer and longer distance water supply projects (Foster et al., 2020), asking for water underground, upstream or across the watershed. And downstream towns had to suffer from water shortages and sewage from upstream (Adel, 2001; O'Driscoll et al., 2010), and the overall water environment of the watershed was getting worse (Yoon et al., 2015). To drain water quickly, cities had constructed increasingly large drainage networks but had had to tolerate increasingly heavy flooding and pollution (Sohn et al., 2020; J. Yang et al., 2024). Various engineering measures in the face of the continuous expansion of the city will always be stretched too thin, forming a "city expansion - engineering construction extension-reexpansion" the vicious circle of escalation. A number of urban engineering measures to improve water problems, especially water supply and drainage projects, did not fundamentally solve the water problems caused by urban development, but transferred the problem to the upstream and downstream of the watershed or even other watersheds (McDonald et al., 2014a; Zevenbergen et al., 2010). If we can't improve this kind of transferring mode of solving urban water problems in time, when the pressure on the watershed is getting heavier and the carrying capacity is getting weaker, the whole watershed system will face extreme deterioration or even collapse of hydrological environment.

Therefore, addressing urban rainwater problems requires coordinated management of engineered and natural hydrological systems. Rather than focusing on individual cities in isolation, the various components of urban hydrological systems need to be integrated into the natural hydrological processes of the watershed, with consideration given to both runoff regulation and pollutant reduction. If river systems become overburdened and hydrological connectivity is impaired, their capacity to provide water resources and ecological services necessary for sustainable urban development will be significantly reduced. Maintaining the hydrological and ecological functions of watersheds is therefore essential for addressing urban water problems at their source and ensuring long-term water security. Consequently, watershed-oriented urban rainwater management has emerged as an increasingly important research and planning topic.

This research advocates a watershed-scale approach to urban rainwater management based on the interactions between urbanization and watershed hydrological processes. Under the combined influence of climatic and environmental changes, rapid urban expansion increasingly results in water-related problems that often extend beyond city boundaries. Consequently, effective rainwater management requires addressing the conflicts for restoring watershed hydrological functions and promoting sustainable urbanization.

Given the rapid development of small and medium-sized cities in eastern China, the Nansihu River Basin (NRB) provides a representative case for investigating the impacts of urbanization on hydrological processes, hydroecology, and water security. The study of the NRB can improve understanding of watershed-scale rainwater management under the changing environmental conditions and provide scientific support for spatial planning, sustainable urban development, ecological restoration, water ecosystem protection, and water resource allocation.

1.2 Research objectives and research questions

1.2.1 Research objectives

The primary goal of this research is to evaluate the impacts of urbanization on hydrological processes, the hydroecology, and water security functions at the watershed scale. Based on these assessments, a watershed level rainwater management framework is proposed to mitigate storm and flood disasters and support the sustainable development of the watershed.

To achieve the purpose, the specific objectives of the research are as follows.

- (1) To develop a watershed-scale rainwater management framework that addresses the limitations of conventional city-centered stormwater management approaches and promote integrated watershed management.
- (2) To characterize the level of urbanization within the watershed and assess its impacts on watershed hydrological processes.
- (3) To assess watershed hydroecological and water security functions to understand ecological conditions and water-related risks.
- (4) To formulate a watershed-scale rainwater management plan for the study area based on the integrated assessments of urbanization, hydrological processes, hydroecological functions, and water security.

1.2.2 Research questions

The primary objective of this research is to explore rainwater management at the watershed level, and it aims to address the following five research questions.

- (1) Why should the hydrological effects of urbanization be addressed with integrated watershed management?
- (2) Which key indicators should be used to assess the level of urbanization? How can these indicators be used to characterize the mechanisms through which urbanization affects hydrological processes at the watershed scale?
- (3) Which methods should be used to assess the characteristics of hydrological-cycle components, and which temporal and spatial scales should be considered?
- (4) Which indicators can be used to characterize hydroecological functions at the watershed scale? When models are used to assess ecosystem services, how should their parameters be selected and adjusted to ensure the accuracy and applicability of the model outputs?
- (5) How should water security be assessed, and which indicators should be considered?

1.3 Organization of the dissertation

This research contains six chapters.

Chapter 1 is an introduction, which introduces the background of the research, presents the research questions and organizes the logical framework of the research.

Chapter 2 is the theoretical foundation. It involves the theoretical foundations related to hydrological effects of urbanization and rainwater management, as well as hydroecology and water security. The related approaches, along with their advantages and limitations, are presented.

Chapter 3 is an overview of the study area. In this chapter, basic physical geography and socioeconomics of the study area, Nansihu River Basin, China, are introduced. It also analyzes the current research status and problems in rainwater management in Nansihu River Basin, China. In addition, it also involves the introduction of the database, including the data items used in this research, types and sources, description of the use and basic processing.

Chapter 4 describes the methodology used in this research, which consists of five sections that correspond to the results in Chapter 5. The first section explored rainwater management strategies at the watershed level, differing from urban or smaller scale rainwater management, exploring the holistic nature of watersheds as well as presenting principles and ideas for watershed rainwater management design. The next four sections all address the methods used for the research and analysis needed for rainwater management strategies at the watershed level. The second section is about assessing the level of urbanization. Three indicators, namely, population change, LULC change and economic structure, were selected, which can effectively and comprehensively assess the urbanization level of the watershed.

The third section describes the method used to analyze the characteristics of watershed hydrological cycle elements - precipitation, surface runoff, and evaporation temporally. The cyclical changes were analyzed using the Morlet wavelet function and the trend changes were analyzed using MK. The characteristics of their intra-annual distributions were analyzed by concentration degree (Cd), concentration period (D), and variation coefficient (Cv). Moreover, Urban-rural differences in storm water and characterization of stormwater-surface runoff were also analyzed. Spatially, the spatial distribution characteristics of the hydrological cycle elements were analyzed using the Kriging interpolation method.

The fourth section covers the hydroecological assessment of the watershed, using three indicators - water conservation capacity, carbon storage, and habitat quality. They are assessed using the annual water yield, carbon storage, and habitat quality module of the INVEST model. The fifth section is the water security assessment of the watershed. Three factors were chosen: water source protection, inundation risk and water quality.

Chapter 5 presents the results of the study. This chapter has five sections. The first section assesses the level of urbanization. The second section is to analyze the characteristics of the hydrological cycle elements during the urbanization process. The third and fourth sections are hydroecology and water security analyses. After a comprehensive analysis of the watershed, a rainwater management plan for the watershed is developed.

Chapter 6 summarizes the main conclusions of this research and answers the research questions, limitations of this research, and recommendations for work to be done in the future.

Parts of this dissertation (Section 4.4.1 and 5.3.1) have been published previously in peer-reviewed journals. All such publications are clearly indicated in the relevant chapters.

2 Theoretical backgrounds

2.1 Urbanization and hydrological effects of urbanization

2.1.1 Urbanization

Urbanization responds to the economic, cultural and social changes in human societies and refers to the process of concentration of population (Gu, 2024), economic activities, culture and other social elements from rural to urban areas, resulting in the expansion of the size of cities, an increase in the proportion of the urban population, and the spread of urban lifestyles.

Different international organizations and scholars have their own definitions and understandings of urbanization. The United Nations Human Settlements Programme (UN-Habitat), in its International Guidelines on Urban and Regional Planning, emphasized that urbanization is a process of change in the form and function of the environment in which human beings live and involves aspects of urban and regional planning, land use and infrastructure development. The Food and Agriculture Organization of the United Nations (FAO), in its Guidelines on Defining Rural Areas and Developing Indicators for Development Policies, discusses the application of the degree of urbanization, in particular the methodology for defining cities, towns and rural areas in international comparisons. The Encyclopaedia Britannica defines urbanization as the growing concentration of population in urban areas, reflected in the expansion of cities and the sustained growth of their resident populations. Economist Simon Kuznets (Castells-Quintana, 2018; Kuznets, 1985) defines urbanization as the process of population concentration from rural to urban areas, emphasizing the economic structural changes behind the changes in the distribution of the population structure, while Colin Clark (Rothbarth, 1941) regards urbanization as the process of conversion of the population from the primary to the secondary and tertiary industries, with emphasis on the transformation of the industrial structure.

The Chinese academic community holds different interpretations of the concepts of “urbanization” and “townization”.

(1) Urbanization: Generally, it is defined as the growing concentration of residents in cities, accompanied by economic, social, and cultural transformations resulting from this shift.

(2) Townization: Some scholars argue that it refers specifically to the concentration of rural residents in county-level towns, with particular emphasis on small towns development (H. Feng et al., 2025; Guan & Rowe, 2016).

Since “urbanization” in English covers both cities and towns, “urbanization” can refer to both the migration and aggregation of rural populations into major urban centers and the process of population concentration in small towns. In China, the two have been subdivided into “urbanization” and “townization” to emphasize the difference in their geographic focus. In the 1980s, in the early stage of the Reform and Opening Up, China adopted a development strategy focused on small towns in order to reduce construction costs, due to its weak economic base and abundant land resources. The expansion of township and village enterprises, together with the local absorption of rural labor, promoted a form of “townization” that prioritized small-town development, which is an economically practical path to urbanization (Darning, 1997;

Guldin, 2018). Under this model, there was a rapid growth in the number of small towns, and they have become important carriers of transition from rural to non-agricultural populations (Kassiola, 2017).

2.1.2 Natural and social hydrological cycles

2.1.2.1 Hydrological cycle and its elements

The hydrological cycle process is the transformation of water in different forms and the exchange between the oceans and the land over and over again, which generally includes evaporation from the surface of the water surface, atmospheric transport, condensation and precipitation, soil infiltration, and production and convergence.

On a global scale, the process of the hydrological cycle can be viewed as beginning with evaporation from the oceans (Oki & Kanae, 2006). Evaporated water vapor rises into the atmosphere (Pruppacher & Jaenicke, 1995), where part of it remains over the oceans, condenses in the cold to form precipitation, and returns to the oceans (T. Schneider et al., 2010); the other part is transported by air currents to land, where it condenses in the cold to form precipitation and falls to the land surface (Sherwood et al., 2010). Part of the water evaporates again to form water vapor into the atmosphere, while the other part becomes surface runoff, providing recharge for rivers and lakes, and eventually into the ocean (Bengtsson, 2010). Then part of the water infiltrates into the rock layers and soil and becomes soil water or subsurface runoff, which eventually also flows into the ocean (Seiler & Gat, 2007).

Based on the spatial regions where water exchange occurs, hydrological cycle processes can be divided into two types: water exchange between the ocean and the land (Trenberth & Fasullo, 2013), and the internal hydrological cycle of oceans and land (Barry, 1969; Ruud J., 2014). These two types are not completely independent but are interconnected. The hydrological cycle describes the movement of water vapor from oceanic sources to terrestrial environments, and the land in turn returns some of the water to the oceans in the form of runoff (Makarieva & Gorshkov, 2007). In this process, water is also exchanged between the atmosphere, hydrosphere and lithosphere through evaporation, precipitation and infiltration (Bodnar et al., 2013).

The global hydrological cycle is a closed system (Kundzewicz, 2008; Linton, 2008), but the regional hydrological cycle is an open system (Rockström et al., 2014; Trenberth et al., 2011). The watershed-scale hydrological cycle is a specific realization of the hydrological cycle in a specific spatial context and is the most basic unit of terrestrial hydrological cycle research. It is the transition from the macroscopic global scale to the microscopic local scale. A healthy watershed hydrological cycle should be sustained mobility, good water quality and good water ecosystems in the context of a balanced natural and social functioning of the watershed water system (Ahn & Kim, 2017; Hagemann et al., 2015; Music & Caya, 2007). The ideal state is close to the undisturbed state, that is, the original state before urban development.

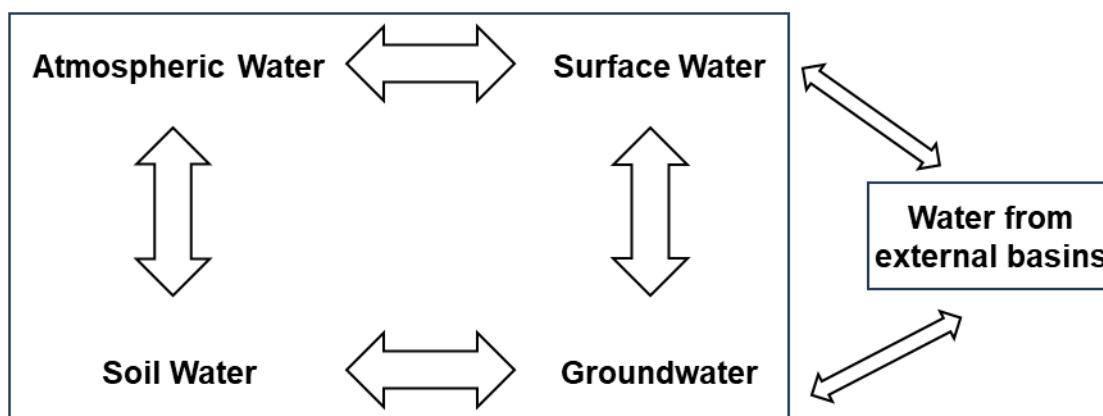


Figure 2-1: Natural hydrological cycle process in a watershed (Source: Author)

2.1.2.2 The natural hydrological cycle process

In the natural hydrological cycle (Figure 2-1), water in a watershed is stored in the earth, soil and ocean in gaseous, liquid and solid forms in an orderly manner under atmospheric movement, solar radiation and the Earth's gravity according to a number of links such as precipitation - evaporation - infiltration - runoff - storage (Figure 2-2). The average value of the amount of water in each link is maintained stable and changes cyclically, in dynamic balance (Peixóto & Oort, 1984).

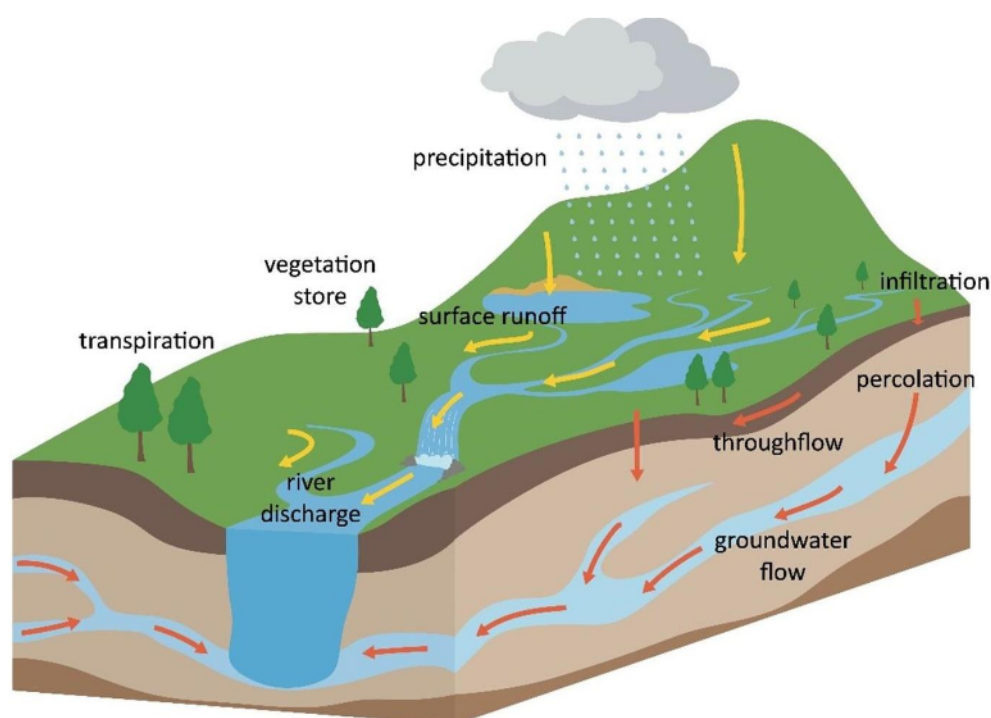


Figure 2-2: Hydrological cycle in a drainage basin (Source: <https://www.internetgeography.net>)

2.1.2.3 The social hydrological cycle process

The hydrological cycle process has experienced a transition from the natural hydrological cycle to the natural-social hydrological cycle (Figure 2-3) (D. Yang et al., 2021). The simply natural hydrological cycle has no longer existed since the appearance of human civilization. The social

hydrological cycle is the process by which humans obtain water resources from nature and consume them in order to satisfy their living and production needs, and it creates a strong interaction with the natural hydrological cycle, changing the movement of the hydrological cycle on Earth.

During the Stone Age, human activities had a limited impact on the hydrological cycle, utilizing natural water sources for fishing and hunting and simple farming. These effects were localized and short-term.

During the agricultural period, human activities had three effects. (1) First, land reclamation, which changes the type of land use, mainly changing the “infiltration” and “runoff” link. (2) Second, agricultural irrigation, the amount of water directly serving humans, the hydrological cycle process increases the “water withdrawal” link. (3) Third, deforestation, mainly changing the “evaporation” link. All these human activities increase soil erosion and water consumption, while groundwater recharge decreases (Rahmani & Danesh-Yazdi, 2022).

After the Industrial Revolution, the impact of human activities on the hydrological cycle became more pronounced. Large-scale industrialization and urbanization have led to massive water pollution, overexploitation of surface and groundwater, and diversion of natural water bodies (Loaiciga et al., 1996). In addition, water quality problems have been exacerbated by industrial discharges and urban drainage, affecting the natural processes of the hydrological cycle and its quality. Human activities also have a series of secondary effects, such as temperature changes due to the greenhouse effect and the urban heat island effect on localized urban microclimates, which affect the precipitation and evaporation of the hydrological cycle (Douville et al., 2002; Kondoh & Nishiyama, 2000).

The social hydrological cycle retains the natural hydrological cycle on the basis of the addition of water withdrawal, water utilization, water transfer and water drainage, making the hydrological cycle process more complex and the problems arising from it more serious.

(1) Water withdrawal

The process of water withdrawal is that humans demand water from nature. Water from rivers, lakes, and groundwater is extracted through pumping stations or diversion channels and transported through pipes or ditches to the place of use. Modern technology has helped ingest large quantities of water and water withdrawal is the first step of water consumption. In some places, the natural flow of water is altered by artificial power, which enables water to flow from a low to a high elevation.

(2) Water utilization

Water is withdrawn for use in agricultural, industrial and domestic activities. Agricultural activities account for 80% of the water used for human activities. Among the main uses of water in agriculture are crop irrigation, livestock farming, fish farming, agricultural product processing and ecological water use (Rosegrant & Ringler, 1999). Of these, the largest consumption is for irrigation, which accounts for 70-90% of total agricultural water use globally (Mekonnen & Hoekstra, 2016). This is mainly due to the fact that large-scale agricultural land needs to be watered regularly and the traditional method of diffuse irrigation causes a great waste of water (Howell, 2001).

In arid regions, where crop production is almost entirely dependent on manual irrigation, water demand is high. Industrial water includes water directly involved in the manufacturing process, which is the most consumed part of industrial water, as well as auxiliary production, such as cooling water, boiler water and washing water (Flörke et al., 2013). Domestic water includes direct drinking water, water for cleaning and sanitation, and water for green irrigation. Domestic water is involved in all aspects of daily life, and different uses have different requirements for water quality (Bradley & Bartram, 2013). Drinking water, for example, is of extremely high quality and must be purified and disinfected to ensure that it is safe. As the economy grows and the population explodes, the demand for agricultural and industrial products, as well as for daily life, increases dramatically, that led to increased water demand (U. A. Schneider et al., 2011). Excessive water extraction has led to problems such as declining groundwater levels and drying up of water resources in some regions.

(3) Water transfer

Water transfer is an artificial way of allocating water resources, in which water is transported from water-rich areas to water-poor areas through artificial canals, pumping stations and other engineering facilities, so as to fulfill the requirements of production, life and ecological environment protection in these areas (Gohari et al., 2013).

Some countries in the world have developed some water transfer projects. For example, China's South-to-North Water Transfer (SNWT) Project is the world's largest water transfer project (C. Liu & Zheng, 2002), spanning 15 provinces in China's four major river basins: the Yellow River Basin, Yangtze River Basin, Huaihe River Basin and Haihe River Basin. It is to transfer water from the Yangtze River Basin to North China to mitigate the water scarcity (Q. Zhang, 2009). India's National River Linkage Program is to transfer water resources from the flood-prone northern region to the arid and semi-arid southern region by linking river systems across India's major river systems (Misra et al., 2007). Similar projects include the California State Water Program in the United States, the Snowy Mountains Scheme in Australia and the Great Man-Made River Project in Libya (Ghassemi & White, 2007).

Although water transfer can solve the problem of water shortage in some areas, it also brings some negative impacts.

First, water transfer projects change the natural distribution of water resources. Excessive water diversion may lead to insufficient water supply in water source areas, undermining the sustainability of water resources. This, in turn, can cause ecosystem imbalance, decline in biodiversity, and threaten the survival of some fish and aquatic plants (Albert et al., 2021; McDonald et al., 2014b). The habitats of terrestrial animals along the route have also been destroyed. In addition, as the water transfer project connects different water systems, it may lead to biological invasion of water receiving areas (Gallardo & Aldridge, 2018).

Secondly, the water source areas, because of the large amount of water resources being transferred out, may lead to an insufficient supply of local water resources, affecting the local residents, agriculture and ecological needs, and destroying the sustainability of water resources in the water source areas (Tang et al., 2014; WANG et al., 2006).

(4) Water drainage

Drainage involves sewage and wastewater from industry, agriculture and household as well as rainwater (Parkinson, 2002). Wastewater sewage generally needs to be treated in a sewage treatment plant before being discharged, but in practice, many enterprises secretly discharge sewage in order to reduce costs, seriously damaging the surrounding water bodies and causing harm to the health of local residents (Ahmed et al., 2021). Unlike runoff from nature flowing into rivers and ocean, residential rainwater flows through rainwater outlets into the underground pipe network, and is discharged into rivers, lakes, and other water bodies (Bocanegra-Martínez et al., 2014).

Increased human activity directly drives the impact of human activities on the hydrological cycle becomes more obvious, gradually forming a coupled nature-society hydrological cycle model (Alberti et al., 2011). It has two significant features.

Firstly, the dual driving force. The natural hydrological cycle, originally driven externally by solar energy and gravity and internally by natural forces, has transformed into a dual “natural-artificial” driving force under human intervention (Qiu et al., 2024; H. Wang et al., 2013). The original laws of nature have been broken: water not only flows downstream but also upstream (Grill et al., 2015); it can flow not only in lakes and oceans but also through urban pipe networks. It flows in any direction and space according to human needs (Best, 2019).

Secondly, the dual hydrological cycle elements. It means, the hydrological cycle elements include not only those of the natural hydrological cycle elements, but also those related to human socioeconomic development (Ferraro et al., 2019). Water resources possess not only ecological functions but also economic and social attributes (R. Li et al., 2023). This encompasses issues of equity and security in water resources, water use efficiency, and the finite nature of water resources (Jnawali et al., 2022; Shao et al., 2022). Consequently, the study of water resources has expanded beyond its original natural science domain to encompass socioeconomic development and the humanities and social sciences.

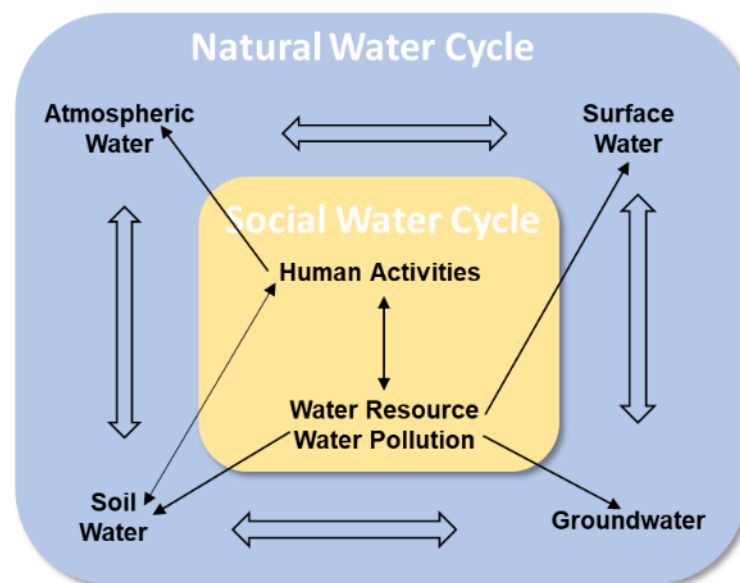


Figure 2-3: Coupled natural-social hydrological cycle in river basins (Source: Author)

At the current stage of human development, the natural hydrological cycle and the social hydrological cycle are intertwined (Vogel et al., 2015). The social hydrological cycle exists based on the natural hydrological cycle (Sivapalan, 2015), ingesting water resources and discharging sewage wastewater into the hydrological cycle, which has an irreversible negative impact on the natural cycle of water and far exceeds the self-regulating capacity of river systems.

However, as long as the social cycle of water pays attention to following the laws of the natural cycle of water, restraining the use of water, do not easily change the spatial and temporal route and the amount of hydrological cycle, pay attention to the degree of treatment of sewage, so that the recycled water discharged into the natural water body to meet the requirements of the environmental capacity of the water body of the self-purification, we can make the perturbation of the hydrological cycle to maintain in the acceptable range, so that it can provide an orderly and sustainable service for human beings.

2.1.3 Hydrological effects of urbanization

2.1.3.1 Definition of hydrological effects of urbanization

Hydrological effects are phenomena in which natural or human-induced changes in the geographic environment led to alterations in the processes and hydrological characteristics of the hydrological cycle. In this process, the flow, distribution and quality of water may be significantly affected.

The urbanization hydrological effect is the process of urbanization, caused by land use changes and human activities, on the hydrological cycle and its related processes. It is specifically manifested in a series of hydrological problems such as urban flooding, water shortage and water pollution. The hydrological effect of urbanization is not only a direct result of urbanization but also constitutes an important part of urban hydrology research, providing a theoretical basis and practical guidance for solving urban water problems. Through scientific research and engineering practice, the negative impacts of urbanization hydrological effects on urban ecology and society can be mitigated, and green and sustainable urban development can be promoted.

2.1.3.2 Hydrological effects of urbanization

The hydrological effects of urbanization are mainly characterized by increased surface runoff, decreased groundwater recharge, increased flood risk, deterioration of water quality, and disruption of the hydrological cycle in the watershed.

(1) Impact of urbanization on precipitation

The urban heat island effect is the most widespread impact, referring to the fact that temperatures in urban centers are generally higher than in suburbs and rural areas (Parker, 2010). This results in warmer, less dense air over cities, causing it to rise and form a low-pressure area. This updraft can trigger or increase convective precipitation, leading to more frequent extreme events such as thunderstorms and short-duration rainfall (Baik et al., 2007). Urban buildings slow down the movement of these air currents, forcing them to rise in place and reinforcing this effect (Giridharan et al., 2004). In other words, under the same climatic

conditions, urban areas receive more precipitation and are more intense than suburbs and rural areas (Miao et al., 2011; H. Wang et al., 2024). Its impact is most pronounced in summer (Dixon & Mote, 2003; Karimi et al., 2023).

In short, urbanization not only increases total precipitation, especially during the rainy season, but also significantly increases the frequency of extreme precipitation events (Steensen et al., 2022). This leads to a clear spatiotemporal distribution trend in precipitation, with precipitation decreasing outwards from urban areas (N. Li et al., 2006).

(2) Impact of urbanization on runoff

Runoff is defined as the process of water flowing along the earth's surface, river networks, and channels. It's water volume after precipitation reaches the ground and undergoes processes such as infiltration, evaporation, and retention (Dang et al., 2010). Runoff includes both underground runoff and surface runoff.

The impact of urbanization on runoff is mainly reflected in changes in underlying surface properties (Niehoff et al., 2002). With urban expansion, natural land surfaces are replaced by urban land surfaces. Under natural conditions, rainwater is largely consumed through vegetation interception, soil infiltration, and replenishment of groundwater, with only a portion forming surface runoff. After urbanization, due to the reduction of vegetation and the increase of impermeable surfaces in cities (roads, squares, building roofs, etc.), the consumption of rainwater has decreased significantly, and almost all precipitation is rapidly converted into surface runoff (B. Feng et al., 2021; Z. Sun et al., 2013; K. Yang et al., 2011). Artificial drainage systems have exacerbated its problems. Original natural waterways have been altered, with urban drainage systems added to them. While these pipe networks are designed to promptly discharge rainfall, when precipitation intensity exceeds their design standards, rapidly converging surface runoff cannot be drained in time, leading to urban flooding (Bibi et al., 2023; Schreider et al., 2000).

The natural hydrological cycle is slow and continuous. However, urbanization simplifies it into an extreme "precipitation → rapid runoff" pattern (S. Huang et al., 2024). The effects of urbanization on runoff are reflected in higher runoff volumes, elevated peak flows, and an earlier occurrence of peak discharge (Miller et al., 2014).

Additionally, this has triggered a series of chain reactions. For instance, reduced infiltration directly leads to insufficient groundwater recharge, causing a decrease in the base flow of rivers that rely on groundwater during dry seasons, and even causing them to dry up, severely impacting the ecological health of these waterways (Kiflay et al., 2025). During floods, the immense scouring force of increased peak flows results in channel erosion and deepening, destroying the habitats of surrounding organisms (Tregnaghi et al., 2010).

(3) Impact of urbanization on water quality

The pollution of runoff water quality by urbanization mainly includes point source pollution and non-point source pollution in two ways (J. Li et al., 2011). The expansion of urban areas is accompanied by significant discharges of industrial wastewater and household sewage into surface runoff systems, and this wastewater is rich in metals, heavy metals, organic pollutants,

radioactive pollutants, bacteria, viruses and so on (Holeton et al., 2011; Mallin et al., 2009). Moreover, the pollutants accumulated on the urban ground, roof and in the atmosphere are brought into the river by rainwater flushing (Sánchez et al., 2015), it deteriorates the water quality, but also strengthens the ground and riverbed scouring.

2.2 Rainwater management and concepts

2.2.1 Development of rainwater management

The development of rainwater management systems has gradually evolved from a single-model system initially focusing on urban hydrological management to a collection of models containing multiple elements, multifunctionality, and decentralization (Steffen et al., 2013). This shift indicates a transition in rainwater management from stormwater control to integrated management of water quantity, water quality, and ecological protection (Zawilski et al., 2014). This diversified management model emphasizes the need to not only deal with the immediate impacts of rainwater and flooding, but also to consider the long-term impacts on urban ecosystem, biodiversity, and the quality of life of residents (Y. Chen et al., 2016; Rockström et al., 2002).

At the policy and regulatory level, with the advancement of rainwater management concepts and practices, a range of corresponding policies and regulations has been established by national and local governments (Fricano & Grass, 2014; Schuetze, 2013). These policies and regulations have been continuously improved and enriched, making rainwater management more standardized and systematic (Imteaz & Moniruzzaman, 2018). In addition, the importance of community participation and multisectoral cooperation has also begun to be emphasized (Gao et al., 2018), and the promotion of public participation and interdisciplinary cooperation has become an important aspect of rainwater management (Herringshaw et al., 2010). By educating the public to understand and support these measures, as well as encouraging private landowners to adopt rainwater harvesting and utilization systems, the concept of rainwater flood management can be effectively rooted in the community and enhance the coping capacity of the city as a whole.

These changes not only enhance the city's resilience to extreme weather events but also promote the restoration and protection of the urban ecosystem, resulting in a new system of integrated, multi-layered, and interactive rainwater management. This system is more in line with the requirements of sustainable development and can enhance the ecological function of cities and improve the living environment of urban residents while improving the city's flood control and drainage capacity.

2.2.2 Some rainwater management concepts

2.2.2.1 Low Impact Development

The United States was one of the first countries to begin research on urban rainwater control, and in 1972 proposed best stormwater management practices (BMPs) (Villarreal et al., 2004). BMPs are all measures that can reduce or prevent pollution from occurring, and the core of the concept is to achieve source control through engineered measures to reduce runoff and thus reduce the potential for pollution of the water body (Lee et al., 2012).

The LID concept was developed from BMPs and introduced in the late 1990s (Dietz, 2007). It is an ecological rainwater management strategy that integrates rainwater management and environmental control into the landscape through the establishment of decentralized, small-scale infrastructures and the combination of site development (Gilroy & McCuen, 2009; Qin et al., 2013), design and planning, ecological protection, and rainwater management techniques, to manage rainwater from the source, control pollution, and improve the urban hydroecosystem (Palla & Gnecco, 2015). It is an ecosystem-based approach to rainwater management based on the principle of simulating natural hydrological conditions (Pyke et al., 2011).

LID measures mainly include structural (engineering) measures and non-structural (non-engineering) measures (Rosa et al., 2015). Structural measures include bioretention belts (rain gardens), green roofs, rainwater tanks, permeable pavement, planted swales, and vegetative filter strips (Chang et al., 2018). Non-engineering measures are non-technical means other than ordinances, policies, economic instruments and engineering to enhance rainwater control (Ishimatsu et al., 2017). Previous studies indicated that stormwater runoff can be reduced by 30–99% (Richards et al., 2015) through the application of LID measures, with peak flows delayed by 5–20 minutes (Fassman & Blackbourn, 2010), and effectively remove pollutants from the runoff (Shutes et al., 1997). With LID measures, higher peak flows attributable to increases in impervious surfaces would be reduced and the natural hydrological cycle would be restored and improved.

2.2.2.2 Sponge City

In 2013, China proposed the “Sponge City” concept and started the trial construction in 2015 (Lv et al., 2019; K. Yu et al., 2015), which has been popularized and implemented in many cities across the country by 2025 (Z. Guo et al., 2024; Z. Zheng et al., 2025). Sponge city is a new concept of urban rainwater management (Figure 2-4), aimed at enhancing the city's ability to absorb, infiltrate, store and purify rainwater through natural and artificial ways, mitigating urban flooding, improving the water environment, and enhancing the effectiveness of using water resources and urban ecosystem function (Zhan et al., 2016).

However, sponge city based on LID is not fully equivalent to LID (H. Jia et al., 2025). Consider the complex and changing water problems in China (Q. Zhang et al., 2024), these problems should be managed in an integrated manner, but not in a separate way. Therefore, sponge cities should comprehensively consider water resources, water environment, hydroecology and water security, so that cities have good resilience and resistance in the face of environmental changes (Z. Zheng et al., 2025). Moreover, the way to build a sponge city is diverse and should not be limited to LID facilities. Sponge city should make full use of soil, river system, vegetation and other natural elements, to restore the hydrological effects to their undeveloped state as much as possible (Xu et al., 2018).

Sponge watershed is a watershed rainwater management concept applied at a larger spatial scale based on the sponge city concept (Ding et al., 2017). Viewing from the holistic nature of the watershed, it covers the upstream, midstream and downstream areas, coordinates the allocation of water resources and ecological protection among regions, and restores the healthy function of the watershed ecosystem (Q. Chen et al., 2022). Meanwhile, it takes into account

the objectives of flood control, water supply, ecological protection and pollution control, and improves the comprehensive management capacity of the watershed (Cai, 2022).

2.2.2.3 Water Framework Directive

The Water Framework Directive is a key European Union policy document for river basin management, aiming to achieve a “good ecological status” for river basins (Hering et al., 2010). While it doesn't provide direct guidance on rainwater management, its core principles offer indirect guidance. It emphasizes integrated river basin management and the restoration of water ecosystems (Chave, 2001; Mostert, 2003).

The “integration” of watershed management is reflected in two aspects. On the one hand, it emphasizes that water bodies such as surface water, groundwater, and coastal water bodies, which are in different spaces, are a cyclical and interconnected whole, emphasizing integrated management. However, it also includes the comprehensive management of water quality, water quantity, and hydrological ecology, which is not only about controlling water pollution, but also includes the restoration of hydrological cycle processes and biodiversity.

It requires the development of a River Basin Management Plan (RBMP) with the River Basin District as the smallest management unit. The RBMP identifies all pressures affecting water conditions, including urban stormwater runoff, impervious surface expansion, and drainage system overflows. EU Member states must assess the impacts of urbanization on runoff and flood processes in their river basin management plans and propose control measures.

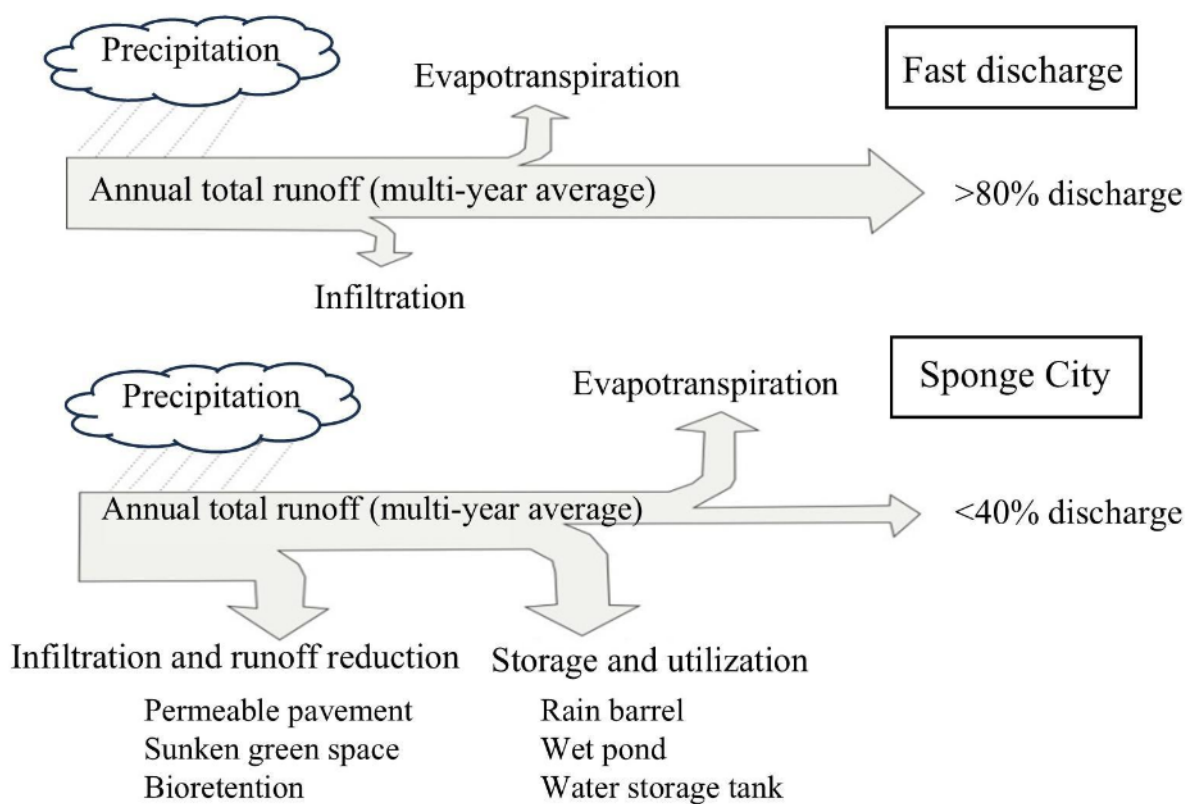


Figure 2-4: Sponge city vs. Dominate rainwater fast discharge model (Source: Sponge City Construction Technical Guide)

3 Study area

3.1 Natural geographical overview

(1) Geographic location

Nansihu Lake is composed of four connected lakes, namely, Weishan Lake, Shaoyang Lake, Dushan Lake and Nanyang Lake, which are connected by natural and artificial rivers, extending from the southwest of Shandong Province to the northern part of Jiangsu Province, and is the 6th largest freshwater lake in China (Figure 3-1). In 1960, Erjiba Dam was constructed at the narrowest part of the lake, and Nansihu Lake was divided into two parts, with the upper lake in the north, including mainly Shaoyang Lake, Dushan Lake and Nanyang Lake, with area of 602 km², and the lower lake in the south, including Weishan Lake and part of Shaoyang Lake, with area of 664 km².

The Nansihu River Basin (NRB) is located between 34°24'~35°59'N and 114°52'~117°42' E. The area of the watershed is 31,700km², of which the water area is 1,266km². The length is 119.10km, the average width is 10.60km, and the shoreline length is 316.20 km. Divided by Nansihu Lake and the Beijing-Hangzhou Grand Canal, the NRB is split into the eastern and western areas. The eastern part of the basin consists of the low mountains of central and southern Shandong and foothill alluvial plains, with altitude between 100-600 m. The western part is the Yellow River floodplain, formed by sediment deposition in the middle and lower reaches of the Yellow River.

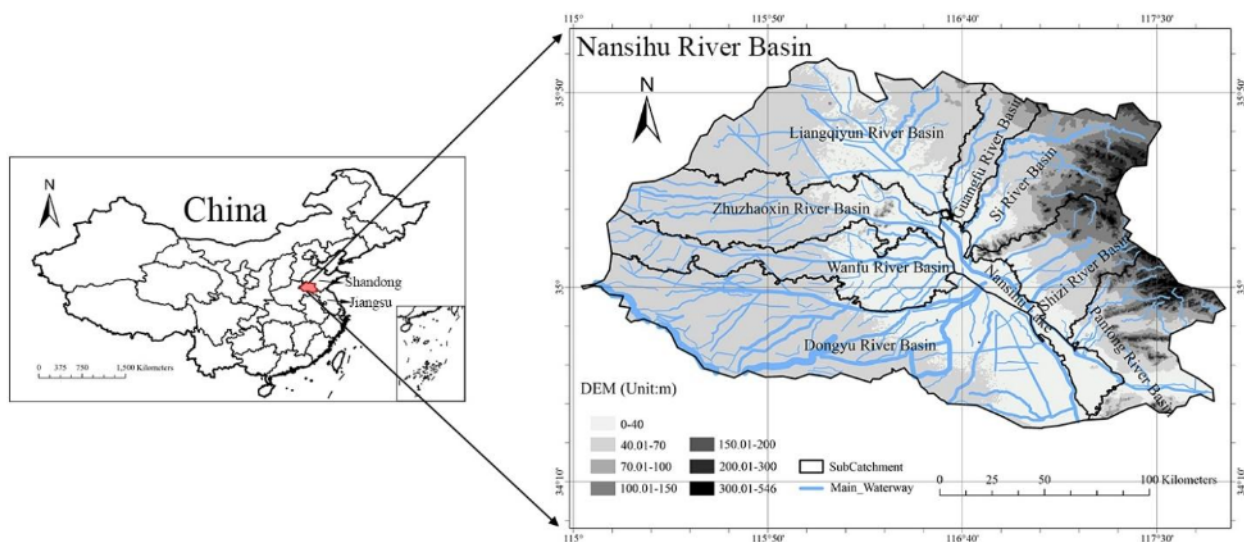


Figure 3-1: Nansihu River Basin in China (Source of administrative boundaries: China National Platform for Common GeoSpatial Information Services-MAP WORLD)

(2) Climatic characteristics

The NRB belongs to a temperate monsoon climate. It is situated in the warm temperate zone and falls within a semi-humid continental monsoon climate region. Influenced by monsoon circulation, this region experiences rainy summers, cold and dry winters, windy springs, and cool autumns, exhibiting typical lake climate characteristics. The annual average temperature of the lake area is 14.2°C, while that of the surrounding land is 13.7°C. Due to the higher heat

capacity of water compared to land, the lake area warms up more slowly than the surrounding land, forming a “warm zone” centered on the lake surface. Both annual and daily temperature ranges are relatively small. Additionally, there is a noticeable pattern where the temperature variations increase progressively with distance from the lake. The fluctuation in temperature range is approximately $\pm 11^{\circ}\text{C}$. The lowest temperature is usually in January, reaching as low as -13°C ; the highest temperature is usually in July, with the temperature reaching up to 38°C . The frost-free period in the NRB is relatively long, typically exceeding 200 days. The freezing period for rivers and lakes is relatively short, with an average ice thickness of about 15 cm.

Influenced by the continental monsoon climate, cold air in winter comes from high-latitude continental regions, bringing northerly winds and resulting in cold and dry conditions. In summer, the NRB is controlled by the Indian heat low, with winds mainly from the ocean, more southerly winds, leading to high temperature and heavy rainfall. These climatic conditions lead to the frequent occurrence of droughts and floods in the NRB. The annual average precipitation is 690 mm, with most rainfall concentrated in summer and autumn. In contrast, winter and spring receive limited precipitation, often causing river interruptions and leading to severe spring droughts.

Evaporation is an important factor affecting the hydrological cycle and energy balance of natural water bodies. Evaporation in the NRB accounts for about 58-65% of precipitation over land. Land surface evaporation is influenced by factors such as vegetation cover, topography, soil characteristics and atmospheric conditions, with annual evaporation averaging around 1700 mm. Water surface evaporation, on the other hand, is influenced by atmospheric conditions, water quality and turbulence intensity, with annual evaporation averaging around 1500 mm. Although the relative humidity over the lake surface is slightly higher than that over the land, the intensity of evaporation is rather weaker than that of the land surface due to the more stable atmosphere over the lake.

(3) River systems

Nansihu Lake on its eastern, western, and northern sides receives inflows from more than 30 counties, cities, and districts across four provinces-Jiangsu, Shandong, Henan, and Anhui. A total of 53 rivers flow into the lake (Table 3-1). The average annual inflow to the lake is 2.96 billion m^3 , while the average annual outflow is 1.92 billion m^3 . Since its formation, Nansihu Lake has maintained an average water depth of over 2 meters, with a maximum storage capacity of 2.2 billion m^3 . After the construction of the Erjiba Dam in 1960, the total maximum reservoir capacity of the lake increased to 4.7314 billion m^3 . Among this, the flood control capacity is 3.029 billion m^3 .

The primary water supply for Nansihu Lake comes from river runoff within the watershed. Since the 1970s, a significant amount of Yellow River water has been diverted for irrigation in the western part, with a portion of the remaining water flowing into Nansihu Lake. According to statistics, the annual water inflow from Jiangsu, Anhui, and Henan province is approximately 524 million m^3 . The outflow, regulated by the Hanzhuangzha and Linjiaba, has an average multi-year runoff of 307 million m^3 . The water system of NRB generally maintains the spatial pattern in its natural state, but its structural characteristics have changed significantly due to

urbanization, such as a significant decrease in the structural stability and connectivity of the river network.

Table 3-1: Main rivers in the NRB

	The eastern part			The western part		
	Name	Area (km ²)	Length (km)	Name	Area (km ²)	Length (km)
The upper lake	Si	2366	159	Dongyu	5923	175
	Guangfu	1367	48	Zhuzhaoxin	4206	141
	Baima	1052	60	Liangjiyun	3306	88
	Cheng	916	7	Fuxing	1812	54
	Beisha	505	53	Dasha	1638	60
	Jie	193	55	Xinwanfu	1330	71
	Long	116	20	Zhushui	571	49
	Xinan	75	15	Laowanfu	563	33
	Shizi	53	5	Cai	322	36
				Yaolou	113	
				Xizhi	96	14
				Hui	85	26
				Yangguantun	69	
				Longgong	52	15
				Laoyun	30	
The lower lake	The eastern part			The western part		
	Name	Area (km ²)	Length (km)	Name	Area (km ²)	Length (km)
	Xinxun	663	22	Lukou	525	
	Panlong	296	22	Zhengji	497	
	Xuewang	242	35	Fengpei	338	
	Fangzhuang	82	11	Wagongzhuang	310	
	Hanzhuangyun	77	3	7 small rivers	166	
	Jiangji	54	3			
	Zhongxin	58	7			
	Xiaosha	54	3			
	Dongni	53	5			
	4 small rivers	104				

3.2 Socioeconomic overview

The NRB is located in the southern part of the North China Plain, characterized by a dense population and rapid urbanization. The watershed has a flat terrain and abundant water resources, making it an important grain production and aquaculture base in China. Additionally, the region is rich in mineral resources and it's also a key energy production base in China.

(1) Administrative divisions

The administrative area of the NRB covers the junction zone of Jiangsu Province, Shandong Province, Henan Province and Anhui Province (Figure 3-2), extending from the southwest of Shandong Province southward to the north of Jiangsu Province, with the entire lake area and the majority of the rivers located in Shandong Province, which belongs to the five cities of Jining, Heze, Zaozhuang, Tai'an and Linyi, with a small portion of the southern part of the basin belonging to Peixian County and Tongshan County of Jiangsu Province, and a small portion of the western part of the basin located in Henan Province and Anhui Province. Due to the availability of the required materials and data, the actual study area for this research is the Nansihu Basin within Shandong Province and Jiangsu Province. The detailed administrative divisions of the watershed are shown in the Table 3-2, containing a total of six prefecture-level cities, Jining, Heze, Zaozhuang, Tai'an, Linyi, and Xuzhou, with 33 counties, county-level cities and districts and an area of approximately 27,000 km².

Table 3-2: The district of the NRB

Province	Prefecture-level city	Count	District/County/County-level city
Shandong	Jining	11	District: Jining (Rencheng, Yanzhou); County-level city: Qufu, Zoucheng; County: Jinxiang, Jiaxiang, Yutai, Weishan, Sishui, Wenshang, Liangshan
	Heze	9	District: Heze (Mudan, Dingtao), County: Caoxian, Chengwu, Shanxian, Juye, Yuncheng, Juancheng, Dongming
	Zaozhuang	6	District: Zaozhuang (Xuecheng, Shizhong, Yicheng, Taierzhuang, Shanting); County-level city: Tengzhou
	Tai'an	3	County-level city: Xintai, County: Ningyang, Dongping
	Linyi	1	County: Lanling
Jiangsu	Xuzhou	3	District: Tongshan, County: Fengxian, Peixian

(2) Economic development

The NRB mainly includes the cities of Zaozhuang, Jining and Heze city (Figure 3-2). The total population was about 20 million people in 2022. The average population urbanization rate of the basin was 55.22%, lower than the 65.2% in the mainland China. Due to the traditional industrial structure, the imbalance between water resource availability and demand, transportation infrastructure and policy support, the economic development of the basin had been slower than that of other coastal areas in Shandong Province, resulting in the lower urbanization level of the cities in NRB, which were mainly engaged in primary industry, with farmland, forest land, and fishery areas accounting for approximately 80% of the NRB. The main agricultural crops include rice, wheat, cotton, and soybeans, which has turned the region into an important center of grain and cotton production nationwide. Due to the abundant water resources of Nansihu Lake, the NRB is also a key freshwater aquaculture base in Shandong

Province. Nansihu Lake is a shallow nutrient lake, which is rich in fish, shrimp, reeds, lotus and other aquatic economic animals and plants, and is the main economic source for fishermen in NRB. Additionally, the region is an important livestock breeding base in Shandong Province, supporting the farming of pigs, cattle, and sheep.



Figure 3-2: District and counties of the NRB (Source: Author)

The NRB has well-developed industries, such as iron smelting, mining, chemicals, machinery, pharmaceuticals, and food processing reaching a relatively high level of development within China. Additionally, the region is endowed with abundant coal reserves of high quality, making it one of China's major energy production bases. There are 12.7 billion tons of proven coal resource reserves in the NRB, accounting for 65% of Shandong Province. At the beginning of the Reform and Opening up period, agriculture dominated in the NRB, and with the adjustment of industrial structure, the share of secondary and tertiary industries has continued to rise. Taking gross domestic product (GDP) of Jining, Heze and Zaozhuang, the major cities in the NRB, as an example, the percentage of secondary industries is around 40% in 2022.

(3) Transportation

The NRB has a great transportation location and various transportation modes, such as railroads, highways, waterways and airways are very convenient (Figure 3-3). The Beijing-Hangzhou Canal connects several tributaries and channels of the Nansihu Lake, and runs directly to the Yangtze River through Xu Zhou and Yangzhou to the south, connecting the north and south. The Jinpu Railway passes through Yanzhou, Tengzhou, Zoucheng and Zaozhuang, and the newly-built Beijing-Shanghai High Speed Railway has Qufu East Station, Tengzhou East Station and Zaozhuang Station in the district, which have grown to be a significant motivator for the social and economic development of the district. Beijing-Fu High Speed Railway and 104, 105, 220, 327 four national highways and 17 provincial highways all pass through the watershed, constituting a well-connected highway transportation network.

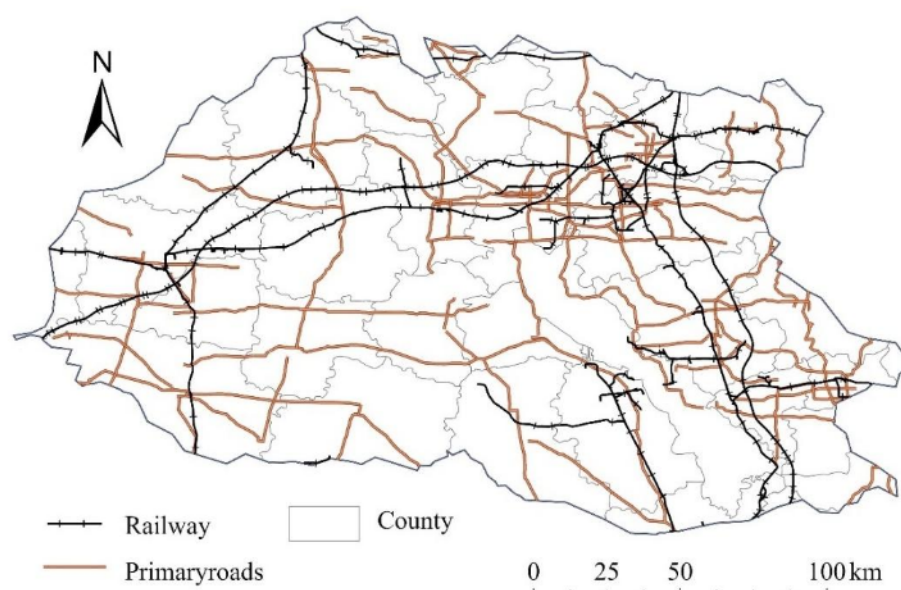


Figure 3-3: Main railway and primary roads of the NRB (Source: Open Street Maps)

3.3 Current research and issues on rainwater management in the NRB

As an important flood storage area in the Yellow River and Huaihe River Plain, an important freshwater lake in northern China, and an irrigated agricultural area in Shandong Province, the Nansihu Basin also faces problems of water scarcity and urban flooding. Over the years, many scholars and government policy makers have launched academic research and established policies on water resources management, flood prevention and ecological restoration. Specific important initiatives are described below (Table 3-3).

(1) Academic research

From the published articles so far, the related research mainly focuses on the water quality and aquatic biological system in the Nansihu Lake area, including water quality monitoring, distribution and migration of pollutants, etc., while fewer studies have been published for the river basin area.

At the watershed level, from the perspective of water resources management, some scholars have proposed various optimization methods and models, such as setting up different inflow scenarios, adopting different water resources allocation strategies, and emphasizing the balance between economic benefits and policy risks (G. Huang & Loucks, 2000; Z. Sun et al., 2013). Improvement of the ecological compensation mechanism to face the problems of unreasonable resource allocation structure and increased pressure on ecological protection due to the ecological and economic development of the NRB (S. Yu et al., 2011), and to realize the synergistic development of the NRB's socio-economy and ecological protection (Hou & Shi, 2009; Y. Liu et al., 2020).

Some scholars have quantified and assessed the ecosystem service functions of NRB (X. Sun et al., 2017; M. Yu et al., 2018; Q. Zhang et al., 2021) and predicted that with the acceleration of urbanization, the value of water yield would be significantly higher and flood risk would

increase accordingly (H. Guo et al., 2016). While other ecosystem service functions such as water conservation, habitat quality, and carbon storage decreased (X. Sun et al., 2019). However, the Grain for Green Program which is converting cropland to forest or wetland, have been shown to be effective in improving habitat quality, with an average improvement of 9%-17% (H. Zhang et al., 2018). The contradiction between ecological protection and economic development needs to be regulated by reasonable land use planning and ecological protection policies.

In addition, there are several studies on the impacts of climate change and human activities on hydrological cycle processes (Z. Sun et al., 2011; X. Yang et al., 2008). The water area of the NRB had increased, and the river system in general still maintains the spatial pattern under the natural status, but the structural characteristics had been changed significantly, and the structural stability of the river network had been reduced by 4.30%, and the connectivity rate and the actual union had been reduced by 21.82% and 21.62%, respectively (Y. Jiang et al., 2017). The hydrological elements, such as precipitation and evaporation, showed regular cyclical changes (Q. Chen et al., 2022; Tian et al., 2018; W. Zhang et al., 2020). The characterization of flood season precipitation (Gong et al., 2015; Zhu et al., 2015) can support water resource risk analysis and flood control planning from a theoretical perspective.

Moreover, some water quality and rainfall monitoring platforms based on Web and Remote Sensing technologies (Jing & Zhang, 2019; H. Wu et al., 2011) provide more accurate and timely data, which makes it easier for decision makers to make more timely and scientific responses to face flood disasters.

(2) Government and policy guidance

In order to effectively manage the water resources in the NRB and coordinate the work of Jiangsu and Shandong provinces in urban drainage, water use and water pollution control, the Nansihu Water Resources Management Office was established in 1983 under the Yishusi River Basin Administration, Huai River Commission, Ministry of Water Resources of China, and it was renamed to Nansihu Water Resources Management Bureau in 2003.

In November 2021, Special Planning for Ecological Protection and Restoration of the Nansihu River Basin (2021-2035) was released (Department of Natural Resources of Shandong Province, 2021), which proposed measures for the ecological protection and restoration of the NRB. It made it clear that it was necessary to comprehensively establish ecological corridors by means of returning cropland to wetlands, returning aquaculture farm to beaches and supplementing ecological water, so as to promote the construction of nature reserves and improve the ecological functions of wetlands. It required to promote ecological restoration of mines in the region, transforming mining subsidence zones into cropland or wetland parks, and enhancing the capacity of the region to regulate rainfall and flooding. There is also a need to improve regulatory capacity of ecological protection.

In August 2022, the Ecological Protection and High Quality Development Planning for the Nansihu River Basin in Shandong Province was published (Shandong Province Government, 2022). It focused on water environment, hydroecology, water resources, water disasters “four

water” issues, highlighting ecological protection and restoration, strict guarding of cropland and permanent basic cropland, boundary of ecological protection and urban development.

At the same time, the four counties (cities and districts) along the Nansihu Lake (respectively, Weishan, Yutai, Rengcheng and Tengzhou) would be considered in terms of the development of specialty industries and infrastructure construction. It adhered to the idea of systematic treatment of mountains, water, forests, fields, lakes, grasses and sands, considered comprehensively the pollution prevention and treatment, ecological restoration and water security of the NRB in Shandong province. Based on this, in November of the same year, the Implementation Program for the Ecological Protection and High Quality Development of Nansihu River Basin in Jining City was developed (Jining City Government, 2022), which defined the key tasks of the ecological protection of NRN and the development goals. It was required to accelerate the construction of the separation of stormwater and sewage, and it should be fully completed by the end of 2023. It was clear that the of Sponge City Concept will be implemented in all kinds of building districts, water system management and drainage facilities and other projects, and the area of sponge city would reach more than 50% of the built-up area by 2025. It demanded to strengthen the construction of Provincial NRB Nature Reserve, optimize the range and functional zones of the Nature Reserve, effectively maintain ecosystem integrity, systematicity and stability, and strictly guard the security boundaries of natural ecology.

In October 2023, Shandong-Jiangsu-Anhui-Henan four provinces jointly issued the Comprehensive Discharge Standard for Water Pollutants in the NRB (Shandong Province Government et al., 2023). It was the first unified program led by the country to coordinate the determination of water pollutant emission limits, and the four provinces combined with its local practical adjustments to revise the emission standards of the NRB within the range of its own province. It creates a cross- provincial and cross-basin water pollution control, which is of great significance in building a water ecological and environmental governance.

(3) Practical measures

It includes engineering measures and ecological measures. Among them, engineering measures involve ①reinforcing embankment dam to prevent flood overflow during the rainy season, which could otherwise inundate surrounding farmland and residential areas. ②Increase drainage pump stations. Multiple drainage pump stations constructed in low-lying areas to ensure timely water discharge after flooding, thereby reducing disaster risks. ③Rainwater collection for reuse. That is, the excess rainwater from the rainy season is collected and used for irrigation in dry seasons, which can solve the problem of rainwater flooding and save water resources at the same time.

Ecological measures are mainly combined with sponge city construction. It repairs the degraded wetlands in and around the Nansihu Lake and restores its function of water storage and water conservation. By planting aquatic vegetation around the lakes and rivers, natural rainwater retention areas have been formed to reduce the pollution burden of rainwater flowing directly into the lakes and rivers. The construction of separate stormwater and sewage systems has also been strengthened to avoid industrial and domestic wastewater entering natural water bodies together with rainwater to pollute water sources. Facilities that can absorb and store

rainwater, such as permeable pavement, rain gardens and green roofs, had also been constructed in some public spaces within the city. In addition, the rainfall, water level and water quality monitoring and early warning system has been improved to enable real-time online monitoring of precipitation and water pollution, and to launch relevant contingency plans before the coming of heavy precipitation in order to handle flooding disasters in time.

However, the exploration of Sponge City in NRB is currently in the early stages, and the relevant measures are only localized pilot construction, such as in Jining City, and not yet widely implemented.

Table 3-3: Current research on rainwater management in the NRB

Dimensions	Category	Description
Academic research	Water quality	Water quality monitoring
		The tracking of dissolved organic matter and pollutants, and its impact
		The distribution of heavy metal content in the sediment
	Water resources	Water resource allocation scenario simulation
		Ecological compensation mechanism
	Ecological environment	Quantitative assessment and prediction of ecosystem service functions
		The dynamic change of wetland vegetation
		Impacts of climate change and human activities
	Hydrological cycle processes	Spatiotemporal characteristics and changes
Precipitation characteristics during flood season		
Impacts of climate change and human activities		
Policy guidance	Management Agency	Nansihu Water Resources Management Bureau
		Department of Natural Resources of Shandong Province
		Shandong Province Government, Jiangsu Province Government, Jining City Government
	Policy documents	Special Planning for Ecological Protection and Restoration of the Nansihu River Basin (2021-2035)
		The Ecological Protection and High Quality Development Planning for the Nansihu River Basin in Shandong Province
		The Ecological Protection and High Quality Development of Nansihu River Basin in Jining City
		The comprehensive discharge standard for water pollutants in the Nansihu River Basin (Shandong-Jiangsu-Anhui-Henan four provinces)
Practical measures	Engineering measures	Strengthening embankments to prevent flooding during the rainy season
		More drainage pumping stations to ensure timely drainage of floodwaters
		Rainwater harvesting and reuse
		The construction of separate stormwater and sewage systems

	Ecological measures	LID and Sponge City (Permeable pavement, bioretention grids, green roofs, etc.)
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(4) Existing problems and shortcomings

In recent years, focusing on water resources management, flood prevention and ecological restoration, the government and scholars have taken a variety of measures and achieved certain results, but there are still many shortcomings.

①Lack of systematic overall watershed planning. Most current rainwater management measures focus on localized areas of the city or specific projects, such as wetland restoration, construction of drainage facility and sponge city facilities. However, there was a lack of organic connection among these measures and a failure to integrate rainwater storage, ecological protection and water resource utilization from the river basin as a whole, resulting in an inability to fully realize the overall function of the river basin ecosystem.

② Ecosystem function restoration is incomplete. Although ecological measures such as wetland restoration and vegetation planting have been adopted, the extent and depth of restoration are limited, and the integrity and function of the natural hydrological cycle system in a river basin have not yet been fully restored. The ecological retention function of some key areas has not been sufficiently emphasized, such as the weak natural connectivity between river networks and water bodies, and the instability of water system structures.

③ Integrated management of water security issues is not enough. The coexistence of floods and water scarcity is still prominent, and existing measures rely too heavily on engineering measures and fail to effectively utilize the regulating capacity of ecosystems to improve water security. In the background of frequent occurrence of extreme climate events, the river basin lacks more resilient and adaptive management strategies.

④ Conflicts between urbanization and rainwater management. Rapid urbanization had led to increased surface hardening and a decline in rainwater retention and infiltration capacity, increasing waterlogging and stormwater pressure. Although some cities had adopted Sponge City Concept, implementation had mostly focused on urban built-up areas and has no extend to the watershed level, which led to a lack of collaboration between upstream and downstream. Weak coordination between the public and policy. Public participation in watershed ecological protection and sponge city construction was very low, and awareness of ecological protection had not been popularized. At the same time, there were technical and interest differences in cross-regional policy coordination, making it difficult to form a unified and efficient governance mechanism.

To solve these weaknesses, the overall planning of Sponge City on a watershed level can be promoted to enhance the ability of cooperation among regions, while at the same time strengthening the restoration of ecosystem functions, optimizing the structure of the hydrological cycle, and enhancing the resilience of water security, so as to achieve the dual goals of ecological function restoration and water security from a large-scale point of view.

3.4 Data

This research analyzed the urbanization process and hydrological effects of urbanization in NRB, and evaluated its hydroecology and water security pattern, which required data including climate data, topographic data, socio-economic data and other data (Table 3-4).

Among them, the climate data include precipitation, surface runoff, evaporation and temperature data. There are 15 hydrological stations in the NRB. 8 of the 15 stations were selected with larger control areas, including: Yutai, Sunzhuang, Liangshanzha and Houying in the eastern part; Huangzhuang, Shuyuan, Tengzhou and Xuecheng in the western part. The time scale was about 70 years, covering a wide range of rainfall types such as light, moderate, and heavy rainfall that may occur in NRB. Daily evaporation data were from three meteorological observation stations, Xuzhou, Dingtao and Yanzhou. They were used to analyze the spatial distribution of hydrological cycle elements, long-time trend changes and cyclic changes. Monthly precipitation, evaporation and temperature data were spatially interpolated raster data with a resolution of 1km, and were used as input data for water ecosystem service assessment. Hourly Water Pollution of 25 stations in NRB (every three hours or six hours) was calculated as daily water pollution and monthly water pollution. It was used to analyze water pollution in the water security pattern.

The topographic data, Digital Elevation Model (DEM) (its resolution is 30 meters). There were also two types of GDP and population data, one was spatially interpolated data for China, with a resolution of 1 km, and each raster represented the total value of GDP or the total population within that grid. They were used for the assessment of water ecosystem services. One type of data in excel format for the three cities (Zaozhuang, Jining, Heze) in NRB was used to analyze the urbanization process. Among them, the GDP raster data was forecasted by combining the NLTS image product nighttime lighting data and gridded LandScan population dataset based on GDP value.

Bedrock_depth is raster data with a resolution of 100m, also used for water ecosystem services. Land Use and Land Cover data was downloaded from annual land cover product of China (CLCD) (J. Yang & Huang, 2022). The vector boundaries were used for the year 2023, and the administrative boundaries of some places within NRB have changed in recent years, so this research uses the newest version, changed names and boundaries, and the location and coordinates system are more accurate.

Table 3-4: Data and sources

Category	Data	Year	Description	Sources
Climate data	Monthly Precipitation	2000-2022	Raster data	HadCRUT5 and WorldClim Dataset
	Monthly Temperature	2000-2022	Raster data	HadCRUT5 and WorldClim Dataset
	Monthly Evaporation		Raster data	Hargreaves potential evapotranspiration calculation formula
	Daily Precipitation	1952-2022	Station data	Yishusi River Basin Administration, Huai

	Daily Surface Runoff	1952-2022	Station data	River Commission, Ministry of Water Resources of China
	Daily Evaporation	1963-2020	Station data	
	Hourly Water Pollution	2023	Station data	China National Environmental Monitoring Centre
Topographic Data	DEM		Raster data	Shuttle Radar Topography Mission (SRTM)
Socio-economic Data	GDP Density	2014-2020	Raster data	DMSP-OLS NLTS, LandScan Population Dataset, National Bureau of Statistics of China
	Population Density	2000-2022	Raster data	LandScan Population Dataset
	GDP	1981-2022	-	National Bureau of Statistics of China
	Population	1981-2022	-	National Bureau of Statistics of China
	Road	2001, 2015, 2023	Raster data	Open Street Map
	Railway		Raster data	
	Land Use and Land Cover	2000-2022	Raster data	Landsat 8
Other Data	Boundaries of Administrative Regions in China	2023	Vector data	Ministry of Civil Affairs of China
	Bedrock_depth	-	Raster data	Chinese National Important Geological Borehole Database

4 Methodology

4.1 Methodological framework for rainwater management

The rainwater management strategies proposed in this study were developed through a watershed-scale assessment framework. The methodological framework consisted of four analytical stages (Figure 4-1).

First, the level of urbanization was assessed to characterize the spatial pattern and intensity of urban development within the NRB. Indicators including population, the structure of industrial economy and LULC were analyzed.

Second, the hydrological effects of urbanization were evaluated by analyzing key elements of the hydrological cycle, including precipitation, surface runoff, and evaporation. These analyses were used to examine how urban development altered natural hydrological processes and influenced runoff generation.

Third, watershed conditions were assessed from two complementary perspectives: hydroecology and water security. Hydroecological conditions were evaluated using ecosystem service assessments, including water yield, carbon storage, and habitat quality. Water security was assessed by considering water source protection, flood inundation risk and water pollution.

Finally, based on the characteristics and dominant issues identified in different area, the watershed-scale rainwater management plan was developed.

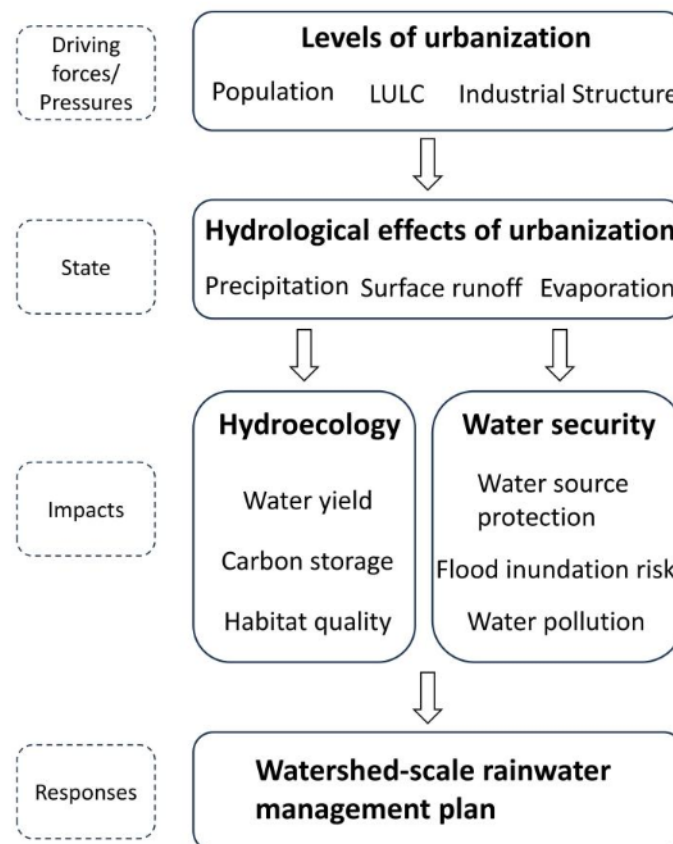


Figure 4-1: Workflow of the dissertation (Source: Author)

4.2 Assess the level of urbanization in a watershed

The level of urbanization is a relativized and fuzzy-bordered concept that is not easy to assess, and some easily controlled and quantitative parameters can be chosen to represent urbanization, such as changes in population, changes in industrial and economic patterns, and changes in LULC.

4.2.1 Changes in population

Population urbanization was assessed using two indicators: the urban population ratio and urban scale. The urban population ratio reflects the proportion of the population residing in urban areas. Higher urban population shares are generally associated with greater levels of urbanization, as people migrate from rural to urban areas, shift from agricultural to non-agricultural employment, and adopt urban lifestyles (Davis, 1965). It is generally accepted that a country or region is highly urbanized when its urban population ratio exceeds 50%. A rate above 70% typically indicates a mature stage of urbanization, whereas areas with a rate below 30% are considered to have low levels of urbanization (Buhaug & Urdal, 2013; Satterthwaite, 2009).

Jining, Zaozhuang, and Heze were selected for analysis because they cover most of the NRB. The urban population ratios of these three prefecture-level cities were used to represent the population urbanization process across the NRB.

In addition to the urban population ratio, urban scale was used to characterize changes in the spatial development of cities. According to China's urban scale classification standard, cities are classified into five categories and seven classes based on their permanent resident population (Table 4-1). The urban scale of county-level administrative units and above within the NRB was assessed for four representative periods (1990s, 2000s, 2010s, and 2020s) to evaluate changes in city size during the urbanization process.

Table 4-1 China's city size classes

City scale		Population (million)
Megacity		>10
Super large city		5-10
Large city	I	3-5
	II	1-3
Medium city		0.5-1
Small city	I	0.2-0.5
	II	<0.2

4.2.2 Changes in the structure of the industrial economy

The structure of the economy can reflect the changes in the level of urbanization through the changes in the proportion of primary-secondary-tertiary industries.

Alongside the urbanization process are changes in the economic structure. In the early stages of urbanization, the proportion of the primary industry declines while the secondary industry grows (Henderson, 2003). At the mature stage of urbanization, the proportion of the tertiary

industry (service industry) increases significantly, reflecting the diversification of urban functions and the emergence of the service industry as the dominant force in the economy (Michaels et al., 2012). The increase in urban population brings about an increase in demand for services (such as education, health care, finance, transportation, culture and entertainment, etc.), further promoting urbanization. It is generally accepted that when the ratio of the tertiary industry to GDP exceeds 50%, the level of urbanization has entered a high stage (Z. Jiang, 2022; United Nations, 2018).

The GDP data of Jining, Zaozhuang, and Heze was used to calculate the proportion and changes in each type of industry separately. Compared with similar regions and countries, it analyzed the characteristics of the region's economic structure and the relative urbanization level. In the time series, the multi-year trends of economic structure changes were observed.

4.2.3 Changes in LULC

To quantify LULC dynamics, a land use transition matrix was employed to analyze the conversion relationships among different LULC types during the study period (Aryal et al., 2023). The transition matrix compares land use maps from two different time periods and records the area converted from one land use type to another, thereby revealing the direction, magnitude, and temporal characteristics of land use change (Fall et al., 2010).

LULC data for 1990, 2000, 2010, and 2022 were used to construct transition matrices for the periods 1990-2000, 2000-2010, and 2010-2022. There are six types of land use in the NRB, namely cropland, forest, grassland, water, bare land, and impervious area, which is also known as construction land.

The level of urbanization was evaluated by examining the conversion among different land use types, with particular attention given to the expansion of construction land. The conversion of cropland, forest, grassland, and other natural land into construction land was considered an indicator of spatial urbanization, reflecting the outward expansion of urban areas. In contrast, the persistence of construction land between two periods indicated the continuity and stability of existing urban development.

Among these indicators, LULC change was further used as the spatial proxy of urbanization in the subsequent hydrological and ecosystem service analyses. This is because urbanization is physically manifested through the conversion of land surfaces, particularly the expansion of impervious areas and the corresponding reduction or transformation of natural and agricultural area. Such changes directly modify land-surface properties relevant to hydrological and ecological processes, including imperviousness, infiltration, evapotranspiration, vegetation cover, carbon storage, and habitat conditions. Therefore, population and economic indicators were used to characterize the broader socioeconomic process of urbanization, whereas LULC change provided the spatial linkage.

4.3 Assess the urban hydrological cycle in a watershed

4.3.1 Hydrological time series method

4.3.1.1 Long-term trends of hydrological cycle elements

(1) Five year moving average

The five-year moving average method was used to analyze the changes of hydrological cycle elements (precipitation or surface runoff or evaporation) in the NRB. It is to average several pre and post values of the hydrological series $x_1, x_2, \dots, x_n$ to derive a new series y_t , which smooths the original series (Wergen & Krug, 2010). The expression is as follows:

$$y_t = \frac{1}{2k+1} \sum_{i=-k}^k x_{t+i} \quad (1)$$

When $k = 2$, it's a five-year moving average.

(2) Mann-Kendall test

Mann-Kendall (MK) test was used to analyze time series of hydrological cycle elements (precipitation or surface runoff or evaporation) and to obtain the trend characteristics and the level of significance (Hirsch et al., 1982; Yue & Wang, 2002). It is seldom disturbed by outliers nor affected by the characteristics of data distribution, and is widely used for trend analysis of hydrological and meteorological time series (Kendall, 1948; Mann, 1945). It requires the constructed statistic U to assess whether there is an upward or downward trend. Its expression is as follows:

$$U = \frac{\tau}{[D(\tau)]^{\frac{1}{2}}} \quad (2)$$

$$\tau = \frac{4k}{n(n-1)} - 1 \quad (3)$$

$$D(\tau) = \frac{2(2n+5)}{9n(n-1)} \quad (4)$$

Where n is the length of time series. As n increases, U quickly converges to a normal distribution. τ is Kendall rank correlation coefficient measuring the monotonic trend in the time series. $D(\tau)$ is theoretical variance of Kendall's τ under the assumption of no trend. k is number of concordant pairs.

Assume that there is no trend in the original series H_0 . When $|U| < U_{\alpha/2}$, H_0 cannot be rejected, it means that the trend is not significant; conversely, the trend is deemed statistically significant. $U > 0$ indicates an increasing trend and $U < 0$ indicates a decreasing trend. $\alpha = 0.1$ was adopted in this research, and $U_{\alpha/2} = 1.64$.

4.3.1.2 Cyclical variations of hydrological cycle elements

In this research, wavelet analysis was used to analyze the cyclical variations of hydrological cycle elements and to identify dominant cycles in the hydrological time series. The analysis focused on three key hydrological elements: annual precipitation, annual runoff, and annual evaporation.

Wavelet analysis was first used for signal processing and analysis by noise reduction, reconstruction, and extraction of signals such as sounds, images, and earthquakes, so as to

determine at which time or frequency domain the vibrational cycles of different signals occur (Debnath & Shah, 2015; Pathak, 2009). It is now widely used in many fields. In geology, various meteorological factors, hydrological processes, and the process of material exchange between ecosystems and the atmosphere can be regarded as signals with cyclic changes over time, so the wavelet analysis method is applicable to the field of geology to analyze the complex time patterns of various geologic processes (Doglioni & Simeone, 2014; Prokoph & Patterson, 2004). For example, the daily and annual cycles of temperature change (Nalley et al., 2013); the cycle of El Niño-La Niña phenomenon and the time period of its appearance (Z. Huang & Morimoto, 2008), and so on.

Wavelet analysis is developed on the basis of Fourier transform. It is a method of multi-resolution analysis of signals through wavelet functions that can effectively provide high resolution in both the time and frequency domains (Sang et al., 2013). It does this by decomposing the time series into the time-frequency domain, which can result in significant patterns of fluctuations in the time series, i.e., cycle change dynamics, as well as time patterns of cycle change dynamics (Torrence & Compo, 1998).

Wavelet function $\psi(t)$ is a class of functions with oscillatory properties that decay rapidly to zero, called mother wavelets, which have the expression as follow (Abramovich et al., 2000):

$$\int_{-\infty}^{+\infty} \psi(t) dt = 0 \quad (5)$$

After stretching and translation, $\psi(t)$ becomes a cluster of functions $\psi_{a,b}(t)$, which called daughter wavelets:

$$\psi_{a,b}(t) = |a|^{-\frac{1}{2}} \psi\left(\frac{t-b}{a}\right), b \in R, a \in R, a \neq 0 \quad (6)$$

Where a is the scale factor, reflecting the period length of the wavelet. b is the translation factor, reflecting the translation in time. Using a series of daughter wavelets, a signal can be computed on different time scales and show detailed characteristic scales. Stretching a larger wavelet window so that it is wider allows for analyzing the more fluctuating parts of the time series and capturing the characteristics of large-scale (low-frequency) events. Conversely, compressing a smaller window will contain information about small-scale (high-frequency) events.

It has two types of transforms: continuous wavelet and discrete wavelet. Continuous wavelet transform transforms the signal by continuously translating and scaling the wavelet function. The result is a two-dimensional time-frequency map, known as the wavelet power spectrum, which provides detailed information about the signal at different scales and time locations. It is commonly used for signal feature extraction (Grinsted et al., 2004).

The continuous wavelet transforms for any function $f(t) \in L^2(R)$ is as follow:

$$W_f(a, b) = |a|^{-\frac{1}{2}} \int_{-\infty}^{+\infty} f(t) \psi\left(\frac{t-b}{a}\right) dt \quad (7)$$

In the above equation: $\bar{\psi}(t)$ is the complex conjugate function of $\psi(t)$; $W_f(a, b)$ is the wavelet transform coefficient.

In practice, time series are often discrete. The discrete wavelet transforms output a set of discrete time and scale coefficients by discretely sampling the signal and performing a wavelet transform. Usually, binary scales and discrete time positions are used. It is commonly used for noise reduction and data compression. In the trend analysis of hydrologically related parameters, the discrete wavelet change is generally used. Then it is expressed as follows:

$$W_f(a, b) = |a|^{\frac{1}{2}} \Delta t \sum_{k=1}^N f(k\Delta t) \bar{\psi}\left(\frac{k\Delta t - b}{a}\right) \quad (8)$$

Where $k = 1, 2, \dots, N$; Δt is the sampling interval time.

Whether continuous or discrete, the wavelet transforms displays both time and frequency domain properties of $f(t)$.

When a is small, the resolution is low for the frequency domain and high for the time domain. Conversely, a larger value of a corresponds to higher frequency domain resolution and lower time domain resolution. As a result, the wavelet transform allows time-domain localization using a window with fixed size but adaptable shape.

The wavelet variance can be expressed as follows:

$$Var(a) = \int_{-\infty}^{+\infty} |W_f(a, b)|^2 db \quad (9)$$

The selection of the mother wavelet is particularly important when wavelet transforming a time series. Factors such as orthogonality, Vanishing Moments, and the width and graph of the mother wavelet need to be considered. Figure 4-2 shows the waveforms of several commonly used wavelet functions, such as Haar Wavelet, Morlet Wavelet, Mexican Hat Wavelet, etc. Orthogonal wavelet functions are typically applied in discrete wavelet transforms, whereas non-orthogonal wavelets are applicable to both discrete and continuous wavelet analyses. In time series analysis, a smooth and continuous wavelet amplitude is generally desired. Therefore, non-orthogonal wavelet functions are more appropriate. Moreover, extracting both amplitude and phase information requires the use of complex valued wavelets, whose real and imaginary components effectively represent phase characteristics.

The Morlet wavelet not only has the non-orthogonality, but also the exponential complex-valued wavelet regulated by Gaussian (Gan et al., 2007; S.-J. Huang et al., 1999). Therefore, in this research, Morlet wavelet function was used, it is a single-frequency complex sinusoidal function under a Gaussian envelope, and it is expressed as follows:

$$\psi(t) = e^{ict} e^{-t^2/2} \quad (10)$$

Where c is a constant, and i is an imaginary number. The stretching scale a is related to T as follows:

$$T = \left(\frac{4\pi}{c + \sqrt{2 + c^2}} \right) \times a \quad (11)$$

When $c = 6.2$, $T \approx a$. That is the scale a and the period T are quantitatively equivalent. With b as the horizontal coordinate and a as the vertical coordinate, the contour plot of $W_f(a, b)$ can be made, which is called the wavelet coefficient of variation plot. The real contour plot of wavelet coefficients can show the cycle change of hydrological series in different time scales and the distribution in the time domain, and then it can reflect the hydrological series' future trend across several time spans (Cohen, 2019); the value of greater than 0 means that the precipitation or other elements of the hydrological cycle is on the high side, and the value of less than 0 means that it is on the low side. In addition, the wavelet variance map can reflect the energy distribution of hydrological time series fluctuations across time scales, which is used to define the dominant period in the evolution of hydrological elements (De Moortel et al., 2004). The main peak of the variance map is the location of the strongest fluctuation energy, the corresponding scale is the first dominant period, and the secondary peak is the second dominant period (Nicolay et al., 2009).

The real part and variance of wavelet coefficients were used in this research to characterize the cyclical characteristics of hydrological time series. Figure 5-7 (a) is wavelet power spectrum, which is the real part of the wavelet coefficients. The vertical coordinate was the time scale, and the horizontal coordinate was the year. Negative values indicate dry seasons, while positive values indicate wet seasons. Figure 5-7 (b) was the variance of wavelet coefficients, reflecting the distribution of various cyclic fluctuations with time scales and the relative intensity. The dominant period of precipitation can be determined by the wavelet variance plot, the vertical coordinate was the value of the variance, the horizontal coordinate was the time scale, the time scale at the peak of the variance wave is the first dominant period, and the secondary peak is the second dominant period of precipitation. Figure 5-7 (c) is a wavelet coefficient plot, the vertical coordinate was the wavelet coefficient, positive values indicate wet seasons and vice versa indicate dry seasons. The horizontal coordinate is the year, and the alternating years of the abundant and dry periods can be clearly showed.

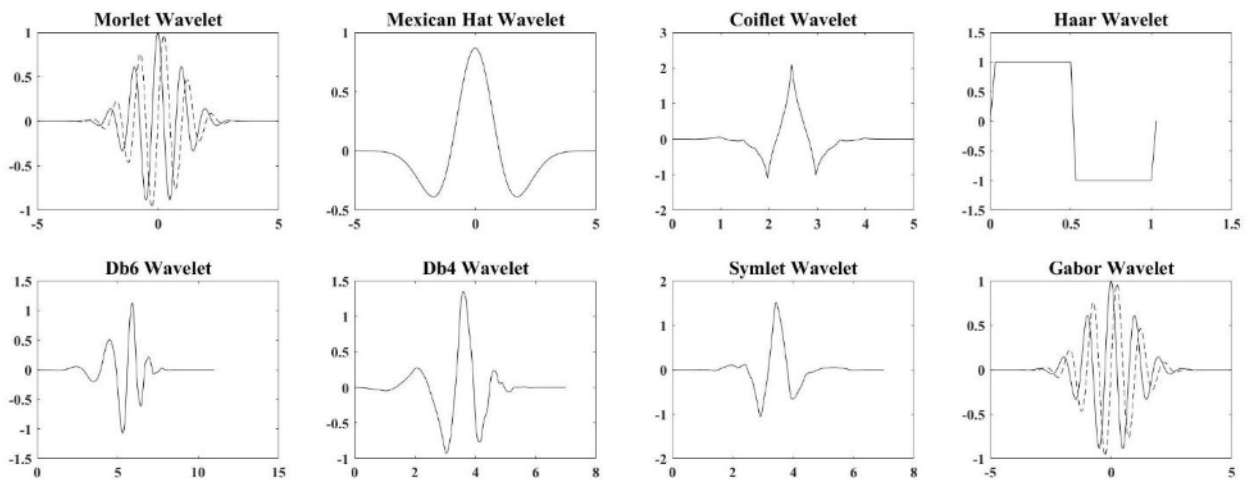


Figure 4-2: Common graphs of wavelet (Source: Author)

4.3.1.3 Intra-annual distribution of hydrological cycle elements

Concentration degree (C_d), concentration period (D), variation coefficient (C_v) and regulation coefficient (C_r) were used to reflect the intra-annual temporal and spatial distribution characteristics of the hydrological series.

Where C_d represents the concentration degree of precipitation (or runoff or evaporation), calculated as the ratio of the magnitude of the resultant vector (R) divided by the annual total precipitation (or runoff) (Darand & Pazhoh, 2022; de Luis et al., 2011). D is the direction of the precipitation (or runoff) vector after compositing, reflecting the month in which the center of gravity of precipitation and runoff concentration occurs throughout the year (X. Li et al., 2011). A year of 365 days can be roughly considered as a circle of 360° , determining the location of the precipitation (or runoff or evaporation) vector for January as 0° , and the monthly azimuths for each of the 12 months as $0^\circ, 30^\circ, 60^\circ \dots 360^\circ$, respectively. The vector value R_i for each month is divided into components in the x and y directions, then the sum vector in the x and y directions are as follow, respectively:

$$R_x = \sum_{i=1}^{12} R(i) \cos \theta_i \quad (12)$$

$$R_y = \sum_{i=1}^{12} R(i) \sin \theta_i \quad (13)$$

The resultant vector R of x and y direction component vectors:

$$R = \sqrt{R_x^2 + R_y^2} \quad (14)$$

C_d and D are as follow, respectively:

$$C_d = \frac{R}{\sum_{i=1}^{12} R(i)} \quad (15)$$

$$D = \arctan(R_y/R_x) \quad (16)$$

The formal of C_v :

$$C_v = \frac{\sigma}{R} = \sqrt{\frac{\frac{1}{12} \sum_{i=1}^{12} (R_i - R)^2}{\left[\frac{1}{12} \sum_{i=1}^{12} R_i \right]}} \quad (17)$$

The formal of C_r :

$$C_r = \sum_{i=1}^{12} \frac{\Phi_i (R_i - R)}{\sum_{i=1}^{12} R_i} \quad (18)$$

$$\Phi_i = \begin{cases} 0, & R_i < R \\ 1, & R_i \geq R \end{cases} \quad (19)$$

Higher C_d values indicate a more concentrated intra-annual distribution; whereas lower values indicate a more even distribution throughout the year. D denotes the time of concentration of

precipitation (or runoff), expressed as a direction angle (0° means January, 30° means February, and so on) (Table 4-2).

C_v and C_r represent the variability and concentration of the annual distribution of precipitation (or runoff or evaporation) (Medvigy & Beaulieu, 2012). A higher C_v indicates greater month-to-month variability and hence a more uneven intra-annual distribution. C_r measures the extent to which the annual total is concentrated within a limited period. A higher C_r indicates that a larger proportion of the annual precipitation (or runoff or evaporation) occurs during a few months, implying stronger seasonality and consequently a greater need for storage and regulation to balance water availability. Conversely, a lower C_r indicates a more evenly distributed annual total and a lower demand for regulation. Although C_d , C_v , and C_r all describe intra-annual distribution characteristics, they capture complementary aspects: C_d reflects the degree of temporal concentration, D identifies the timing of that concentration, C_v quantifies the variability of monthly distribution, and C_r measures the concentration of the annual total and its implication for regulation requirements.

Table 4-2: Angles for each month of the year

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Angle($^\circ$)	345-15	15-45	45-75	75-105	105-135	135-165	165-195	195-225	225-255	255-285	285-315	315-345
Angle($^\circ$)	0	30	60	90	120	150	180	210	240	270	300	330

4.3.1.4 Urban and suburban differences

The influence of urbanization on precipitation is analyzed in terms of the rainfall enhancement coefficient K . K is the ratio of urban precipitation to suburban precipitation. The value of K is greater than 1.0, indicating that urbanization has a significant influence on precipitation. K_1 and K_2 represent annual precipitation and flood season precipitation, respectively. it is expressed as follows:

$$K = \frac{P_u}{P_r} \quad (20)$$

Where, P_u represents urban precipitation and P_r represents rural precipitation.

For the urban-suburban differences in evaporation, only the amount of evaporation was considered.

4.3.1.5 Heavy rainfall events

Heavy rainfall events were analyzed to investigate long-term changes in rainfall characteristics and their hydrological responses within the NRB. Daily precipitation and runoff records from eight hydrological stations covering during 1957-2022 were collected. Historical heavy rainfall events were identified from the precipitation records, and four indicators were extracted for each event: average precipitation, antecedent precipitation, peak flood flow, and runoff depth. The MK test was applied separately to each indicator to evaluate long-term temporal trends.

The results were used to assess changes in the characteristics of heavy rainfall events and their hydrological responses in the NRB.

4.3.2 Spatial distribution

In this research, precipitation and runoff data from the obtained hydrological stations were spatially interpolated into surface data for observing their spatial distribution.

Kriging interpolation, a classical interpolation method based on statistical and geospatial correlation, was used to estimate unknown values of spatially continuously varying variables (Krige, 1951). It assumes that known and unknown points in space are continuous and correlated, that this correlation decreases with increasing distance, and that the values of unknown points are inferred from the values of known sample points. Kriging interpolation has the characteristics of optimal unbiased estimation, spatial correlation and flexible adaptation (Matheron, 1963). Optimal unbiased estimation means that the mathematical expectation of the result of Kriging interpolation is equal to the true mathematical expectation, which means that the mean of the error is 0 and is not either systematically overestimated or underestimated. Spatial correlation means that Kriging interpolation quantifies the spatial autocorrelation of the data by means of a variance function (or covariance function), which describes the degree of spatial variability among different points (van Beers & Kleijnen, 2003). The weights are determined based on the distance among the spatial data points and their variance functions, and are estimated using the trend of neighboring points.

The directional variation of spatial data is also considered, it means that the spatial correlation may be different in different directions, making the interpolation more consistent with the actual distribution of the data. Flexible adaptation means that there are several variants of Kriging interpolation, such as Ordinary Kriging, Simple Kriging, Universal Kriging, and Indicator Kriging, which can be used according to different data characteristics (Kebaili Bargaoui & Chebbi, 2009). Its expression is as follows:

$$\hat{Z}(s_o) = \sum_{i=1}^N \lambda_i Z(s_i) \quad (21)$$

Where $Z(s_i)$ is the estimated value at the i th position, s_o is the predicted position, and N is the number of measurements. λ_i is the weighting coefficient of the measurements at the i th position that satisfies the set of optimal coefficients that minimize the difference between the estimated value $\hat{Z}(s_o)$ and the true value $Z(s_o)$ at position i , as given in the following equation:

$$\lambda_i = \min_{\lambda_i} \text{Var}(\hat{Z}(s_o) - Z(s_o)) \quad (22)$$

The unbiased estimation condition is also satisfied:

$$E(\hat{Z}(s_o) - Z(s_o)) = 0 \quad (23)$$

4.4 Assess hydroecology

The condition of water ecosystems directly affects the hydrological cycle and flood regulation capacity, and effective assessment and utilization of these water ecological functions can

enhance the natural regulation capacity of watersheds and reduce the need and cost of interventions. In this research, the water ecological functions of a watershed are expressed through three aspects: water conservation capacity, carbon storage and biodiversity.

This research applied Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) Model to assess hydroecological functions. It is an open-source software model for mapping and valuing the ecosystem services. It was developed by Stanford University, the Nature Conservancy, the World Wide Fund for Nature and other relevant organizations, InVEST is able to assess a wide range of ecosystem services. It can evaluate and analyze ecosystem services under different scenarios, which can scientifically assess the status of ecosystem services in a region and help in policy and decision making.

In addition, it strongly relies on GIS data, which allows the model to assess changes in ecosystem services in detail at the geospatial scale. And the required data is easily accessible. InVEST Model 3.12.1 version (<https://naturalcapitalproject.stanford.edu/software/invest>) was used in this research.

4.4.1 Water yield

The Annual Water Yield module was applied to simulate the water conservation capacity and multi-year changes in the NRB. Water yield reflects the amount of water generated and regulated by ecosystem processes under different land use conditions. Areas with higher water yield are considered to have greater potential for water resource supply and hydrological regulation, thereby contributing to watershed water conservation. It is based on the Budyko curve and water balance (Budyko, 1974). It is calculated as follows (X. Wang et al., 2022; C. Wu et al., 2022; Zhou et al., 2005).

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \times P(x) \quad (24)$$

$Y(x)$, $P(x)$, and $AET(x)$ are total annual water yield (mm), average annual precipitation, annual actual evapotranspiration (mm) on pixel x , respectively.

$$\frac{AET(x)}{P(x)} = 1 + \frac{PET(x)}{P(x)} - \left[1 + \left(\frac{PET(x)}{P(x)}\right)^w\right]^{\frac{1}{w}} \quad (25)$$

$PET(x)$ is the potential evapotranspiration. $w(x)$ is a non-physical parameter.

$$PET(x) = K_c(x) \times ET_o(x) \quad (26)$$

$K_c(x)$ is the crop coefficient, which is related to evapotranspiration; $ET_o(x)$ is the reference evapotranspiration (mm/d).

$$w(x) = \frac{\min(MaxSoilDepth_x, RootDepth_x) PAWC_x \times Z}{P(x)} + 1.25 \quad (27)$$

Z is an empirical constant that is related to the hydrological and soil environment of the region.

$MaxSoilDepth_x$, $RootDepth_x$ are the maximum depth of soil and root. $PAWC(x)$ is plant available water content, it represents the plant's ability to regulate soil water infiltration and replenishment.

$$PAWC = 54.509 - 0.132sand - 0.003(sand)^2 - 0.055silt - 0.006(silt)^2 - 0.738clay + 0.007(clay)^2 - 2.688OM + 0.501(OM)^2 \quad (28)$$

OM is the soil organic matter content; *sand*, *silt*, *clay* is the percent of key soil components.

LULC (J. Yang & Huang, 2022), annual precipitation (Peng, 2023), annual evapotranspiration, root restricting layer depth (RRLD) (Yan et al., 2020), and PAWC (Hadipour et al., 2024; Sannigrahi et al., 2020) are applied to calculate water yield (Figure 4-4). RRLD denotes the soil depth at which root penetration is strongly restricted, thereby limiting plant growth. PAWC is range from 0 to 1.

In addition, the biophysical table is required to reflect the attributes of LULC types (Table 4-3). LULC_veg (is LULC vegetation) indicates whether the LULC type is vegetated: “1” denotes coverage, while “0” indicates no coverage. It’s to calculate actual evapotranspiration (AET). LULC vegetation indicates the presence of vegetation cover and affects actual evapotranspiration. In this research, cropland, forest, and grassland were defined as 1, indicating vegetation cover; and water, bare land, impervious area were defined as 0, indicating no vegetation cover (M. Guo et al., 2021; Y. Yu et al., 2022; W. Zhang et al., 2025).

Table 4-3: The parameters of biophysical table

description	lucode	root_depth (mm)	Kc	LULC_veg
Cropland	1	2000	0.65	1
Forest	2	5200	1	1
Grassland	3	2300	0.65	1
Water	4	100	1	0
Bare land	5	300	0.2	0
Wetland	6	100	0.3	0

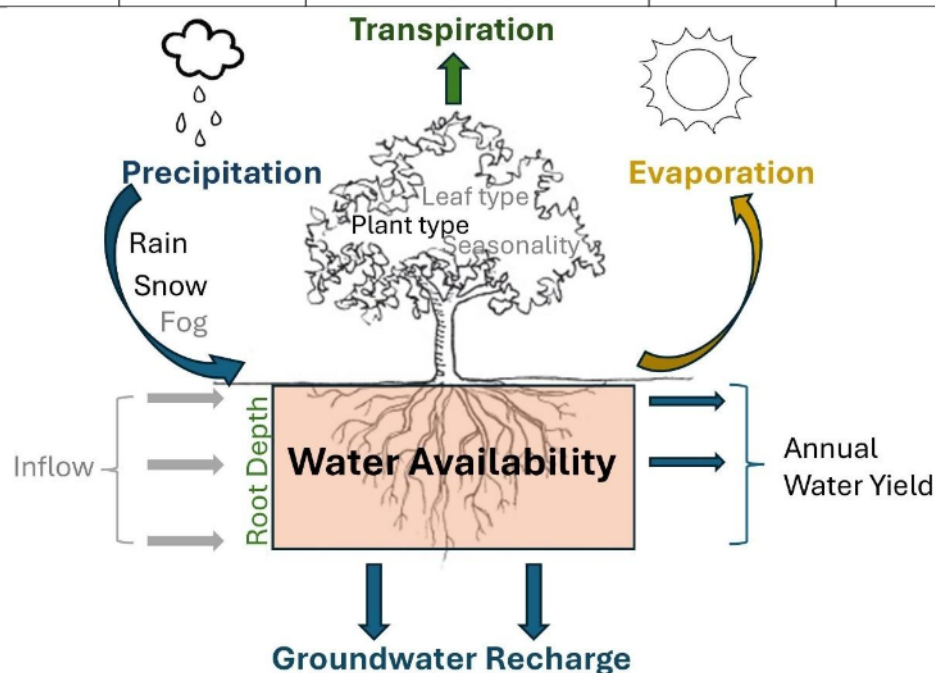


Figure 4-3: Conceptual diagram of the simplified water balance method used in the annual water yield model (Source: User Guide of InVEST Model)

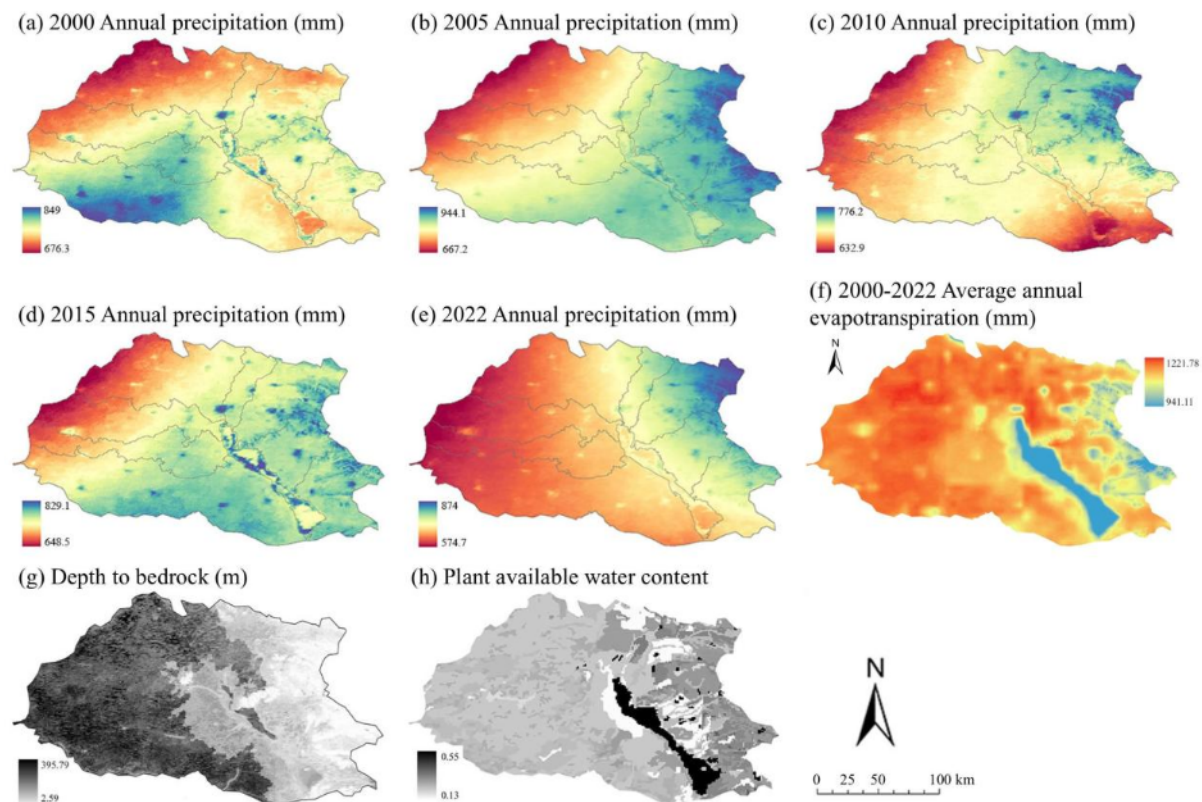


Figure 4-4: Input data of InVEST (Source: Author)

4.4.2 Carbon storage

The process of carbon sequestration also enhances hydrological functions. Increased carbon storage implies an expansion of natural ecosystems capable of absorbing CO₂, such as forests, grasslands, and wetlands (Nowak & Crane, 2002), thereby restoring the hydrological ecology of watersheds closer to its natural state. The InVEST Carbon Storage and Sequestration model was used in this research.

Carbon stocks are influenced by four carbon pools: aboveground, belowground, soil organic matter, and dead organic matter (Figure 4-5). They are stored in different types of LULC (Butsic et al., 2017; Dargains & Cabral, 2021; Khachoo et al., 2024).

Following references (J. Li et al., 2022; P. Li et al., 2023; H. Zheng & Zheng, 2023), the carbon pool parameters for the NRB are presented in Table 4-4.

Table 4-4: Carbon density of different LULC types (unit: t/ha)

lucode	LULC_Name	C_above	C_below	C_soil	C_dead
1	Cropland	10.17	39.33	113.54	1.32
2	Forest	75.81	107.08	146.67	2.15
4	Grassland	67.00	92.57	125.70	8.46
5	Water	0.00	19.85	18.98	0.00
7	Imperviousland	4.47	0.00	105.47	0.00
8	Bare land	2.36	0.00	42.19	0.00

The total carbon stock in the study area is the sum of the carbon stocks in each LULC. The formula for total carbon is as follows:

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \quad (29)$$

$$C_{totali} = (C_{abovei} + C_{belowi} + C_{soili} + C_{dead_i}) \times A_i \quad (30)$$

Where A_i is area of each LULC, i is the number of LULC, C_{above} is carbon stocks in above-ground carbon pools, C_{below} is carbon stocks for underground carbon pools, C_{soil} is carbon stocks in soil carbon pools, C_{dead} is carbon stocks for dead organic carbon pools, C_{total} is sum of carbon stocks.

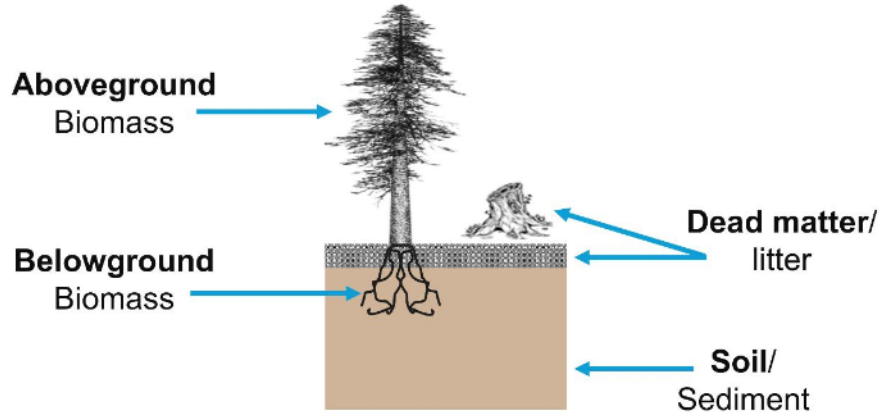


Figure 4-5: Carbon pools included in the Carbon Storage and Sequestration model (Source: User Guide of InVEST Model)

4.4.3 Habitat quality

Habitat quality is defined as the capacity of an ecosystem to provide adaptations to natural ecological conditions and is highly territorial (Terrado et al., 2016). The level of habitat quality reflects the degree of fragmentation of regional habitats and the ability to interfere with habitat degradation (Wiegand et al., 2005). Biodiversity is an important indicator of ecosystem services. InVSET's Habitat Quality module is estimated by analyzing LULC maps and threats to species' habitats (Sallustio et al., 2017). Four primary factors influence habitat quality, including threat intensity, habitat specific sensitivity to threats, the distance between habitat areas and threat elements, and the level of legal protection afforded to the land (Q. Wang & Wang, 2023). The results of the Invest model for calculating habitat quality take a range of 0-1, with the closer the value to 1, the stronger the capacity to mitigate habitat degradation. The formulas are as follows.

$$Q_{xj} = H_j \left(1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z} \right) \right) \quad (31)$$

$$D_{xj} = \sum_{r=1}^R \sum_{y=1}^{Y_r} \left(\frac{\omega_r}{\sum_{r=1}^R \omega_r} \right) r_y i_{rxy} \beta_x S_{jr} \quad (32)$$

$$i_{rxy} = \begin{cases} 1 - \left(\frac{d_{xy}}{d_{rmax}} \right) & \text{if linear} \\ \exp \left(- \left(\frac{2.99}{d_{rmax}} \right) d_{xy} \right) & \text{if exponential} \end{cases} \quad (33)$$

Where x and y is grid cell; d_{xy} is the distance between x and y . d_{rmax} is the maximum effective distance of threat r 's reach across space. i_{rxy} is the impact of threat r that originates in grid cell y on habitat in grid cell x . i_{rxy} can be described by both linear and exponential euclidean distance-decay function. At the maximum effective distance, the impact of the threat is diminished to a mere 5% of its original strength, provided an exponential decay constant of 2.99 is applied.

z and k is the half saturation constant; D_{xj} is the total threat level in grid cell x with LULC or habitat type; R is all modeled degradation sources; ω is the impact weight of threat r ; β_x is the accessible grid cell x ; S_{jr} is the relative sensitivity of LULC type j to threat r .

Q_{xj} is the habitat quality of grid cell x with LULC type j . H_j is the habitat suitability of LULC type j .

In this research, cropland, construction land, bare land, road and railway were chosen as threats. Parameters of sensitivity (Table 4-5) and parameters of threats (Table 4-6) as follows.

Table 4-5: Parameters of sensitivity

LULC	NAME	HABITAT	cropland	construction	bare land	road	railway
1	Cropland	0.30	0.00	0.70	0.40	0.40	0.40
2	Forest	1.00	0.70	0.40	0.20	0.65	0.65
4	Grassland	1.00	0.80	0.60	0.60	0.40	0.40
5	Water	0.80	0.40	0.40	0.20	0.60	0.60
7	Bare land	0.00	0.00	0.00	0.00	0.00	0.00
8	Constructi on land	0.00	0.00	0.00	0.10	0.00	0.00

Table 4-6: Parameters of threats

MAX_DIST	WEIGHT	THREAT	DECAY
4	0.6	cropland	linear
8	0.9	construction	exponential
6	0.5	bare land	linear
3	0.6	road	linear
10	0.8	railway	linear

Where Max_Dist is the maximum impact distance, which indicates the maximum impact distance of various threat elements on habitat quality. Proximity to the degradation source determines the severity of habitat degradation. Specifically, grid cells situated closer to the danger point undergo more intense impacts than those at a distance. A linear or exponential Euclidean distance decay function can be used to describe how a quickly a threat decrease. WEIGHT is the impact of each threat on habitat quality, can take any value from 0 to 1.

4.5 Assess water security

Water security involves ensuring that human society can continuously obtain sufficient, safe and acceptable water to meet living, production and ecological needs. Water security is not only the basis of public health, but also the key to social and economic development and political stability. It is usually assessed from the aspects of water source protection, flooding risk and water pollution.

4.5.1 Water source protection

Water source protection aims to protect and restore the quality and supply capacity of water supply systems. In this research, the boundaries of water source protection areas were delineated by establishing buffer zones around major surface water bodies.

Buffer zones are areas of land around a water body that are designated to reduce the risk of pollutants entering the water body through surface runoff (Anbumozhi et al., 2005). These areas are usually covered with vegetation, such as grass or forest, which absorbs and filters pollutants. Establishing the buffer zone width depends largely on the ecological sensitivity of the specific water body being protected and the LULC of the surrounding area (Correll, 2005). For linear water bodies (rivers), the width of the river channel was used as the basis for determining the corresponding protection buffer. For areal water bodies (lakes and reservoirs), the protection buffer was determined according to the area of the water body. Larger water bodies generally require wider protection zones because of their greater ecological importance and water supply functions. Depending on the level of protection, buffers of varying distances are set to create protected areas. The higher the level of protection, the closer the buffer distance. The classified protection zones were subsequently used to identify areas where land use activities should be more strictly controlled. For example, limiting the development of high-risk industries, banning agricultural activities that use pesticides and fertilizers, and prohibiting the discharge of wastewater. Potential threats to water quality can be reduced by implementing land use planning and establishing protected areas (Lerner & Harris, 2009; Zhukov et al., 2021).

4.5.2 Flood inundation risk

Inundation risk assessment was used to optimize flood protection measures and to develop more scientific land-use policies and emergency management measures to mitigate the impacts of possible future flood hazards on populations and infrastructure. In this research, the Soil Conservation Service Curve Number (SCS-CN) model was used to calculate the flood inundation depth of the watershed (M. Jia et al., 2023). It was developed by the United States Department of Agriculture Natural Resources Conservation Service, and is suitable for designing flood models for small and middle watersheds (Mishra & Singh, 2013). The parameters needed for the model are easy to obtain and the calculation process is simple, mainly relying on LULC, soil type and rainfall data (Lal et al., 2017). And the simulation results can be visualized through the GIS platform.

However, factors such as rainfall duration and rainfall intensity are ignored, and the accuracy may be reduced especially under a single extreme precipitation event. The model follows the water balance equation and is based on two basic assumptions: the ratio of actual infiltration F

to actual runoff Q in the catchment is equal to the ratio of the maximum possible infiltration S to the maximum possible runoff Q_m in the catchment; the initial abstraction I_α is a fraction of the potential storage capacity, or the amount of water before runoff, such as infiltration, or rainfall interception by vegetation; historically. In addition, the maximum possible runoff volume Q_m is equal to precipitation Pre minus the initial abstraction I_α . The model's computed equation is as follows.

$$\frac{F}{Q} = \frac{S}{Q_m} \quad (34)$$

$$Q_m = Pre - I_\alpha \quad (35)$$

Water Balance Formula:

$$Pre = I_\alpha + F + Q \quad (36)$$

Therefore:

$$Q = \frac{(Pre - I_\alpha)^2}{(Pre - I_\alpha + S)} \quad (37)$$

After a large amount of precipitation and runoff data the relationship between I_α and S is obtained as follows

$$I_\alpha = 0.2S \quad (38)$$

So,

$$\begin{cases} Q = \frac{(Pre - 0.2S)^2}{Pre + 0.8S}, & Pre > 0.2S \\ Q = 0, & Pre \leq 0.2S \end{cases} \quad (39)$$

The relation between S and CN is as follows:

$$S = \frac{25400}{CN} - 254 \quad (40)$$

Where CN is the runoff curve, a dimensionless parameter determined by soil type, initial soil moisture, and land use type. CN ranges from 0 to 100, and in actual precipitation events, CN usually has a value between 30 and 100.

Inundation depth was calculated under different rainfall return periods and land use conditions. The minimum and maximum inundation depths derived from these scenarios were used as threshold values. Using the DEM of each sub-watershed, inundation risk was classified into three levels: areas with elevations lower than the minimum inundation depth were defined as high risk zones; areas with elevations between the minimum and maximum inundation depths were classified as medium risk zones; and areas with elevations higher than the maximum inundation depth were considered low risk zones.

In this research, SCS-CN model was used to calculate the depth of flood inundation in NRB. The model needs to determine the value of a CN parameter. Based on the CN reference values given in the U.S. National Handbook and related studies (Fu et al., 2012; Soil Conservation Service, 1956; H. Wang et al., 2012), the CN values for different LULCs were determined as

shown in the Table 4-7. The weighted CN values were then calculated based on the area share of different LULC types in the sub- watersheds (Table 4-8).

Table 4-7: CN value of LULC

LULC	Cropland	Forest	Grassland	Water	Bare land	Impervious land
CN	43	55	58	98	85	81

Table 4-8: Weighted CN values for sub-watersheds

Year	Dongyu	Wanfu	Sihe	Guangfu	Liang qiyun	Panlong	Shizi	Zhuzhaoxin
2000	48.82	48.04	50.38	49.84	48.58	52.20	51.73	49.27
2010	50.36	49.28	52.42	53.08	49.89	53.85	53.79	50.90
2022	51.90	50.75	53.71	55.36	51.69	54.93	54.76	53.03

In this research, the design rainfall for the three cities of Jining, Heze and Zaozhuang, was calculated for different return periods using the Chicago Design Storm and the storm intensity formula, and then its weighted value was calculated to represent the design precipitation (Table 4-9) of NRB, which was used to calculate the runoff volume.

The storm intensity equations of Jining, Heze and Zaozhuang are respectively:

$$q = \frac{2451.987 \times (1 + 0.8931 \lg P)}{(t + 14.249)^{0.733}} \quad (41)$$

$$q = \frac{2578.764 \times (1 + 0.9971 \lg P)}{(t + 13.076)^{0.785}} \quad (42)$$

$$q = \frac{1170.206 \times (1 + 0.919 \lg P)}{(t + 5.445)^{0.595}} \quad (43)$$

Among them, P is design return period (Unit: year), q is design storm intensity (Unit: L/(s/ha)), t is Precipitation duration (Unit: minutes). This research simulated the 2-hour precipitation, so $t = 120$.

Table 4-9: Design precipitation for the NRB

Design rainfall (mm)	10a	20a	50a	100a	200a
Jining	92.33	105.44	122.78	135.89	149
Heze	80	91.98	107.86	119.88	131.89
Zaozhuang	91.75	104.97	122.46	135.68	148.91
Nansihu River Basin	87.08	99.73	116.48	129.15	141.82

4.5.3 Water quality

The analysis of water quality is only for surface water. China's Environmental Quality Standards for Surface Water GB3838-2002 (General Administration of Quality Supervision, Inspection and Quarantine, 2002) (hereinafter referred to as GB3838-2002) was chosen as the evaluation standard for water quality. It is divided into five categories according to the environmental functions and protection objectives of surface water waters. It is generally

believed that if the water quality can reach the standard of water quality of the corresponding functional area, the water system of the watershed is healthy.

Category I: mainly applies to source water and national protected areas.

Category II: mainly intended for use in primary protection zones of centralized surface drinking water sources, including rare aquatic habitats, spawning grounds for fish and shrimp, and habitats for juvenile fish.

Class III: primarily applicable to secondary protection zones of centralized domestic surface drinking water sources, as well as fish and shrimp wintering grounds, migration corridors, aquaculture zones, other fishery waters, and designated swimming areas.

Class IV: intended mainly for general industrial water and recreational water which humans do not come into direct contact with the water.

Class V: primarily applicable to agricultural water and waters designated for general landscape purposes.

China National Environmental Monitoring Centre provides national automatic water quality monitoring data, and this research collected 6-hourly water quality monitoring data of river cross sections in 2023, including water quality category, Chemical Oxygen Demand (COD_{Mn}), Ammonia Nitrogen (NH₃-N), Total Nitrogen (TN) and Total Phosphorus (TP) (Table 4-10). There are 50 monitoring stations in the NRB, excluding incomplete data and inaccurate stations, 25 stations were used in this research, and their spatial distribution covers nearly the entire study area.

Table 4-10: Environmental Quality Standards for Surface Water - Standard Limits for Major Pollutants (GB3838-2002)

No.	Pollutants		I	II	III	IV	V
1	COD _{Mn}	≤	2	4	6	10	15
2	NH ₃ -N	≤	0.15	0.5	1.0	1.5	2.0
3	TP	≤	0.02(Lake, Reservoir 0.01)	0.1(Lake, Reservoir 0.025)	0.2(Lake, Reservoir 0.05)	0.3(Lake, Reservoir 0.1)	0.4(Lake, Reservoir 0.2)
4	TN (Lake, Reservoir)	≤	0.2	0.5	1.0	1.5	2.0

For each of the 25 monitoring stations, the water quality monitoring data for one year were analyzed separately. The percentage of monitoring data classified as water quality Categories IV and V was calculated for each station. Stations with a higher percentage of Categories IV and V were considered to have poorer water quality. The calculated percentages were then reclassified into three classes: 1 (good water quality, <10%), 2 (moderate water quality, 10%–40%), and 3 (poor water quality, >40%).

In addition, this research used the Single Pollution Index (SPI) and the Combined Pollution Index (CPI) to assess the share of each pollutant among all pollutants.

SPI:

$$P_{ij} = Q_{ij} / Q_{si} \quad (44)$$

Average CPI:

$$P_j = \frac{1}{n} \sum_i P_{ij} \quad (45)$$

Among them, i is number of Water Pollutant ($i=1.2.3.4$ is COD_{Mn} , $\text{NH}_3\text{-H}$, TP and TN, respectively); j is number of monitoring station; Q_{ij} is measured value of pollutant concentration i of monitoring station j ; Q_{si} is standard limit of pollutant concentration i (This research followed the environmental quality standard for surface water, Class III); P_{ij} is single pollution index; P_j is combined pollution index; n is count of water pollutant.

4.6 Development of rainwater management strategies

The dominant water-related problems and ecological characteristics of different areas were first identified based on the assessments, and corresponding management strategies were assigned.

The results of urbanization assessment and hydrological analysis were used to identify areas where urban development had significantly altered natural hydrological processes, including increased runoff generation, reduced infiltration capacity, and changes in water balance. These areas were considered priorities for rainwater regulation. The results of hydroecological assessment were used to identify areas with important ecological functions and high ecosystem service values. These areas were considered priorities for ecological conservation and restoration. The water security assessment was used to identify areas facing water-related risks, including water shortages, flood risks, and water quality pressures.

From the perspective of land-use planning and water management, stormwater management at the river basin level is a far more challenging task than planning for individual cities or neighborhoods. The responsible planning authorities must consider the entire water cycle of a river basin—from the headwaters to the mouth—while taking into account flood protection, water quality, ecosystems, urban development, and climate change in an integrated manner (Environment Agency, 2023; Jining City Government, 2022; Regenwasserbewirtschaftung, 2024). Strategic focus key tasks of planning authorities are as follow.

- (1) Integrated river basin planning development of a river basin management plan: coordination of all water-related measures at the river basin level rather than along administrative boundaries.
- (2) Flood risk management identification of flood-prone areas, modeling of heavy rainfall, designation of retention areas, flood protection concepts, and emergency planning.
- (3) Surface runoff management reduction of rapid runoff through infiltration, retention, evaporation, and rainwater harvesting, as well as promotion of decentralized solutions.
- (4) Water quality management reduction of sediments, nutrients, heavy metals, and microplastics in stormwater; protection of rivers, lakes, and groundwater.
- (5) Protection of natural retention areas conservation and restoration of floodplains, wetlands, and natural flood zones as an integral part of flood protection.

- (6) Land-use planning and land use management of urban development, limiting land sealing, designation of flood zones, and integration of water management considerations into municipal and regional land-use planning.
- (7) Climate adaptation taking into account more frequent heavy rainfall, longer dry spells, and an increase in extreme events in all planning processes.
- (8) Data and information management development of GIS databases, hydrological models, remote sensing, sensor technology, and digital twins for the entire watershed.

5 Results and discussion

5.1 Urbanization in the NRB

This chapter analyzed the levels of urbanization from three perspectives: population urbanization, industrial changes, and LULC. Among these, it is changes in LULC that truly influence rainwater management, directly altering the underlying surface of the watershed. While the other two explain the socioeconomic context of these LULC changes. This chapter identified the urbanization process and its drivers in the NRB, providing a context for analyzing hydrological responses.

5.1.1 Changes in population

The urbanization rate of the three main cities in the NRB, Jining, Heze and Zaozhuang was showed in Figure 5-1. It can be seen from the figure that the urban population ratios of all three cities show an increasing trend, reflecting the advancement of the urbanization process. However, there were differences in the growth rates and patterns among the cities, which might be influenced by factors such as local economic development, policy orientation and geographic location.

(1) Zaozhuang: had consistently the highest urban population ratio of the three cities. Zaozhuang's urban population ratio had grown steadily from about 14.3% in 1984 to nearly 60% in 2017. The overall growth trend was relatively smooth, showing stable urbanization development.

(2) Jining City: started slightly lower than Zaozhuang's in 1984, at 11.7%, but grew faster from 1990 and especially significantly after 2005, also approaching 60% by 2017. This might reflect the aggressive urbanization policies in Jining during that period.

(3) Heze City: grew relatively slowly, starting from less than 10% in 1984 to 40.67% in 2017. This indicated that the urbanization process in Heze is slower than in Jining and Zaozhuang, possibly limited by the pace of economic development or other socioeconomic factors.

(4) All three cities are located within Shandong Province, and compared to the urbanization rate in Shandong Province, the relative level of urbanization development in the NRB can be judged. The ratio of urbanized population in Shandong Province had grown steadily from about 15 % in 1984 to nearly 62 % in 2017. Compared to Shandong Province, the growth in the rate of urban population in all three cities, although significantly higher, did not reach the provincial average. Before 2005, Zaozhuang was slightly above the Shandong provincial average, but between 2005 and 2012, it was well below it. This indicates that the region's urbanization is lagging behind relative to other cities in the province. The urbanization process in Heze was significantly slower than in the other two cities for a number of reasons, such as infrastructure development, degree of industrialization, population mobility and other factors. Since the late 1990s, the NRB had entered a stage of accelerated urbanization. Currently, the urbanization rates of the three cities are close to or have exceeded 60%, and are about to enter a stage of high-speed urbanization.

Population data for 1997-1999 and 2005 were missing for Heze City, but this did not affect the overall trend.

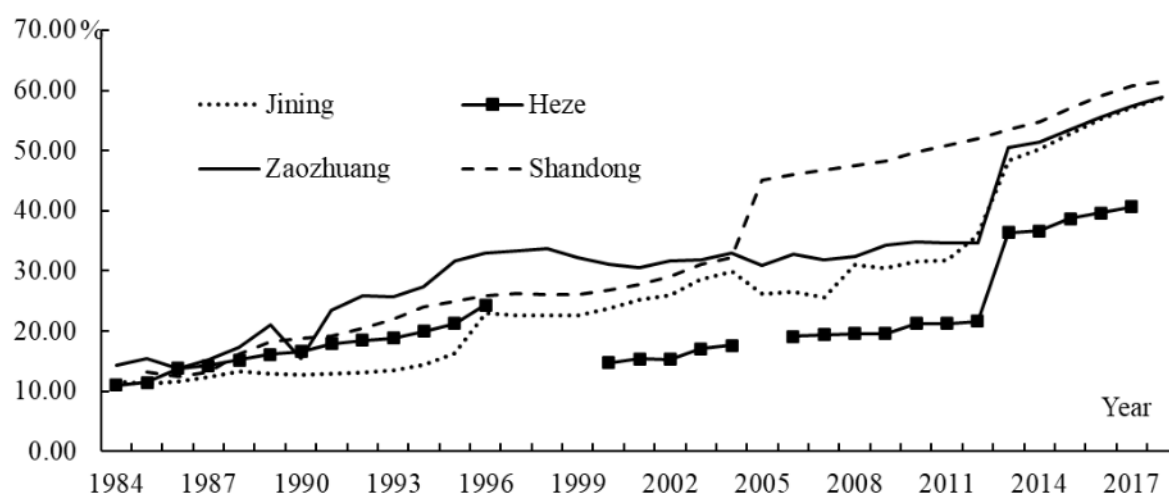


Figure 5-1: Ratio of urban population to total population in Jining, Heze, Zaozhuang and Shandong province (Source: Author)

The cities and towns within the NRB included type II large cities, medium cities and small cities. After the reform and opening up, the size of cities in the NRB had a large development change, some cities gradually developed from medium-sized cities to type II large cities (Table 5-1).

In the 1990s there were 9 type II large cities (27.27%), 18 medium-sized cities (54.55%) and 6 type I small cities (18.18%). During 1990s and 2000s, Fengxian, Yuncheng from the medium-sized cities to develop into a type II large cities. During 2000s and 2010s, Juno developed from a medium city to a large city of type II, and Zaozhuang city center district developed from a type I small city to a medium city. During 2010s and 2020s, Rencheng District in Jining City develops from a medium city to a large city, and Shanting and Xuecheng develop from Type I small cities to medium cities. By 2022, there were 13 Type II large cities (39.39%), 17 medium cities (51.52%) and 3 Type I small cities (0.9%). Taierzhuang District had also seen a significant growth in city size over the past 30 years, but it was still a small city until 2022.

Table 5-1: Urban scale of the NRB in 2022

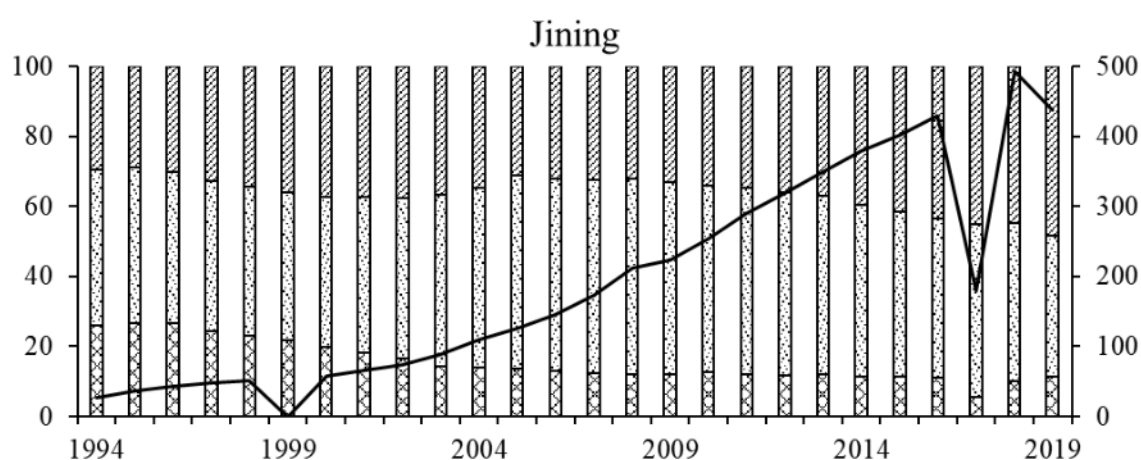
City scale	Population scale	Name of city
II Large city	1-3 million	Caoxian, Tengzhou, Yuncheng, Peixian, Shanxian, Xintai, Tongshan, Fengxian, Mudan, Zoucheng, Juye, Lanling, Rencheng
Medium city	0.5-1 million	Juancheng, Dongming, Liangshan, Chengwu, Dingtao, Jiaxiang, Wenshang, Dongping, Ningyang, Jinxiang, Qufu, Weishan, Shizhong, Yanzhou, Xuecheng, Sishui, Shanting
I Small city	0.2-0.5 million	Yicheng, Yutai, Taierzhuang
II Small city	<0.2 million	/

5.1.2 Changes in the structure of the industrial economy

Figure 5-2 showed that the proportion of primary industry in Jining had been decreasing year by year, reflecting the gradual decline in the contribution of agriculture to the economy. After reaching its peak around 2004, secondary industry had gradually stabilized and declined slightly. The proportion of tertiary sector has continued to rise, indicating the growth of the service industry. GDP had continued to grow rapidly from a low level in 1994, especially after 2009. The primary industry in Zaozhuang had been on a similar downward trend to that of Jining. The proportion of secondary industry peaked in 2004, and had fluctuated since then but was stable overall. The proportion of tertiary industry had increased year on year, indicating a gradual shift in the economic structure towards a service-oriented one. GDP had shown an overall upward trend, although there had been some fluctuations between 2014 and 2019. The proportion of primary industry in Heze City had gradually decreased, consistent with the trend of the other two cities. The proportion of secondary industry had slightly decreased after attaining a peak in 2009. The proportion of tertiary industry has increased annually, showing a gradual increase in reliance on the service sector. GDP had been growing year by year since 1994, and the growth rate accelerated after 2009, especially after 2014.

(Note: Jining was missing data on GDP in 1999, and Heze was missing data on the proportion of three industries and GDP in 1999.)

In summary, the three cities had similar patterns of industrial transformation, but the specific industry proportion and GDP growth rates reflected their own unique economic dynamics and regional development differences. All three cities showed an evolution of the industrial structure favoring secondary and tertiary industries, with the tertiary industry increasing most significantly, reflecting a general trend in modern economic development. The proportion of the primary industry had continued to decline, and between 2004 and 2009, the proportion of secondary industry in Jining and Heze showed a drum-like shape, it maenad that industry in both cities was developing at a high rate during this time period. The GDP of all three cities showed a significant growth trend, especially after 2009. This phenomenon may be associated with the broader context of China's rapid economic growth.



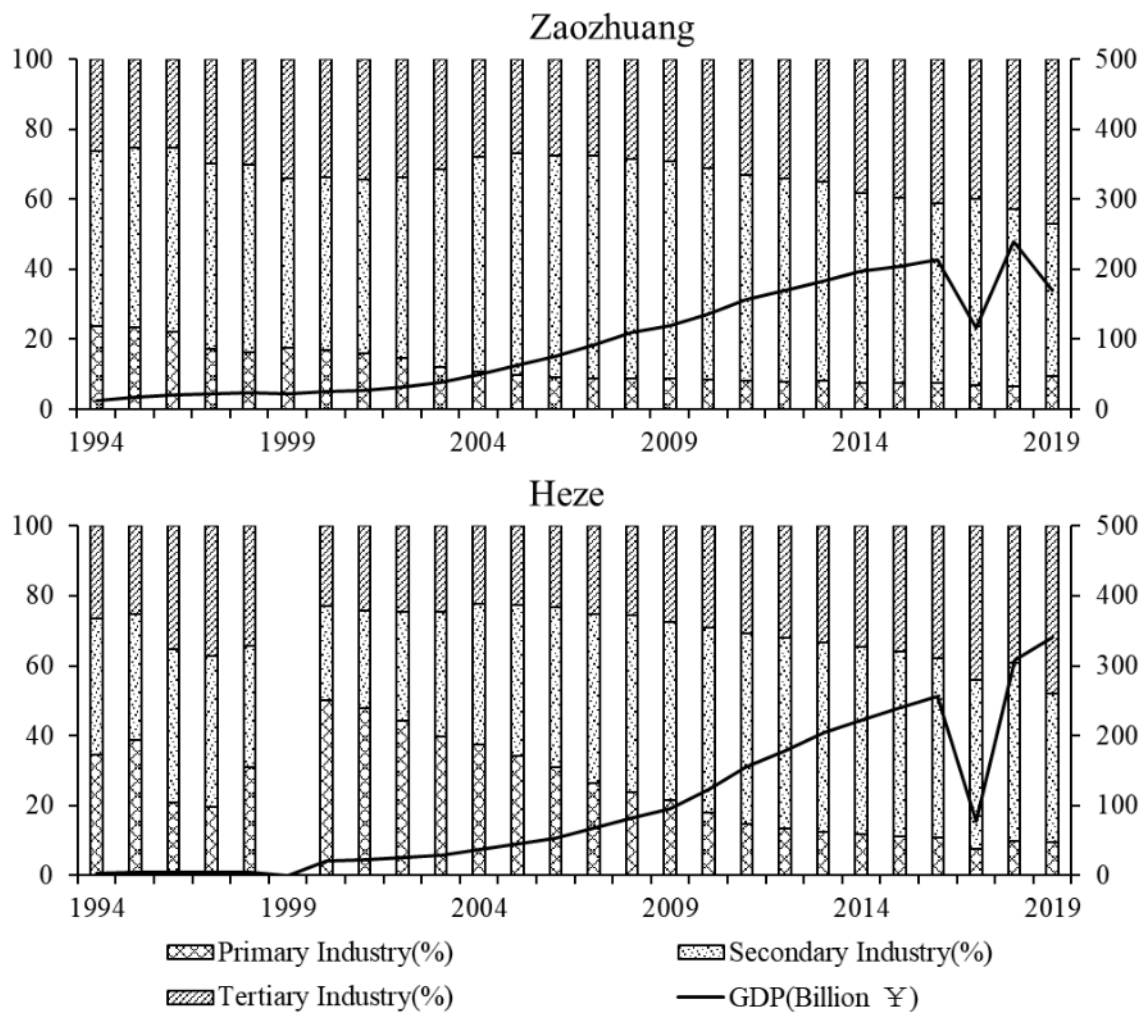


Figure 5-2: Ratio of three industries and GDP in Jining, Heze and Zaozhuang (Source: Author)

5.1.3 Change in LULC

Figure 5-3 showed the LULC maps in in four periods, 1990, 2000, 2010, and 2022. Cropland and impervious area accounted for the largest percentage of LULC, adding up to about 95% of the total area. But the area of cropland had been decreasing and the area of impervious area has been increasing.

NRB is an important grain production base in Shandong Province, and cropland is the most widely distributed in NRB, which is widely distributed in the Foothill alluvial plains in the eastern part and the Yellow River floodplain in the western part. From Table 5-2, it can be seen that the proportion of these four periods is 84.57%, 80.79%, 75.68% and 72.36% respectively, a decrease of 12%, the area decreased by 3464.43 km². Especially, the most obvious decreased was from 2000 to 2010. As shown in Table 5-3, the decrease of cropland was mainly converted to impervious area, which was 969.18 km², 1008.33 km², and 1121.37 km² from 1990-2000, 2000-2010, and 2010-2022, respectively, because urban expansion occupied part of the cropland.

The second was water area. This was due to the policy of Grain for Green Program implemented by the local government in order to protect the waters of NRB. The forest was mainly located in the hilly and mountainous areas in the eastern part at higher elevations. The area of forest in the four periods was 168.31km², 186.33km², 194.90km², and 267.04km². It showed an increasing trend, with a total increase of 98.73km² during the four decades. Table 5-3 showed that the increase in forest was mainly from cropland and grassland. This was also due to the Grain for Green Program policy. The area of grassland in the NRB was very small, mainly concentrated in the Tayyi Mountainous Region in the eastern part, with a decrease of 231.43km², and inflow was less than outflow, and the type of converted land was mainly cropland, followed by forests and impervious area. The percentages under the four periods were 1.38%, 1.17%, 0.88%, and 0.56%, respectively.

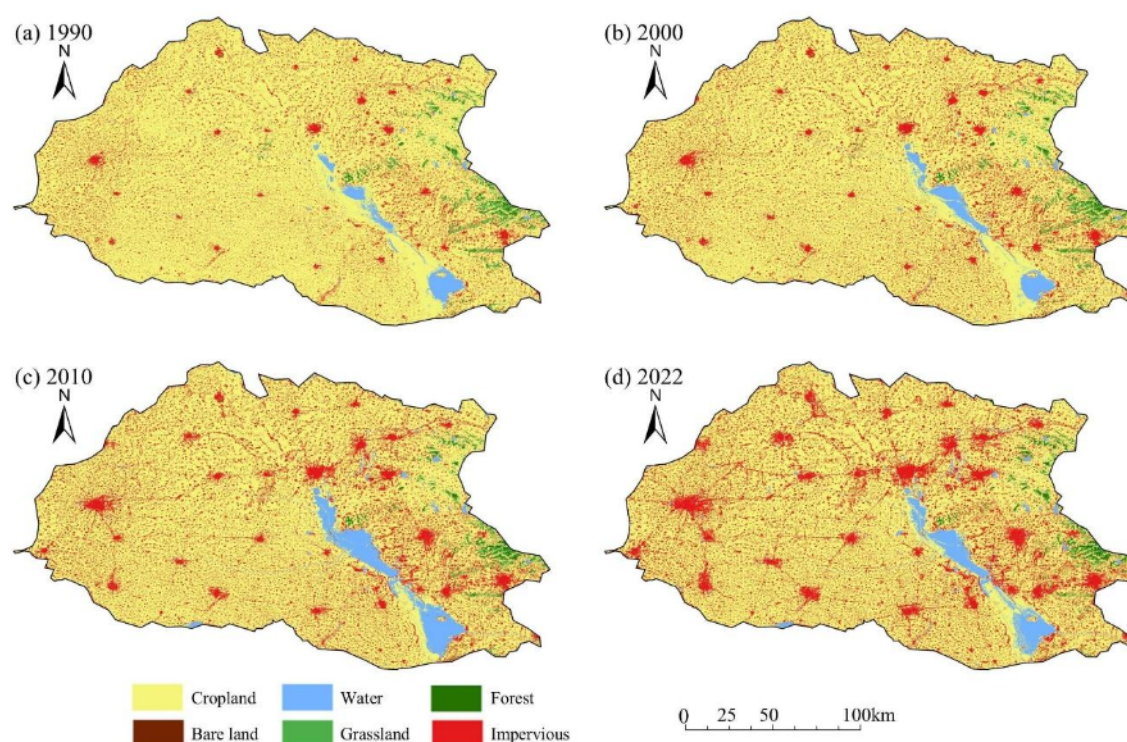


Figure 5-3: LULC maps in 1990, 2000, 2010 and 2022 in the NRB

(Source: Landsat-derived annual land cover product of China)

The water area was influenced by precipitation. The LULC type along the lake changed frequently, mostly between water and cropland, and the water area showed an increasing trend between 1990 and 2022, with an increase of 492km², which was close to doubling. This was partly due to the precipitation pattern, the increase of precipitation in these three periods, which led to the expansion of the water area. In addition, the local government had implemented a series of conservation measures, including the establishment of protected areas and restrictions on activities in specific areas. The inflow to water area were greater than the outflow, and both the inflow and outflow were mainly associated with cropland.

The NRB was in a stage of accelerated urbanization, with rapid population and economic development contributing to the expansion of impervious surfaces. It can be observed clearly

in Figure 5-4 that the impervious area had been increasing, with a total increase of 3102.44km², from 11.62% to 22.56%. Impervious area was mainly converted from cropland.

Bare land had a decreasing trend. From 1990 to 2022, a decrease of 0.8 km² in bare land area was observed, which was due to the continuous reclamation and utilization of some abandoned mining areas and subsidence areas. From 1990 to 2000, the bare land was mainly converted to impervious area; there was not much change from 2000 to 2010. From 2010 to 2022, it was mainly converted to impervious area and cropland.

Table 5-2: Area and proportion of LULC types

		Cropland	Forest	Grassland	Water	Bare land	Impervious
1990	km ²	23980.43	168.31	391.29	519.47	1.30	3294.67
	%	84.57	0.59	1.38	1.83	0.0046	11.62
2000	km ²	22908.27	186.33	332.84	646.00	0.62	4281.45
	%	80.79	0.66	1.17	2.28	0.0022	15.10
2010	km ²	21457.20	194.90	249.59	1177.11	3.03	5270.28
	%	75.68	0.69	0.88	4.15	0.0107	18.59
2022	km ²	20516.00	267.04	159.86	1011.59	0.50	6397.12
	%	72.36	0.94	0.56	3.57	0.0018	22.56
1990-2022	km ²	-3464.43	98.73	-231.43	492.13	-0.80	3102.44

Table 5-3: LULC transition matrix in the NRB (Unit: km²)

(a) 1990-2000

		2000					
		Cropland	Forest	Grassland	Water	Bareland	Impervious
1990	Cropland	22770.03	13.39	45.28	181.45	0.02	969.16
	Forest	24.96	140.96	0.61	0.20	0.00	1.58
	Grassland	49.81	31.64	286.85	0.86	0.31	21.81
	Water	60.71	0.31	0.01	454.07	0.00	4.36
	Bareland	0.12	0.04	0.12	0.29	0.00	0.73
	Impervious	1.68	0.00	0.00	9.24	0.00	3283.62

(b) 2000-2010

		2010					
		Cropland	Forest	Grassland	Water	Bareland	Impervious
2000	Cropland	21347.69	14.70	25.64	509.12	0.19	1008.32
	Forest	19.95	161.48	1.57	0.37	0.00	2.86
	Grassland	71.10	18.69	222.33	0.29	2.51	17.80
	Water	14.74	0.03	0.00	626.43	0.00	4.69
	Bareland	0.03	0.00	0.03	0.07	0.3267	0.17
	Impervious	3.70	0.00	0.00	40.82	0.00	4236.45

(c) 2010-2022

		2022					
		Cropland	Forest	Grassland	Water	Bareland	Impervious

2010	Cropland	20159.71	47.92	35.30	92.87	0.02	1121.37
	Forest	13.25	178.96	1.20	0.26	0.00	1.23
	Grassland	77.77	40.05	122.84	0.02	0.14	8.77
	Water	261.96	0.10	0.00	899.09	0.00	15.96
	Bareland	0.316	0.00	0.52	0.04	0.33	1.83
	Impervious	2.30	0.00	0.00	19.32	0.00	5247.97

5.2 Hydrological effects of urbanization in the NRB

In this chapter, three important elements of the hydrological cycle, precipitation, surface runoff and evaporation, were selected to analyze their changes over a long period of time, mainly in terms of trend changes, cyclic changes and intra-annual distributions, the characteristics of extreme rainfall events. Through these analyses, this chapter reveals how urbanization has altered hydrological processes in the NRB.

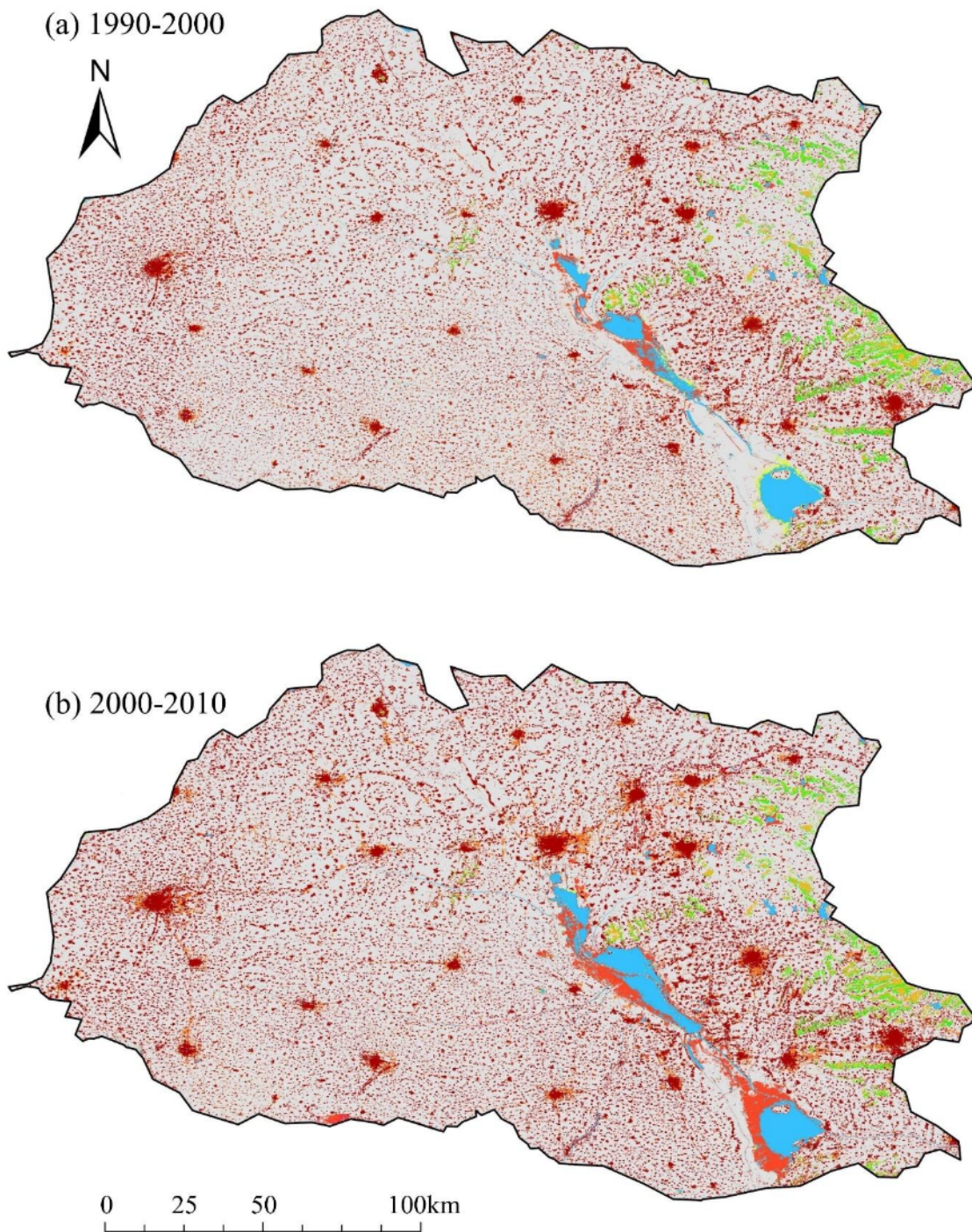
5.2.1 Precipitation

5.2.1.1 Trend changes in precipitation

Five-year moving average analysis and MK test analysis (Table 5-4) were applied to the long series of annual precipitation at the hydrological stations in the NRB to graph the multi-year trend of their precipitation (Figure 5-5 and Figure 5-6) (Figure 5-5 and Figure 5-6 figured both precipitation and surface runoff, surface runoff will be discussed in further chapter 5.2.2.1).

From the results of the MK test, the U value of Liangshanzha station and Houying station were negative and less than -1.96, indicating that their precipitation had a decreasing trend for many years, and the decreasing trend was not obvious; all the others were positive and less than 1.96, indicating that their annual precipitation had a slow increasing trend for many years. The overall precipitation in the NRB is also trending slowly upward. From a localized perspective, the 8 stations showed a decreasing and then increasing trend. At all hydrological stations, precipitation reached a minimum in the mid- to late-1980s, then showed an increasing trend, peaking around 2003 and then gradually decreasing. The maximum of annual precipitation was concentrated in the mid-1960s and early 2000s, and most hydrological stations reached the maximum in 1964 or 2003. The difference between the maximum and minimum precipitation values is about 750 mm, with Huangzhuang station having the largest difference of 829.62 mm.

The change trends of the whole river basin and the 8 hydrological stations were consistent. No significant differences were observed in the change characteristics and trends of precipitation between urban and suburban stations, indicating that urbanization in the NRB has not significantly affected the interannual change or trend of precipitation.



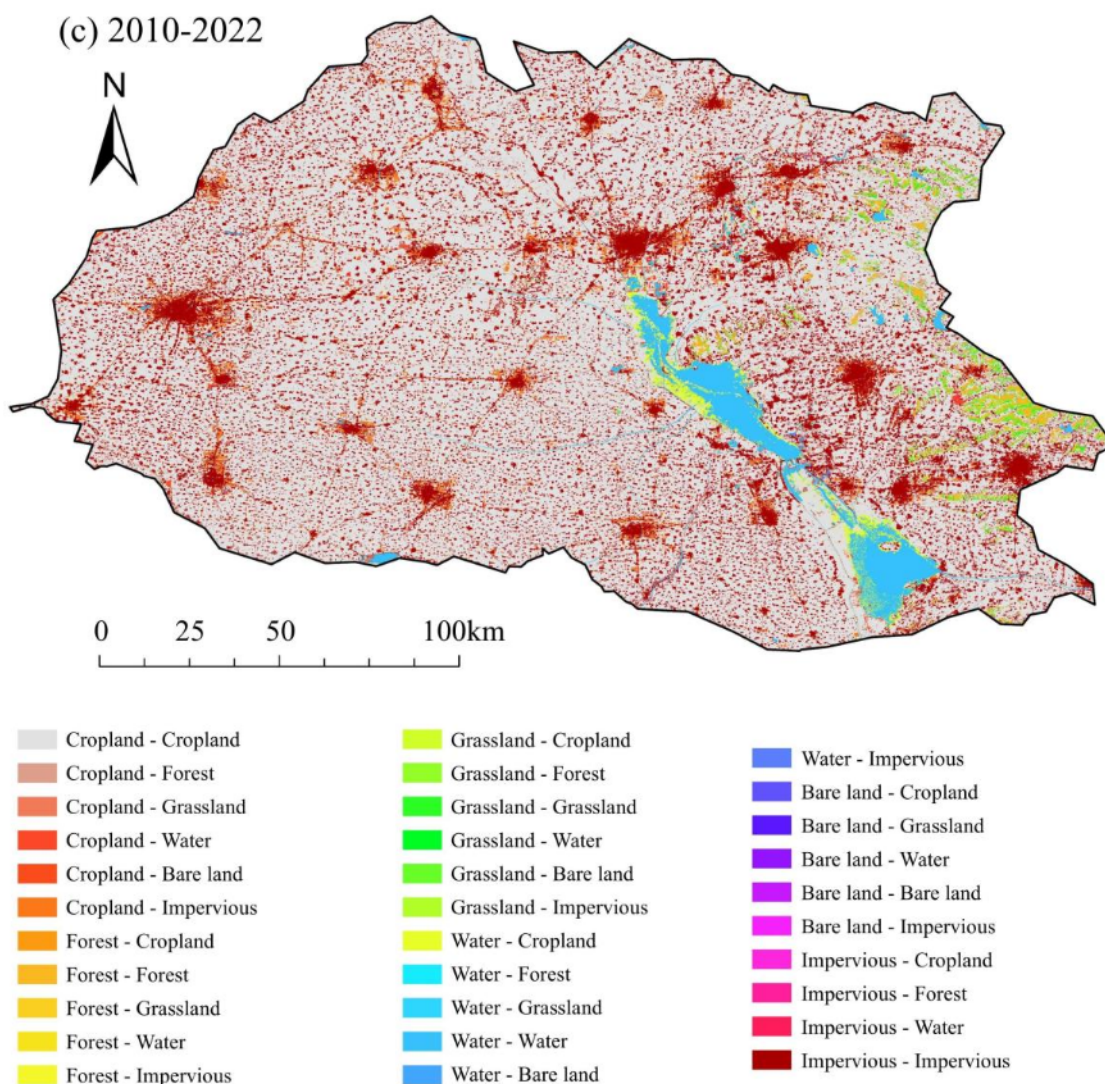


Figure 5-4: LULC conversion maps in NRB (Source: Author)

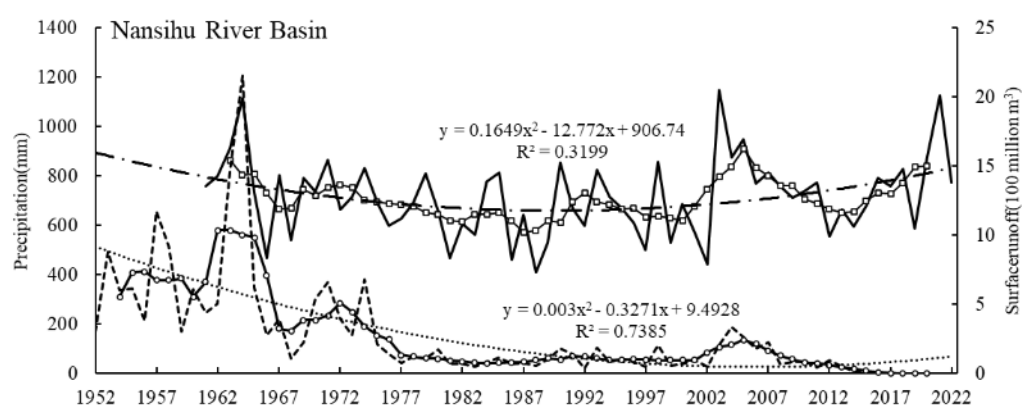
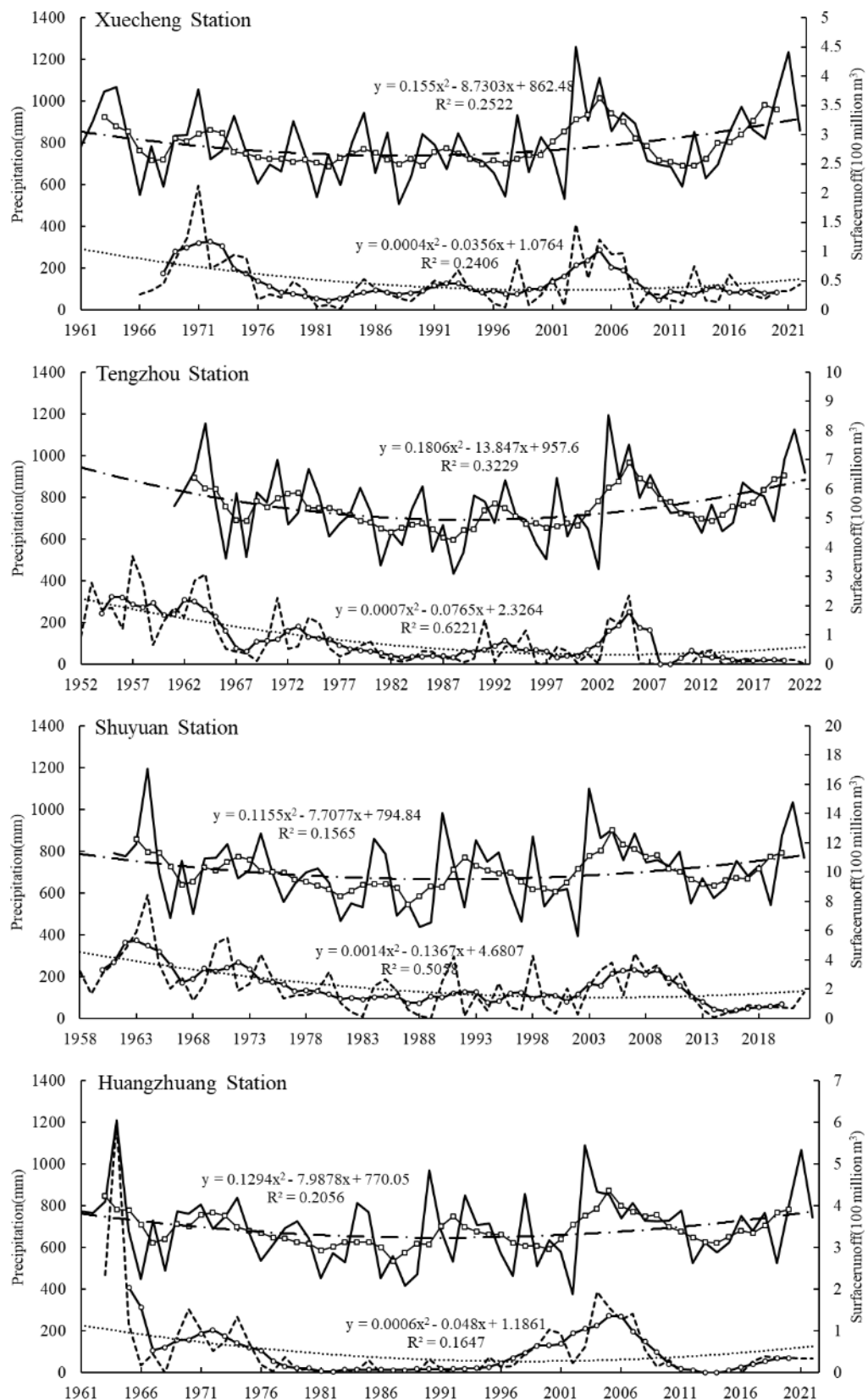


Figure 5-5: Annual precipitation - annual surface runoff trends in the NRB (Source: Author)



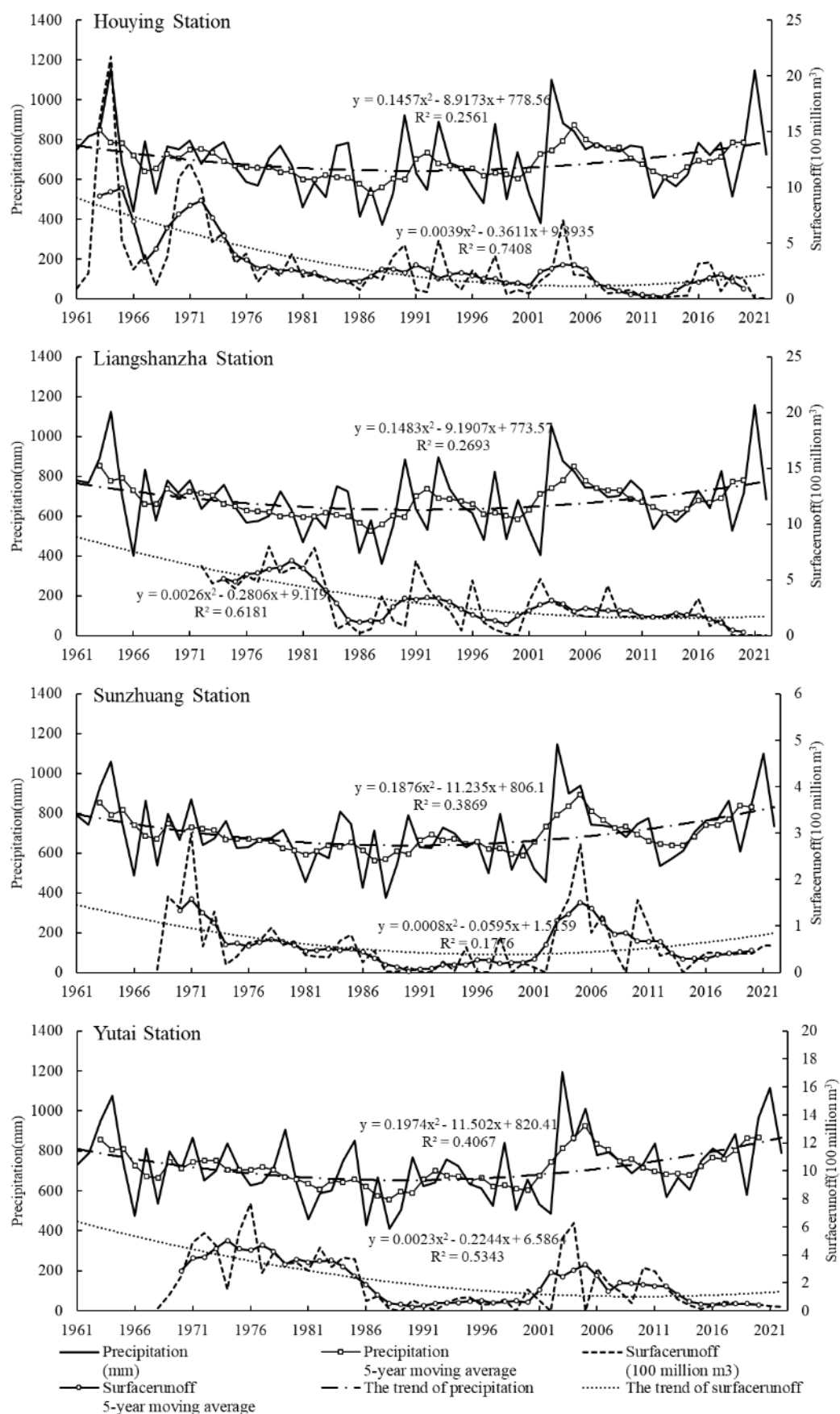


Figure 5-6: Annual precipitation - annual surface runoff trends at hydrological stations (Source: Author)

Table 5-4: MK test of annual precipitation

Station	Year	Mean (mm)	Maximum (mm)	Year of maximum	Minimum (mm)	Year of minimum	U	The trend
Yutai	1961-2022	719.23	1194.27	2003	411.71	1988	0.58	+(N)
Sunzhuang	1961-2022	700.74	1145.36	2003	374.41	1988	0.28	+(N)
Liangshanzha	1961-2022	682.57	1157.17	2021	360.38	1988	-0.46	-(N)
Houying	1961-2022	692.70	1152.51	1964	371.16	1988	-0.32	-(N)
Huangzhuang	1961-2022	692.36	1206.23	1964	376.61	2002	0.11	+(N)
Shuyuan	1961-2022	707.96	1195.67	1964	395.47	2002	0.22	+(N)
Tengzhou	1961-2022	754.55	1193.76	2003	433.11	1988	0.67	+(N)
Xuecheng	1961-2022	795.35	1261.43	2003	506.83	1988	0.79	+(N)
NRB	1961-2022	716.05	1148.36	2003	408.30	1988	0.28	+(N)

Note: + means increasing trend, - is decreasing trend; Y is significant trend, and N is not significant trend

5.2.1.2 Cyclical variations in precipitation

The precipitation in the NRB didn't have a fixed cycle, but was nested in multi-timescale (Figure 5-7(a)). 5-10a and 20-30a fluctuations were obvious, with positive and negative phases alternating, and these two time scales ran through the whole time series, with the distribution of precipitation abundant and scarce, and the distribution of fluctuation extremes was regular, showing a clear relationship between abrupt changes and oscillations, and is the dominant period of the basin's precipitation. In addition, there were several short cycles such as 10-13a, 15-20a, 35-40a, 50-60a.

The wavelet variance plot (Figure 5-7(b)) showed 2 very obvious peaks corresponding to the time scales of 10a and 24a. The largest peak was 24a, indicating that the cycle around 24a had the strongest oscillation and was the first dominant period of precipitation, and 10a was the second dominant period of precipitation, and these two dominant periods played a major role in the precipitation series in the last 60 years, with 24a scale being the most significant. There were also 18a as the third dominant period and 4a as the fourth dominant period, and they only affected the local time series.

Wavelet coefficients were plotted for the two dominant periods 10a and 24a (Figure 5-7(c)), with positive values indicating wet year and negative values indicating dry year. At the 10a scale, precipitation experienced 9 oscillations, with abundant and scarce water lasting for about 3-4 years. After 2022, the wavelet coefficients were still positive, and it was hypothesized that the years 2022-2025 would still be wet years. According to the water resources bulletin of Shandong Province in 2023, the precipitation in Heze City, Zaozhuang and Jining was 21.6%, 4.1% and 1.8% higher than the multi-year average, respectively, which was consistent with the results of the wavelet analysis, and the applicability of the wavelet change method could be verified. On the 24a scale, precipitation experienced 4 oscillations, with abundance and scarcity duration of about 7 and 8 years. The abrupt change points occurred in 1965, 1971, 1980, 1987, 1994, 2003, 2010, and 2019. Based on the wavelet analysis, wavelet coefficients of precipitation were expected to exhibit positive after 2022, suggesting that the NRB would remain in a wet phase during the period 2022-2029.

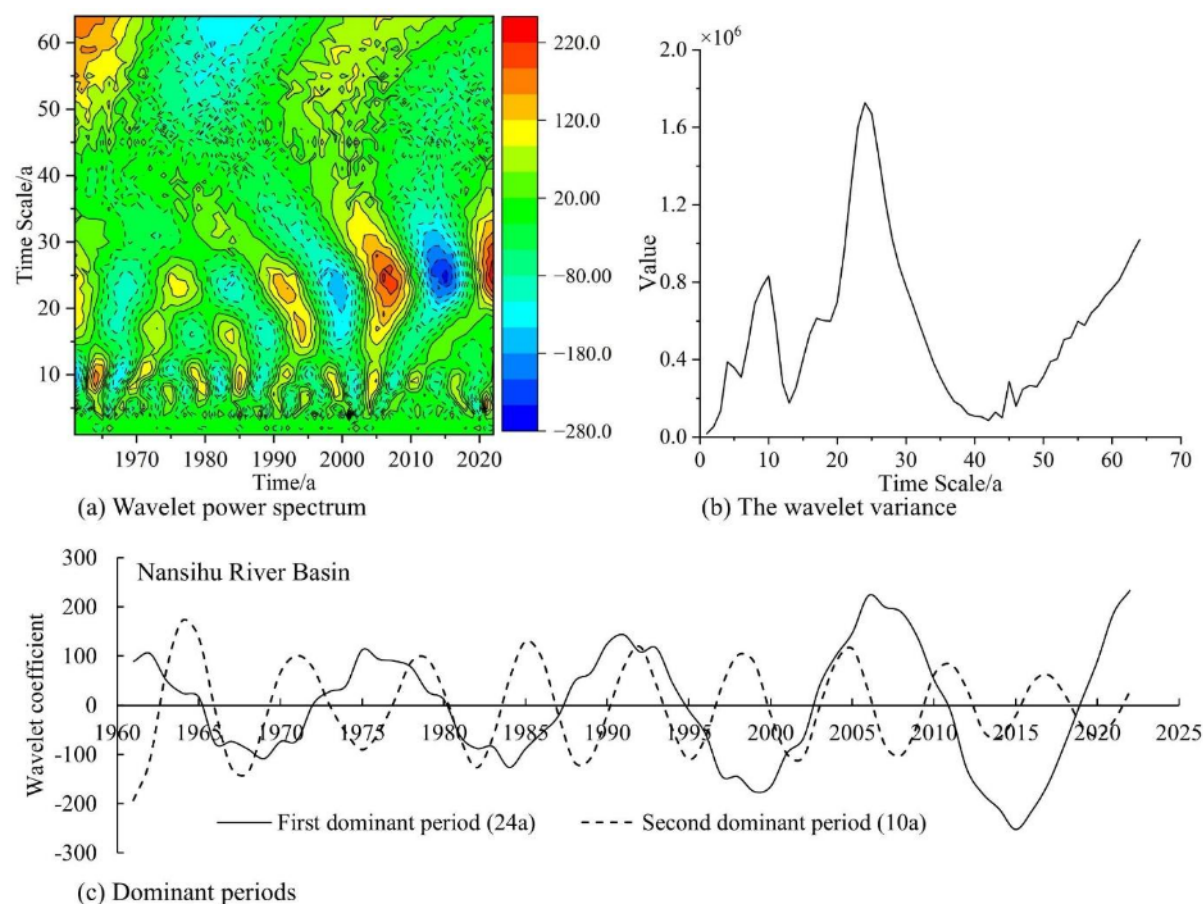


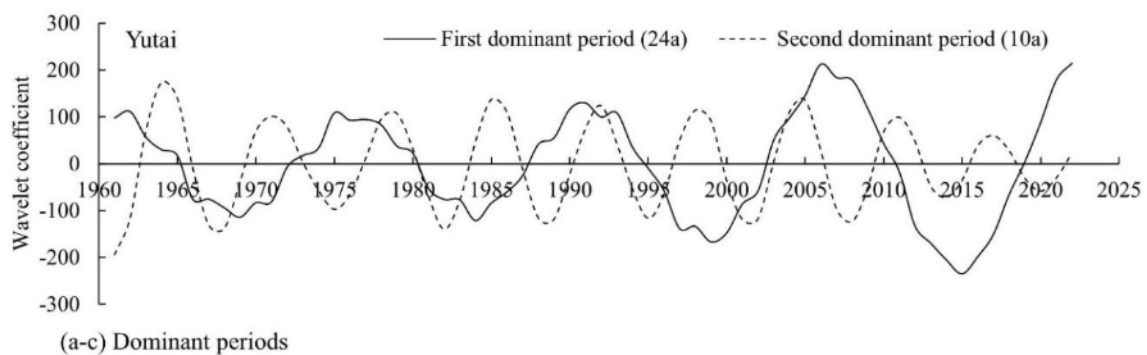
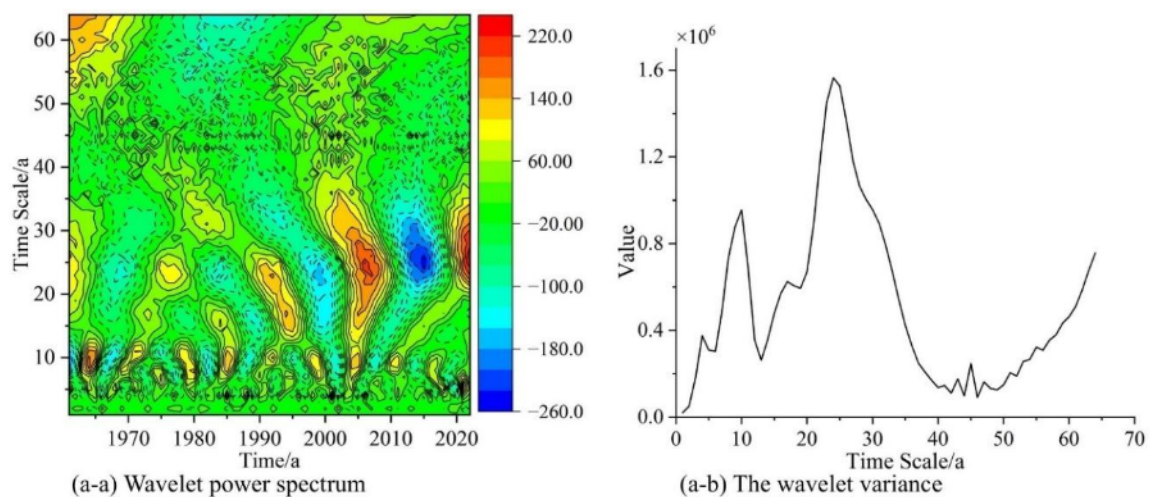
Figure 5-7: Morlet wavelet in the NRB (Source: Author)

Figure 5-8 showed that the wavelet analysis of the annual precipitation has a great similarity, with some differences in the distribution of the time scales. There were also no fixed cycles of precipitation at each hydrological station, but rather multiple time scales nested within each other.

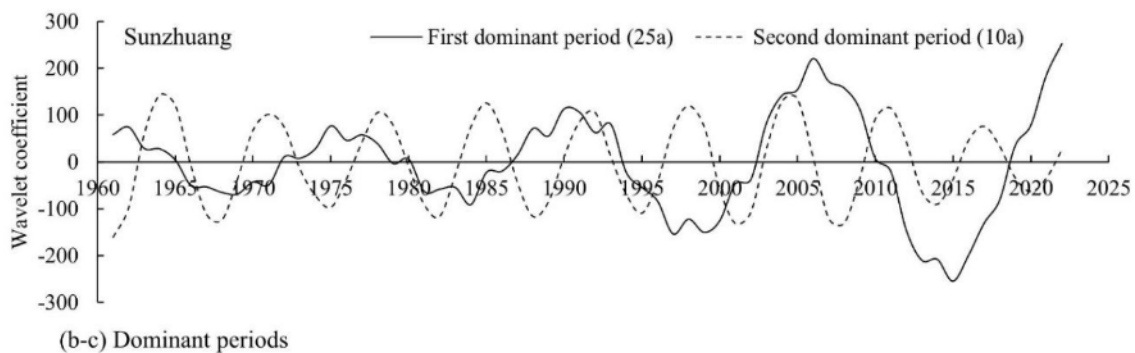
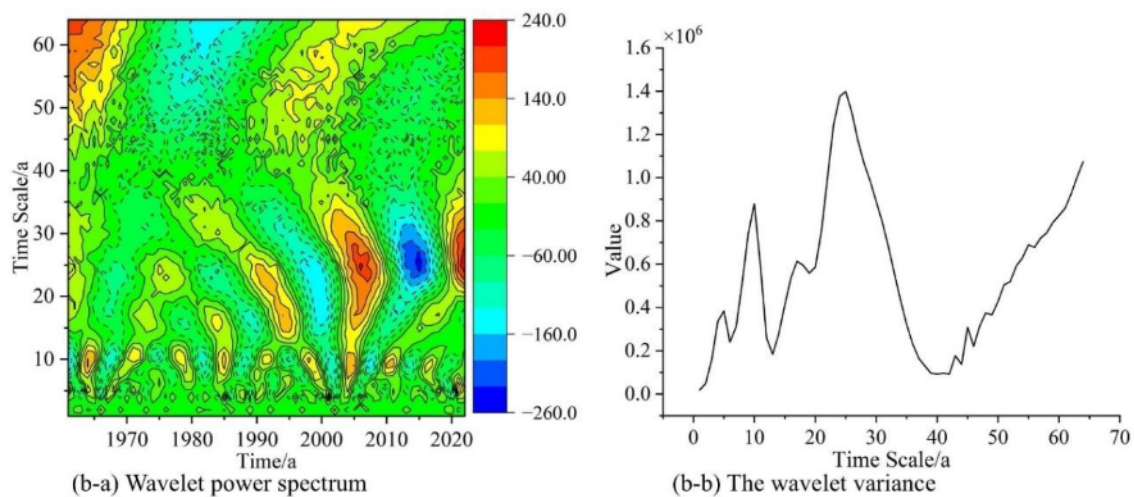
Yutai station has clear fluctuations in the early and late periods on the 20-30a scale, with gradually increasing amplitudes, and its cyclical variations were more stable after 2000. Yutai station had two dominant periods, 24a and 10a, and experienced 4 oscillations on the 24a scale, with abrupt changes points at 1965, 1972, 1980, 1987, 1994, 2002, 2010 and 2019. Each oscillation lasted for around 15 years (Figure 5-7).

On the 10a scale, there were 9 oscillations. The other stations had similar fluctuations as the Yutai station. Their dominant periods were around 24-25a and 8-10a. The dominant periods of Xuecheng were 27a and 10a. On the 27a scale, the early oscillations were weak, with increasing energy after 1982. On the 10a scale, on the contrary, the early oscillations were stable and strong, and after 2011 the energy gradually weakened.

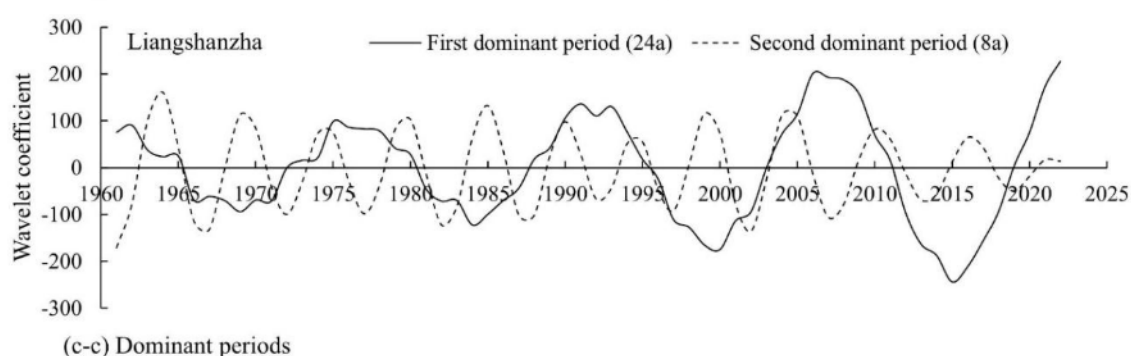
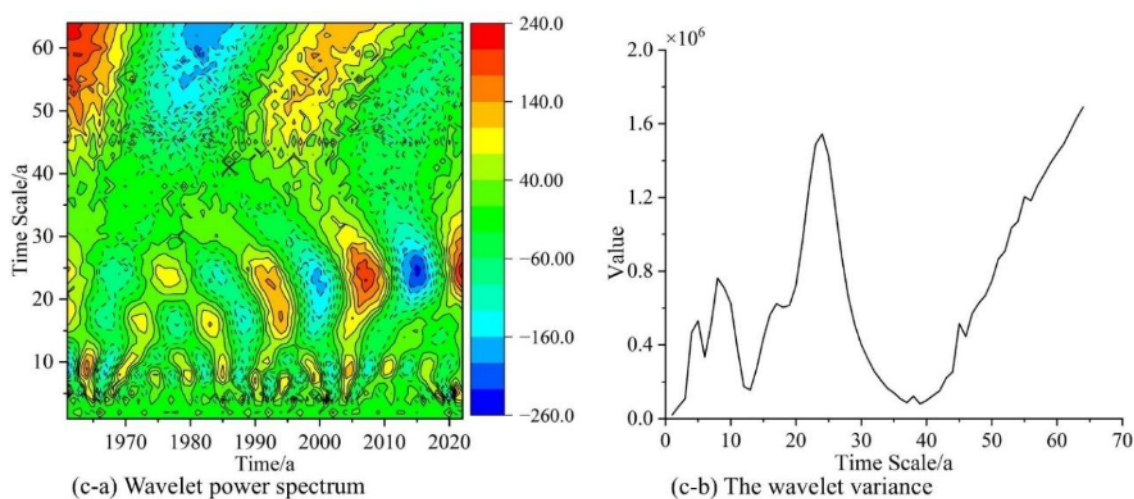
(a) Yutai



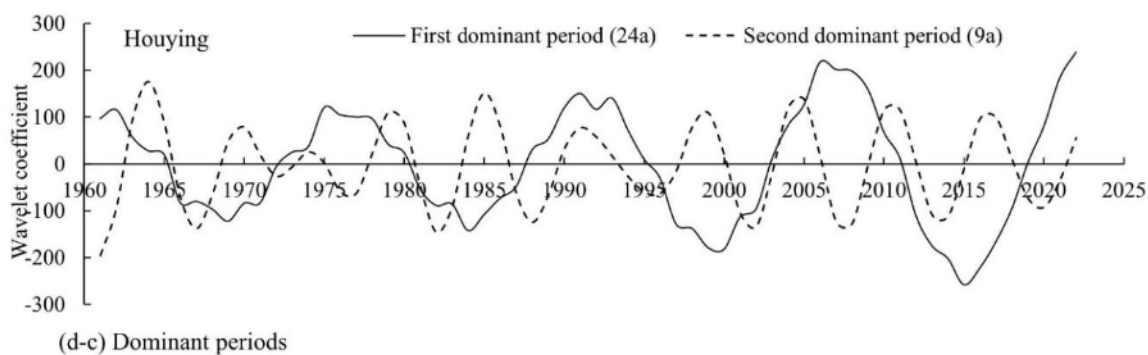
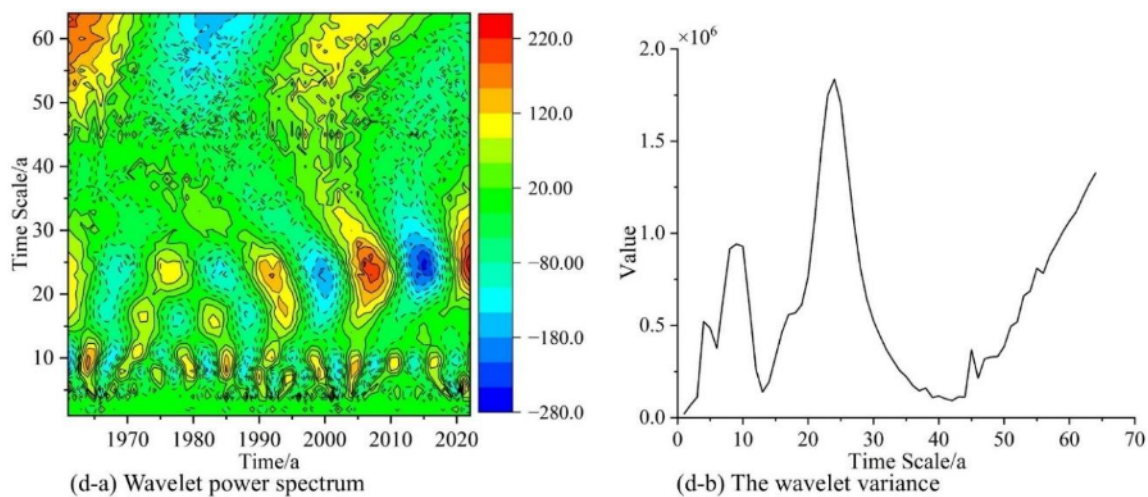
(b) Sunzhuang



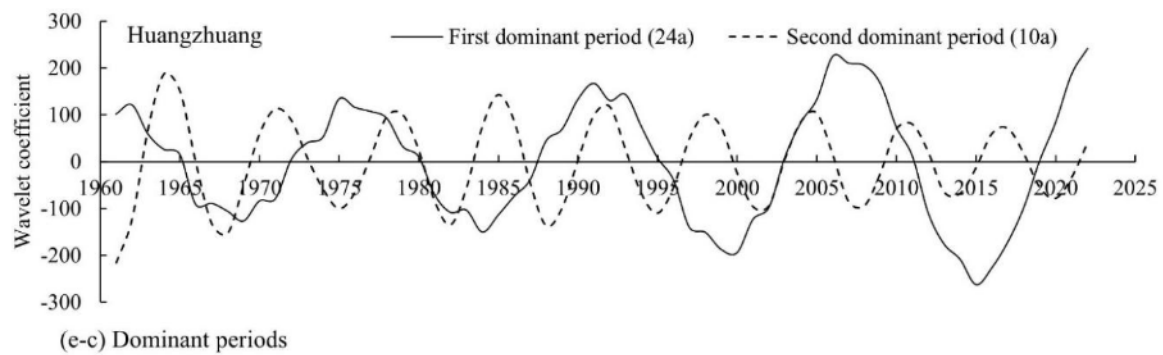
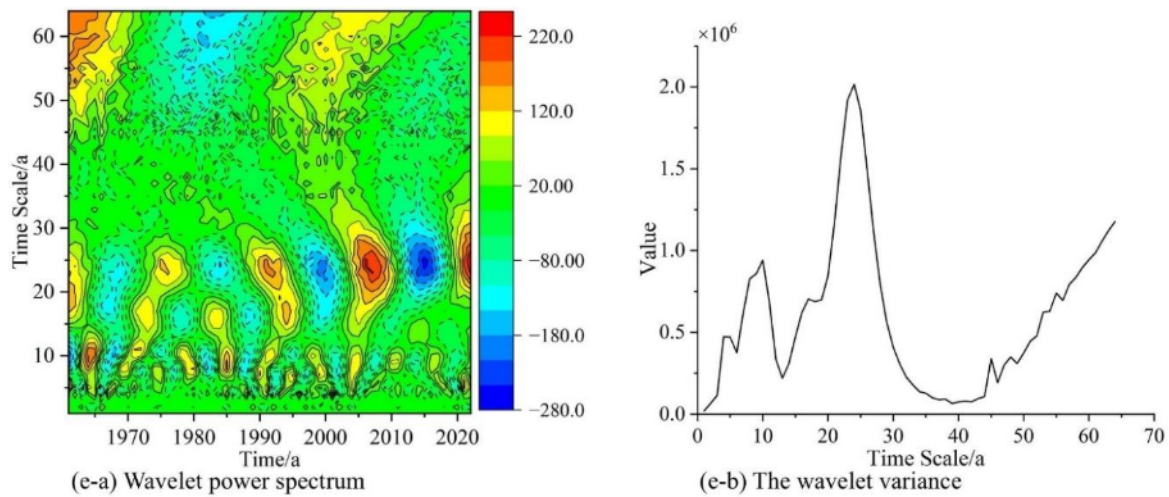
(c) Liangshanzha



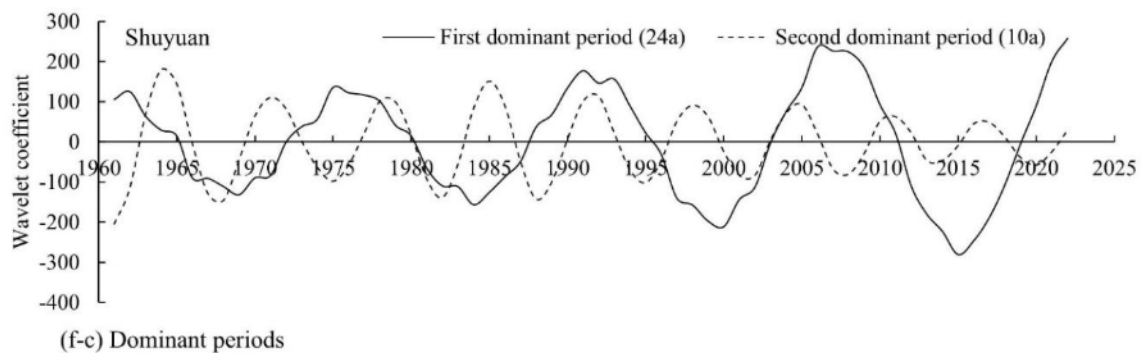
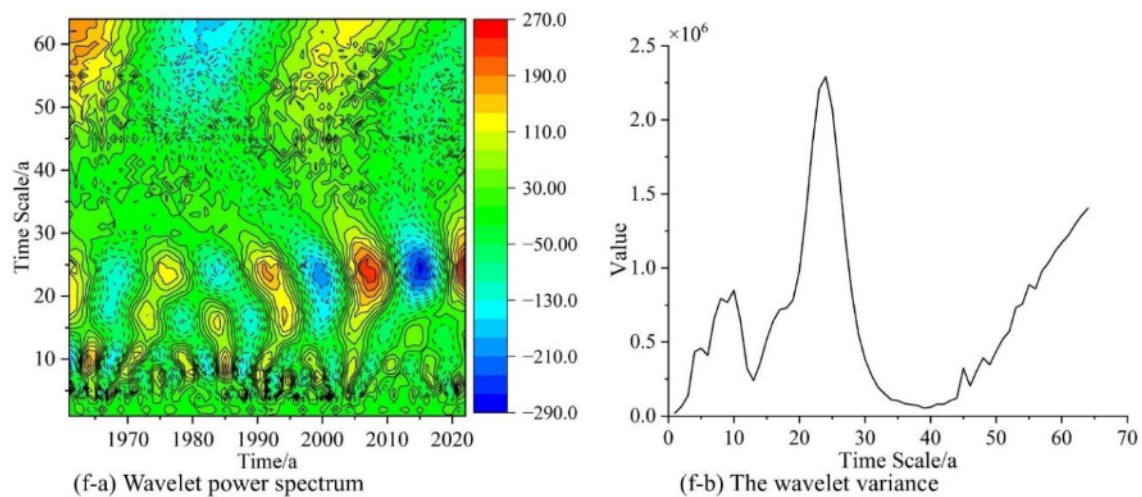
(d) Houying



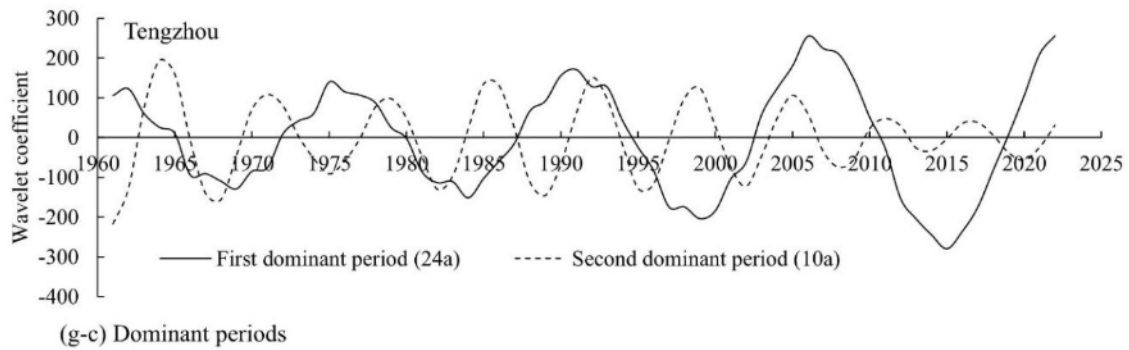
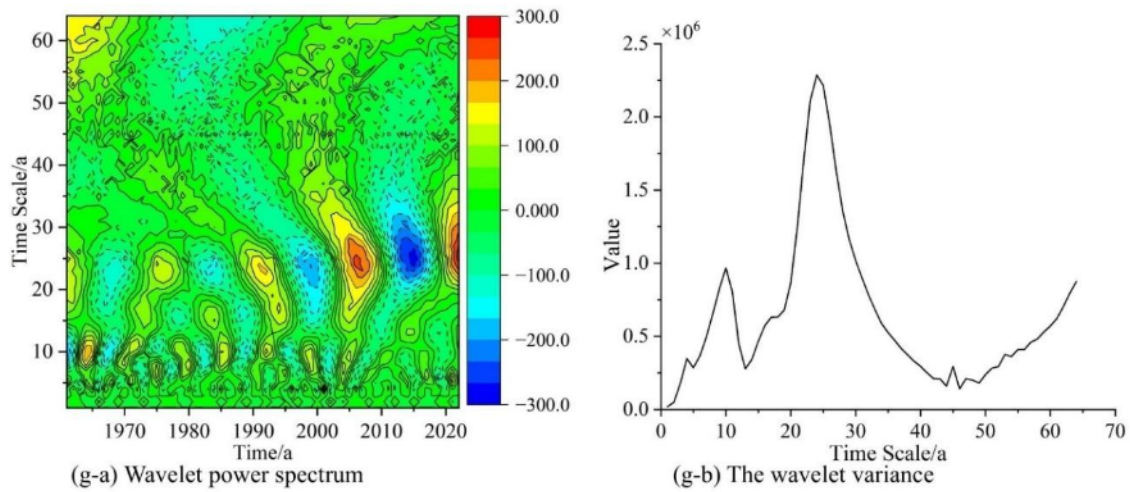
(e) Huangzhuang



(f) Shuyuan



(g) Tengzhou



(h) Xuecheng

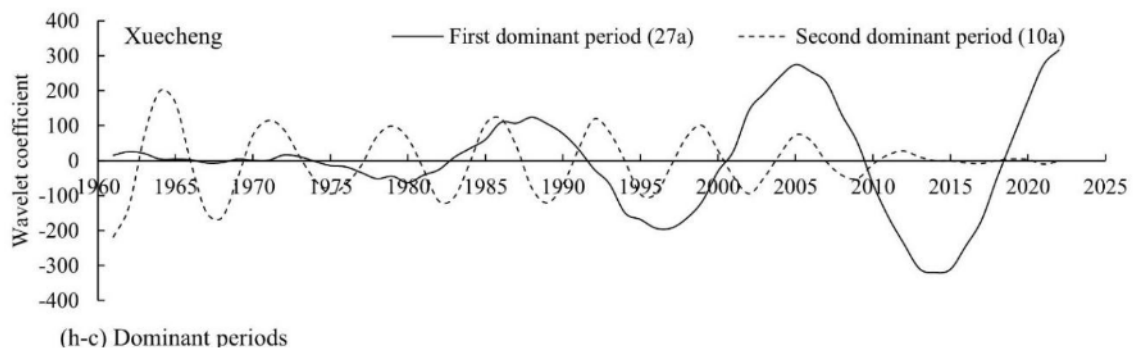
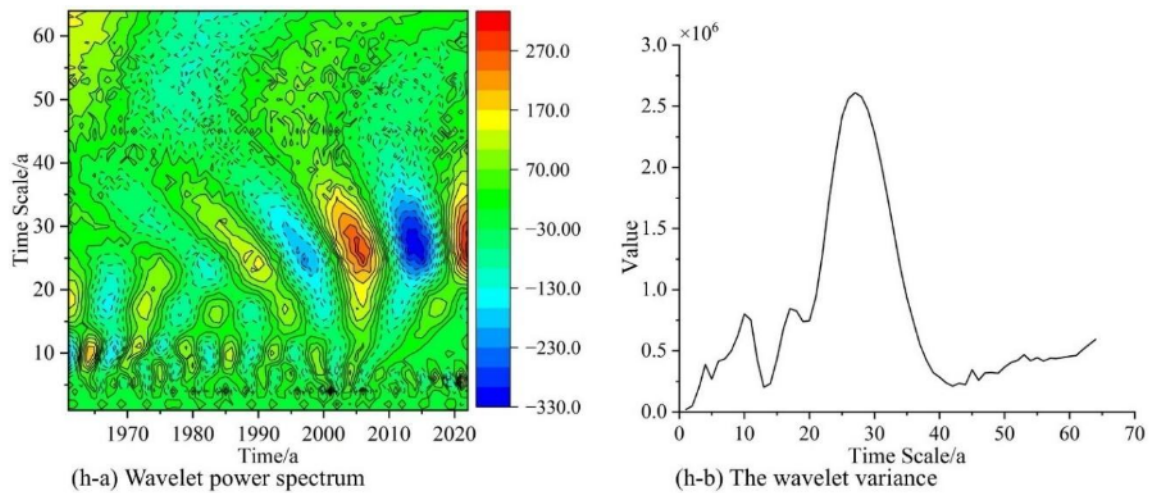


Figure 5-8: Wavelet analysis of hydrological stations (Source: Author)

5.2.1.3 Intra-annual distribution of precipitation

(1) Temporal changes

The NRB is located in the warm temperate monsoon climate belt, and under the influence of the monsoon circulation, the distribution of precipitation within the year was extremely uneven (Table 5-5, Figure 5-9). The annual distribution characteristics of precipitation are similar across hydrological stations, therefore urbanization has no significant impact on the annual distribution of precipitation.

In summer, under the influence of the oceanic monsoon from the Pacific Ocean, strong precipitation was formed, and the rainfall was large and concentrated, generally 418.03 mm-488.08 mm, accounting for 59.87%-63.74% of the annual precipitation.

In winter, under the influence of the Mongolian-Siberian cold stream, the continental monsoon was strong, and the climate was dry and cold, with precipitation of 28.48mm-40.99mm, accounting for 4.06%-5.15% of the year.

Spring and fall were also less rainy, precipitation in spring was 101.42mm-121.95mm, accounting for 14.33%-15.92% of the annual precipitation. The precipitation in fall was 126.55mm-144.34mm, accounting for 17.88%-19.34%. The intra-annual distribution of precipitation at hydrological stations was basically consistent, indicating that the influence of human activities on the intra-annual distribution characteristics and trends of precipitation in the basin was not significant.

Table 5-5: The average annual precipitation of hydrological stations (Unit: mm)

	Spring	%	Summer	%	Autumn	%	Winter	%
Yutai	113.80	15.82	434.31	60.39	135.06	18.78	36.06	5.01
Sunzhuang	111.55	15.92	419.54	59.87	135.29	19.31	34.37	4.90
Liangshanzha	103.23	15.12	418.03	61.24	131.98	19.34	29.34	4.30
Houying	104.24	15.05	427.38	61.70	131.06	18.92	30.02	4.33
Huangzhuang	102.35	14.78	434.29	62.73	127.24	18.38	28.48	4.11
Shuyuan	101.42	14.33	451.24	63.74	126.55	17.88	28.75	4.06
Tengzhou	115.52	15.31	464.44	61.55	137.19	18.18	37.39	4.95
Xuecheng	121.95	15.33	488.08	61.37	144.34	18.15	40.99	5.15

(2) Spatial changes

Figure 5-10 (a) and (b) shows the spatial distribution of precipitation in the NRB during the flood season and the whole year. Influenced by the monsoon and atmospheric circulation, the spatiotemporal distribution of precipitation in the NRB varies significantly, decreasing from the southeast to the northwest, and precipitation during the flood season and the whole year had the same characteristics.

Xuecheng Station and Liangshanzha Station were the center of high and low values, respectively. The significant east-west difference in the intra-annual distribution of precipitation was the result of a combination of climate, geographic location, topography and other factors. The southeastern area has the relatively low latitude, higher temperatures,

frequent cyclone activity, the eastern hills area was easy to form topographic rain. The western part has a low topography, airflow sinking, precipitation was lower than the eastern part.

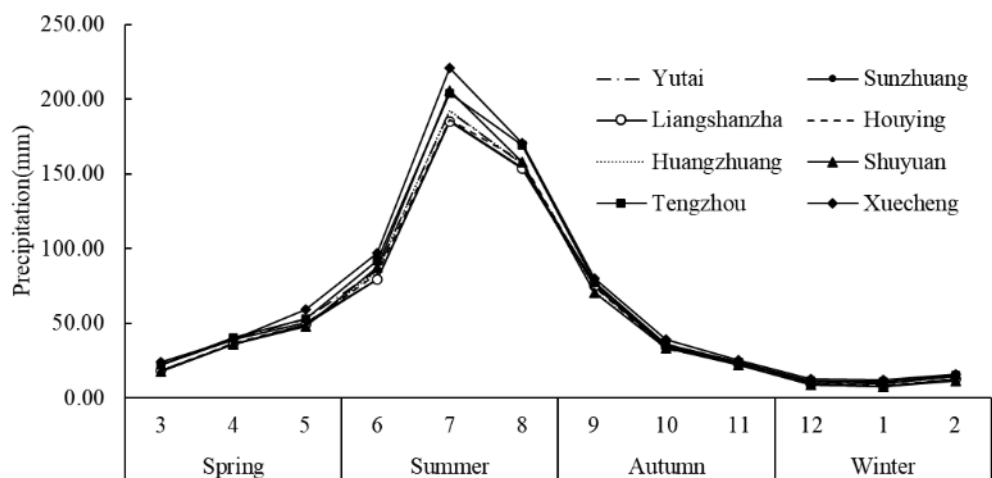


Figure 5-9: The multi-year average seasonal precipitation (Source: Author)

(3) Unevenness characteristic

C_d and D reflect the concentration of precipitation, while C_v and C_r reflect the unevenness of precipitation. The concentration of precipitation within a limited period is reflected by a high C_d value, and the high intensity of precipitation is easy to cause the flooding outbreak and also cause the shortage of water and rainfall in other periods of time.

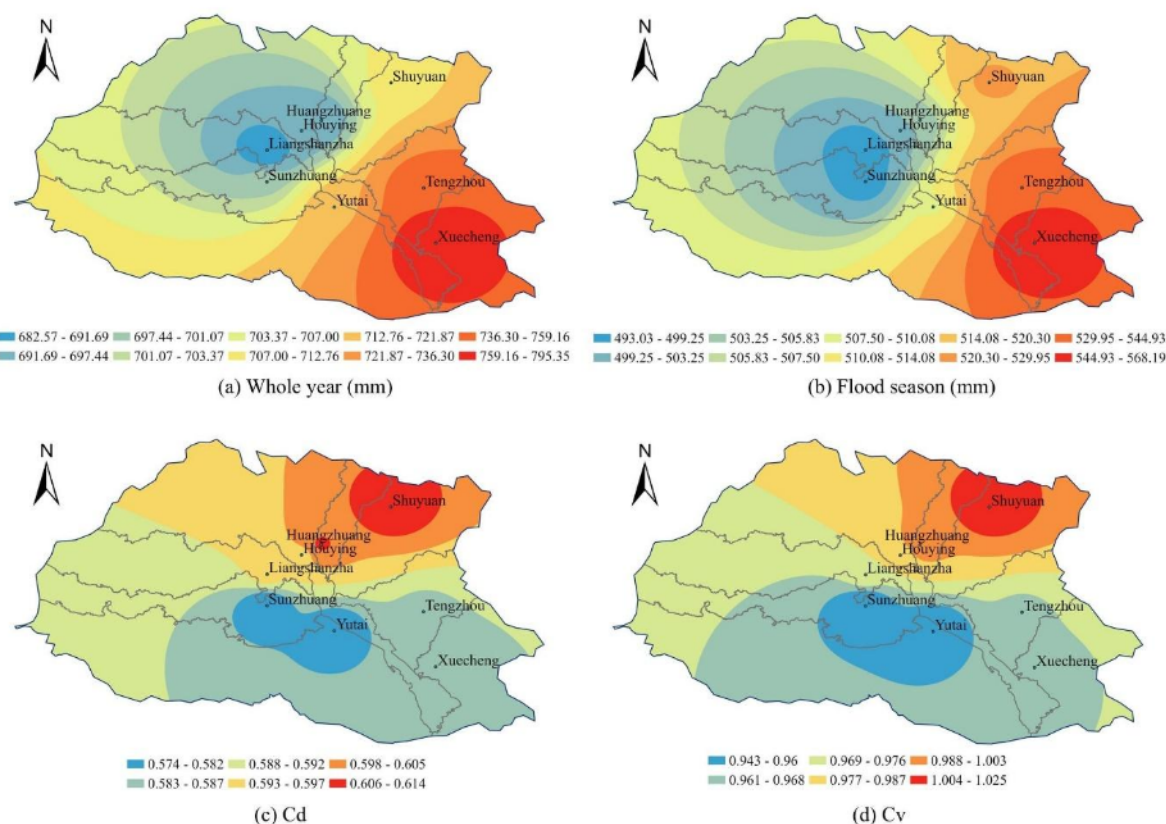


Figure 5-10: Spatial distribution of precipitation in the NRB (Source: Author)

From Table 5-6, the results indicate that precipitation across the entire river basin was primarily concentrated in early July. Peak precipitation dates were July 9th -11th. Due to the movement of the rain band from the Pacific Ocean to the inland, the Peak precipitation dates in the southern part of the basin are earlier than those in the north. C_d of precipitation was 0.57-0.61, C_v was 0.94-1.03 and C_r was 0.38-0.40. From Figure 5-10 (c) and (d), it can be seen that Shuyuan Station was the center of precipitation concentration, Sunzhuang station and Yutai station were the center of precipitation uniformity. The C_d , C_v , and C_r at Shuyuan were 0.61, 1.03 and 0.4, respectively; those at Sunzhuang were 0.57, 0.94 and 0.37, respectively; and those at Yutai were 0.58, 0.94 and 0.38, respectively.

Table 5-6: Unevenness characteristics of precipitation at hydrological stations

	Flood season	Whole year	C_d	D	Peak precipitation date	C_v	C_r
Yutai	509.68	719.23	0.58	187.15°	July 9th	0.94	0.38
Sunzhuang	496.09	700.74	0.57	187.91°	July 10th	0.94	0.37
Liangshanzha	493.03	682.57	0.60	188.48°	July 11st	0.98	0.39
Houying	501.48	692.70	0.60	188.19°	July 10th	0.98	0.39
Huangzhuang	505.19	692.36	0.61	187.67°	July 10th	1.00	0.40
Shuyuan	521.69	707.96	0.61	187.32°	July 9th	1.03	0.40
Tengzhou	541.90	754.55	0.59	187.13°	July 9th	0.97	0.38
Xuecheng	568.19	795.35	0.58	186.74°	July 9th	0.97	0.38

5.2.1.4 Urban and suburban differences in precipitation

Among the 8 hydrological stations, Tengzhou Station was the representative of the urban area, and the other stations were representatives of the non-urban area. The average of annual precipitation from 7 non-urban stations in the same time series was taken and the difference was made with the annual precipitation from the Tengzhou Station in the same time series to compare the changes in the total annual precipitation in the urban and suburban areas. The precipitation difference between urban and suburban areas fluctuated over time and tended to increase (Figure 5-11).

In most of the years, urban areas received more precipitation than suburban areas. Only a few years, namely 1968, 1984, and 1990, exhibited negative precipitation differences. The largest difference occurred in 2022, which was close to 160 mm. Most years after 2000 were relatively wet, with annual precipitation in urban areas reaching as much as 1200 mm. During this period, the precipitation difference remained predominantly positive, indicating that urban areas generally received more precipitation than suburban areas. These findings suggest that the increase in flood-season precipitation may have been partly associated with human activities.

Table 5-7 shows the K values from the 1960s to the 2020s. K is greater than 1.0, indicating that urbanization has a significant impact on precipitation, forming a rainfall island effect to some extent. K for different periods shows an increasing trend in the long time series (Figure 5-12), indicating that the effect of urbanization on the difference between urban and suburban precipitation tends to increase, which is consistent with the trend in Figure 5-11. The low K value for the 1980s is due to the fact that it was during a dry period when both urban and

suburban precipitation were relatively reduced, but the reduction in precipitation in the urban area may not have been as significant as in the suburban area.

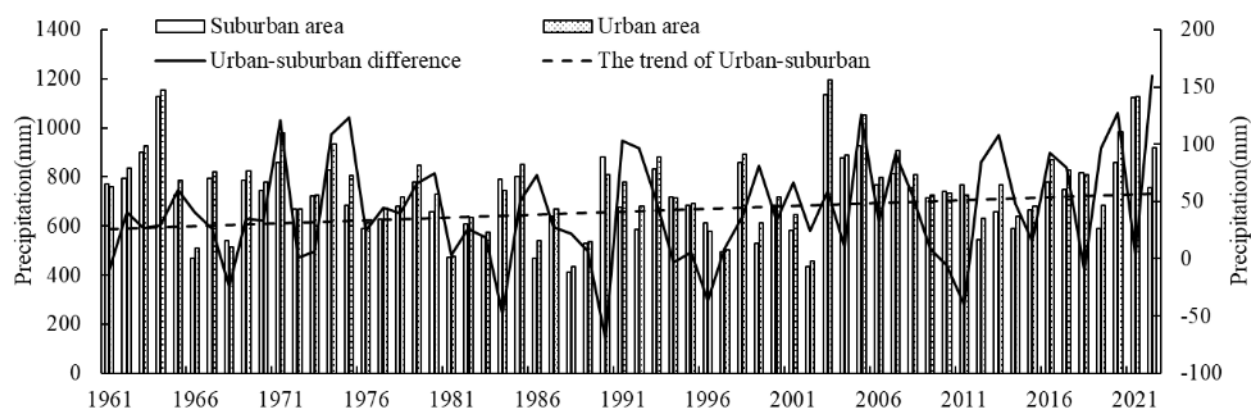


Figure 5-11: Urban and suburban differences in precipitation in the NRB (Source: Author)

Table 5-7: Average precipitation and K for different periods in urban and suburban area

	Annual precipitation (mm)			Flood season precipitation (mm)		
	Suburban area	Urban area	K1	Suburban area	Urban area	K2
1960s	767.39	792.14	1.03	559.90	574.59	1.03
1970s	717.77	774.40	1.08	530.82	571.74	1.08
1980s	593.26	618.66	1.04	414.13	423.28	1.02
1990s	686.77	713.87	1.04	462.79	483.57	1.04
2000s	768.83	819.36	1.07	573.64	609.34	1.06
2010s	689.46	736.22	1.07	487.48	518.55	1.06
2020s	912.63	1009.24	1.11	705.62	787.16	1.12

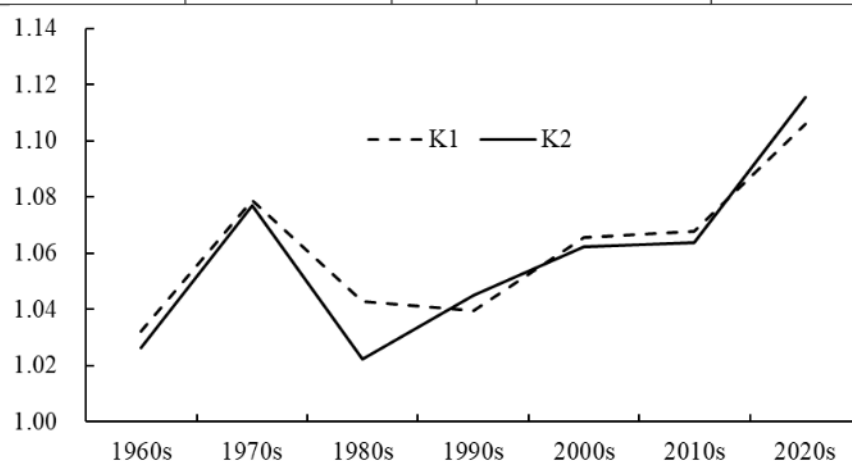


Figure 5-12: The trend of K (Source: Author)

5.2.2 Surface runoff

5.2.2.1 Trend changes of surface runoff volume

Table 5-8 showed the results of the MK test for all hydrological stations and the NRB, and the U values at all hydrological stations were negative, indicating a decreasing trend in surface runoff.

The decreasing trend was significant in Yutai station, Liangshanzha station, Houying station, and Tengzhou station. The decreasing trend was particularly pronounced at Tengzhou Station, located in the urban area. This can be attributed to increasing water withdrawals associated with urbanization. Growing industrial, agricultural, and domestic water demands led to reduced streamflow and lower runoff generation. The construction of water conservancy projects, the upstream interception of a large amount of water resources, so that the downstream water volume was reduced. The U of NRB was -7.37, with a significant decreasing trend. This pattern contrasts with the overall increasing trend in precipitation, indicating that factors other than precipitation, such as human activities and water resource utilization, may have played a dominant role in the long-term decline in runoff (Figures 5-5 and 5-6). Nevertheless, the interannual variability of runoff generally followed that of precipitation. Both variables decreased from the 1960s to the 1980s, increased from the 1980s to the early 21st century, and then declined again thereafter. These results suggest that while precipitation remained an important driver of short-term runoff fluctuations, it was not the dominant factor governing the long-term runoff trend. The highest runoff values were mainly observed during the 1960s and 1970s.

Table 5-8: MK test results of annual runoff

Station	Year	Mean (10 ⁸ m ³)	Maximum (10 ⁸ m ³)	Year of maximum	U	The trend (significance or not)
Yutai	1961-2022	1.91	7.65	1976	-3.61	-(Y)
Sunzhuang	1968-2022	0.58	2.30	1971	-1.03	-(N)
Liangshanzha	1972-2022	2.77	8.02	1978	-4.03	-(Y)
Houying	1961-2022	3.07	21.71	1963	-5.02	-(Y)
Huangzhuang	1963-2022	0.54	6.05	1964	-1.31	-(N)
Shuyuan	1958-2022	2.17	8.42	1964	-0.33	-(N)
Tengzhou	1952-2022	0.82	3.70	1957	-5.22	-(Y)
Xuecheng	1966-2022	0.46	2.12	1971	-1.29	-(N)
NRB	1952-2022	2.68	21.56	1964	-7.37	-(Y)

Note: + means increasing trend, - is decreasing trend; Y is significant trend, and N is not significant trend

5.2.2.2 Cyclical variations in runoff volume

From the real part of the wavelet function (Figure 5-13 (a)), the NRB had obvious fluctuation changes with alternating positive and negative phases on the 25-27a and 15-20a scales,

throughout the entire time series, which was the dominant cycle affecting the runoff volume. Moreover, there were localized cycles of 5-10a and 10-15a. 5-10a cycle mainly affected the time period of 1970-1990, while 10-15a affected the time period of 1995-2015. The interannual variability of runoff was also nested on multiple time scales. The first dominant period and secondary dominant period were 26a and 17a on the full time scale.

On the 26a scale, the runoff volume experienced 3 oscillations, and the abrupt change points were 1976, 1984, 1993, 2002, 2010, 2020, with a duration of 8-9 years. On the 17a scale, there were 4-5 oscillations, and the abrupt change points were 1974, 1980, 1986, 1991, 1996, 2002, 2008, 2013, 2019, with a duration of 5-6 years. The 26a dominant oscillation is currently in a positive phase and shows an increasing trend. Therefore, surface runoff in the near future is expected to remain at a relatively high level and may continue to increase. However, considering the weakening contribution of the 17a scale, the growth rate may gradually slow down.

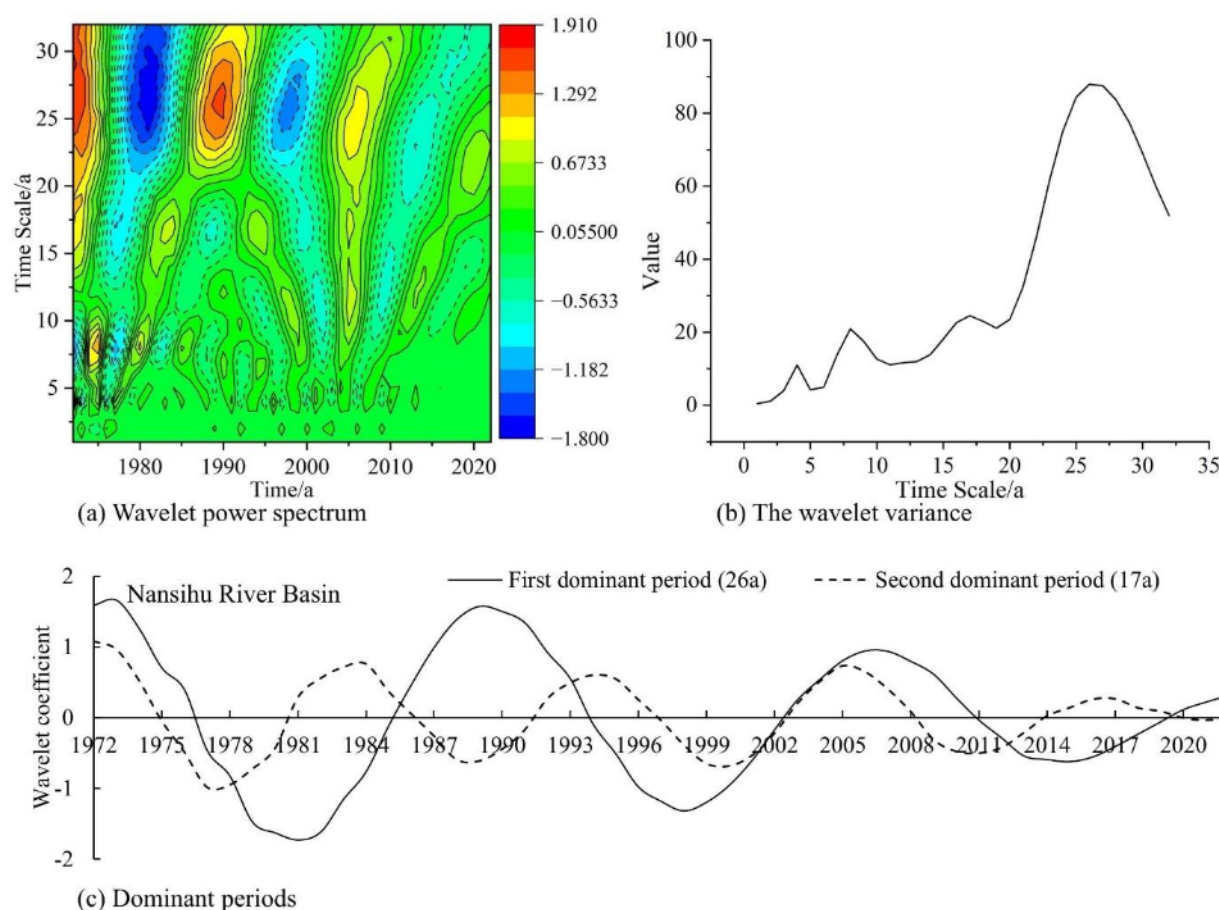


Figure 5-13: Wavelet analysis of multi – year average runoff in the NRB (Source: Author)

Wavelet analysis of the multi-year average runoff at eight hydrological stations (Figure 5-14) was characterized by differences in their cyclical variations, which do not fully correspond to the high consistency of the results of the wavelet analysis of precipitation. The changes in runoff volume at all hydrological stations had nested multiple time scales without a fixed cycle.

Overall, the first dominant periods were concentrated in the range of 20-26a, and the second dominant periods were concentrated in the range of 8-10a and 17a. However, the first and

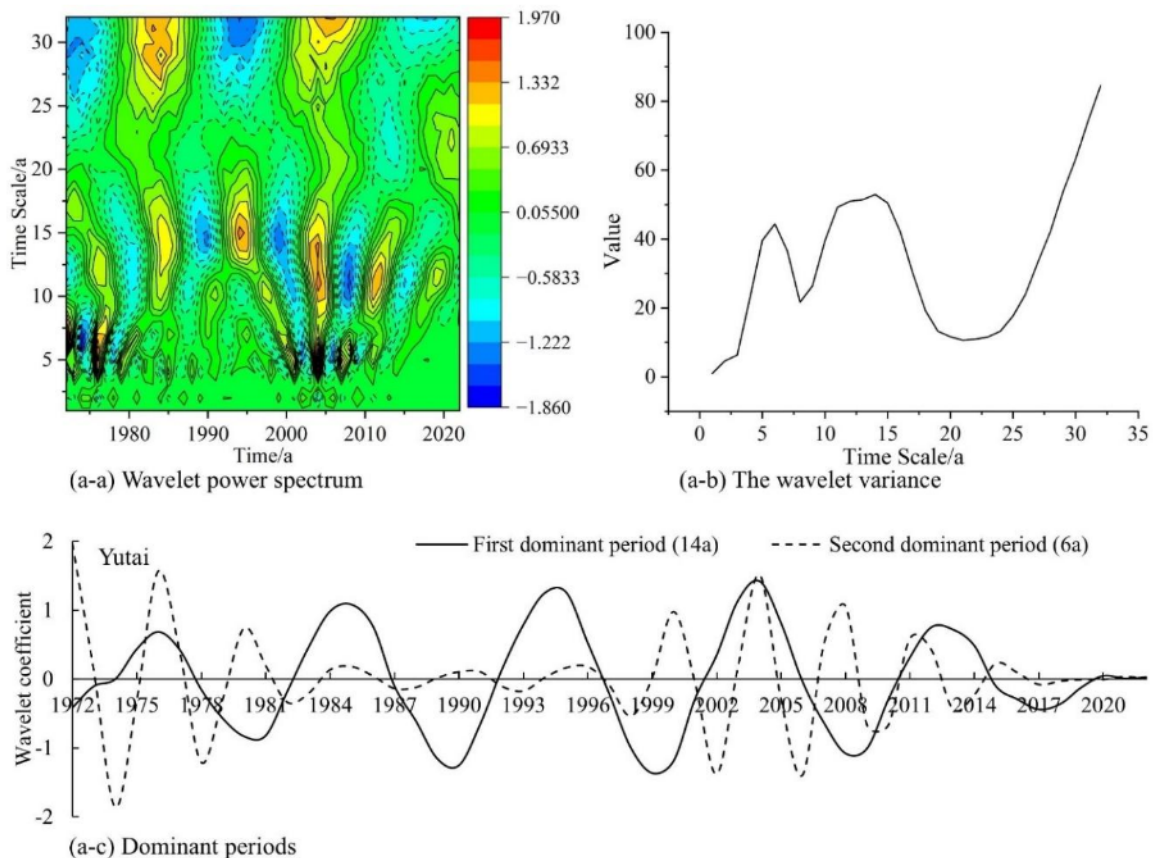
second dominant periods at Yutai station were 14a and 6a, respectively, which were shorter than those at other stations and the NRB. The first and second dominant periods of Sunzhuang were 10a and 22a respectively. It was different from the other stations where the first dominant periods were larger than the second dominant periods. However, the variance of 10a is larger than that of 22a (Figure 5-14(b)). On the scale of 20-26a, most of the hydrological stations in the study time scale experienced 3-4 oscillations.

5.2.2.3 Intra-annual distribution of runoff

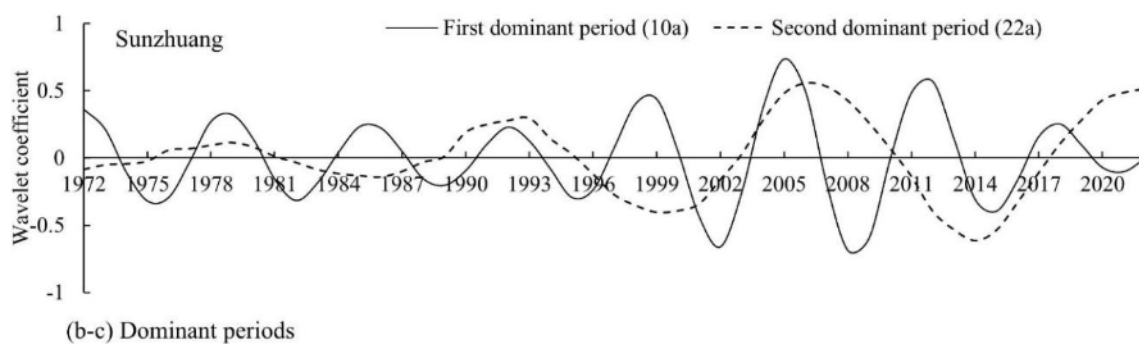
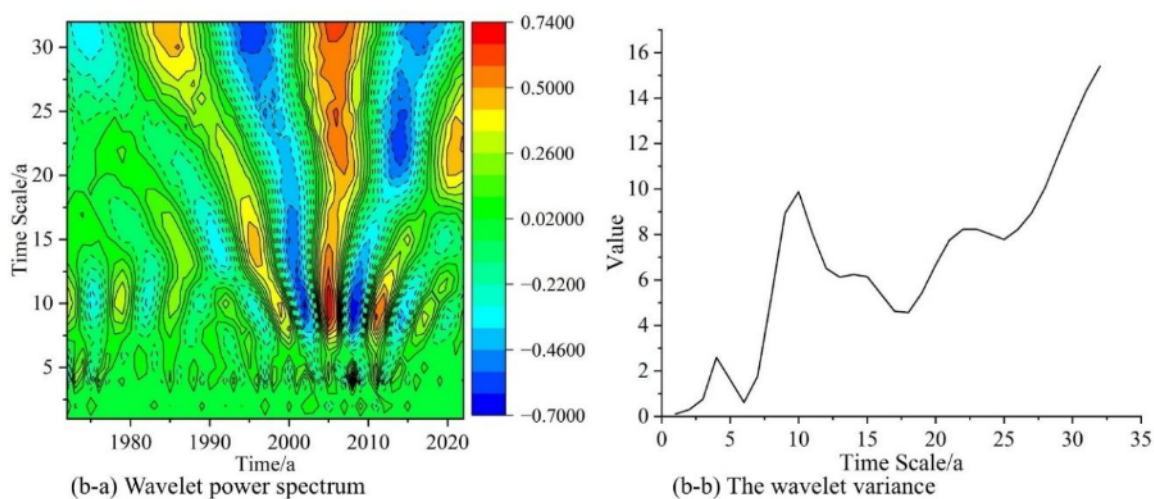
(1) Temporal changes

Similar to precipitation, the intra-annual distribution of runoff was also highly uneven, with maximum runoff occurring from late July to early August and minimum runoff occurring in January (Figure 5-15, Table 5-9). Peak runoff occurred approximately one month later than peak precipitation. This lag can be attributed to the delayed response of the surface and groundwater systems. Following rainfall events, time is required for the soil and subsurface to become saturated before overland flow is generated, resulting in a delayed runoff response.

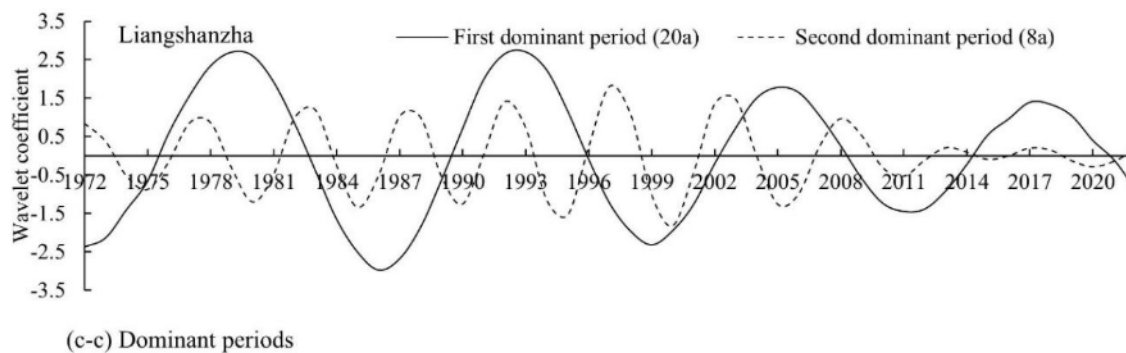
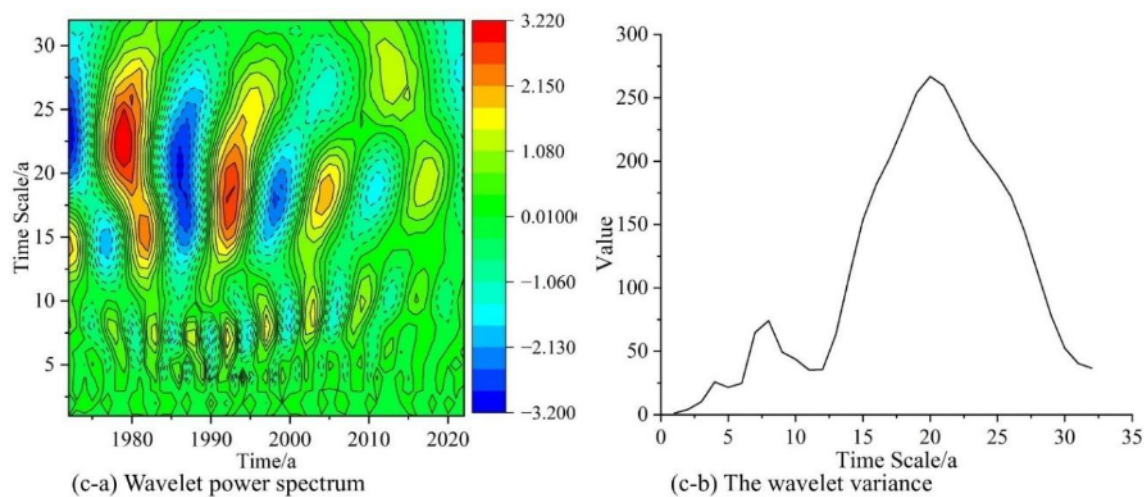
(a) Yutai



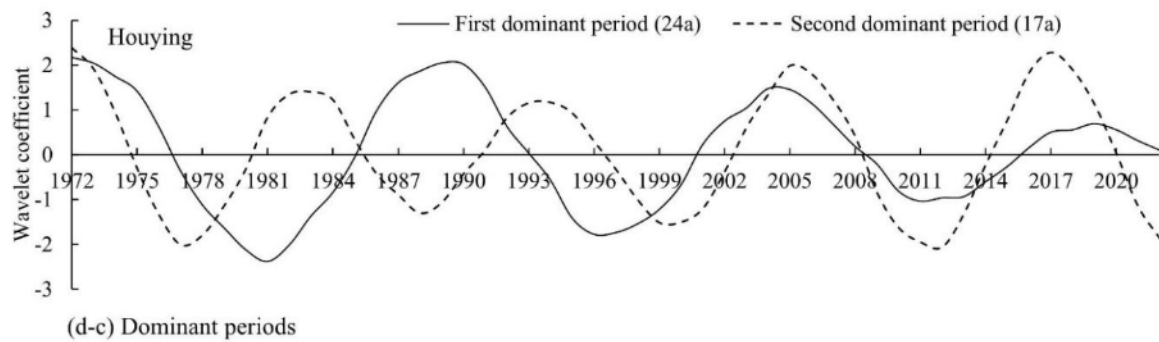
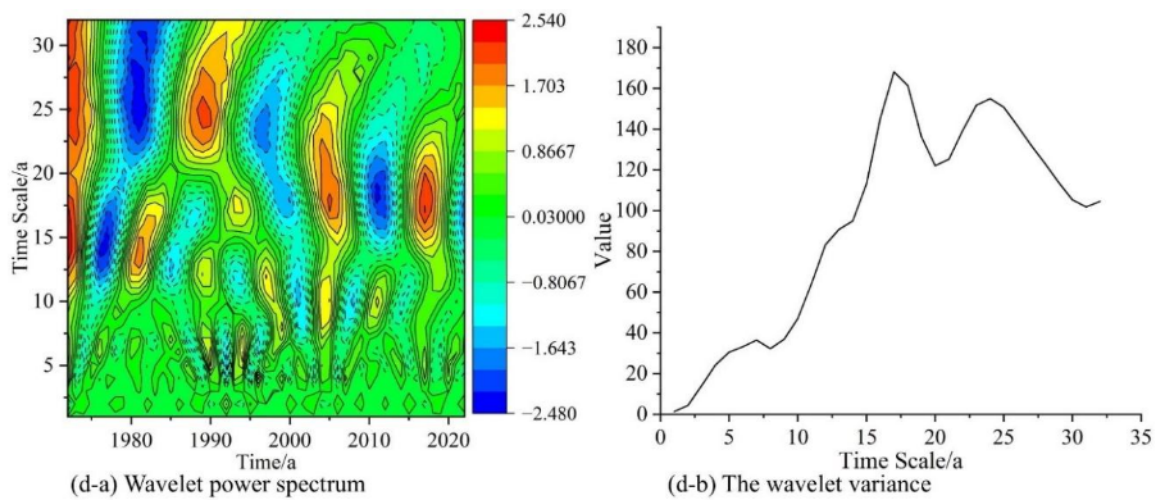
(b) Sunzhuang



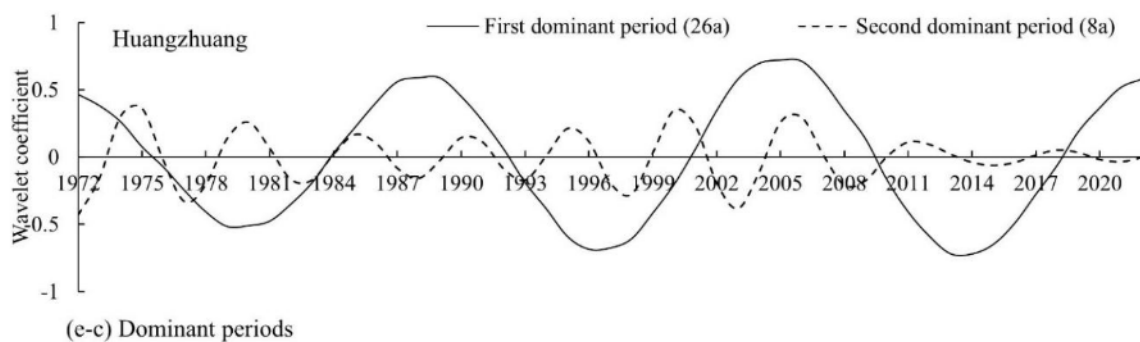
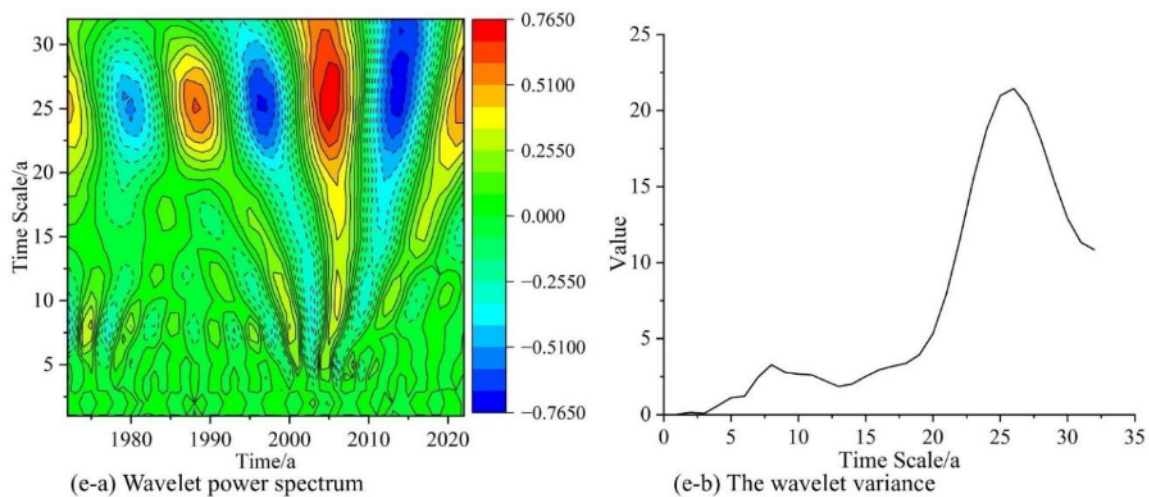
(c) Liangshanzha



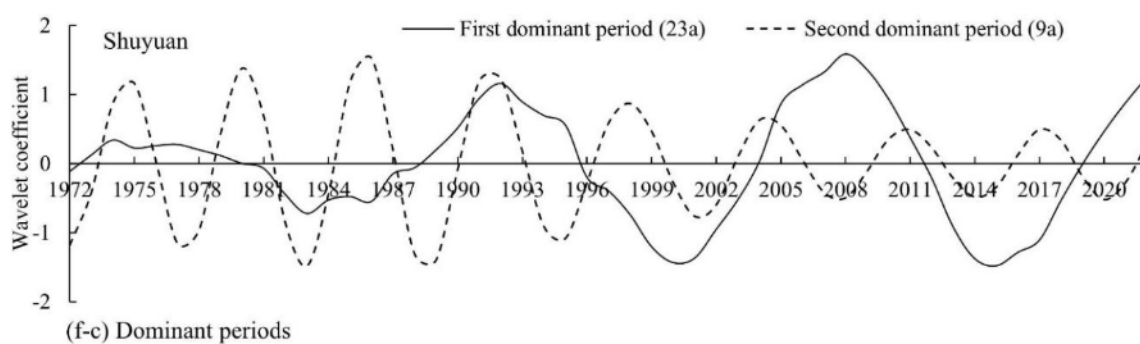
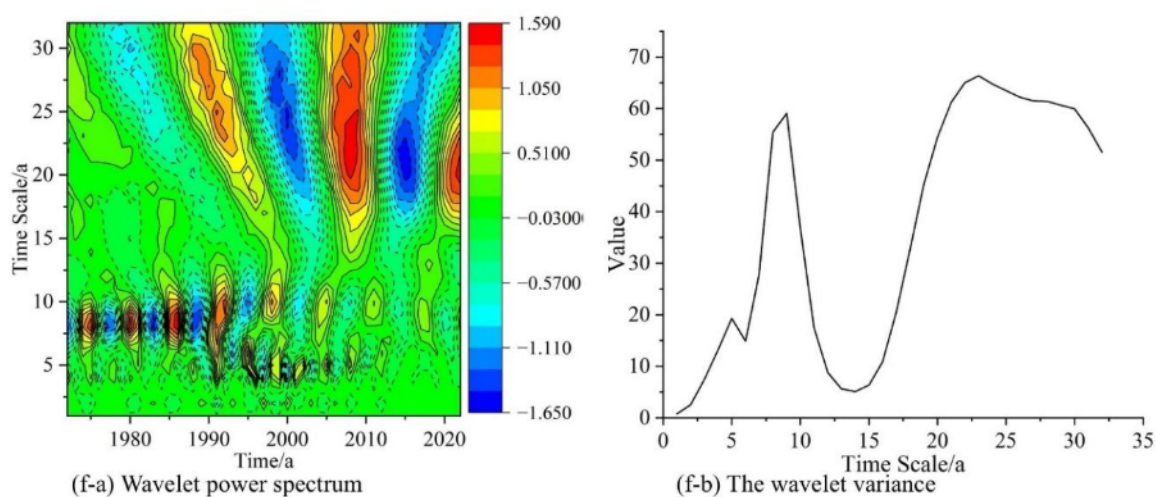
(d) Houying



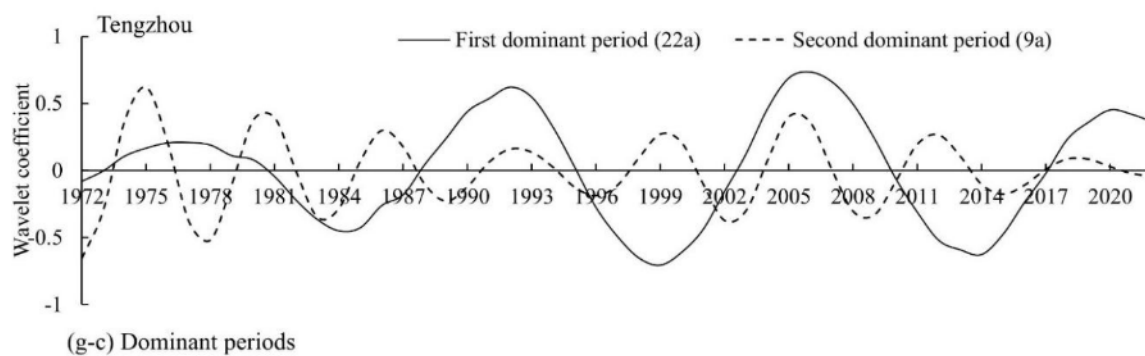
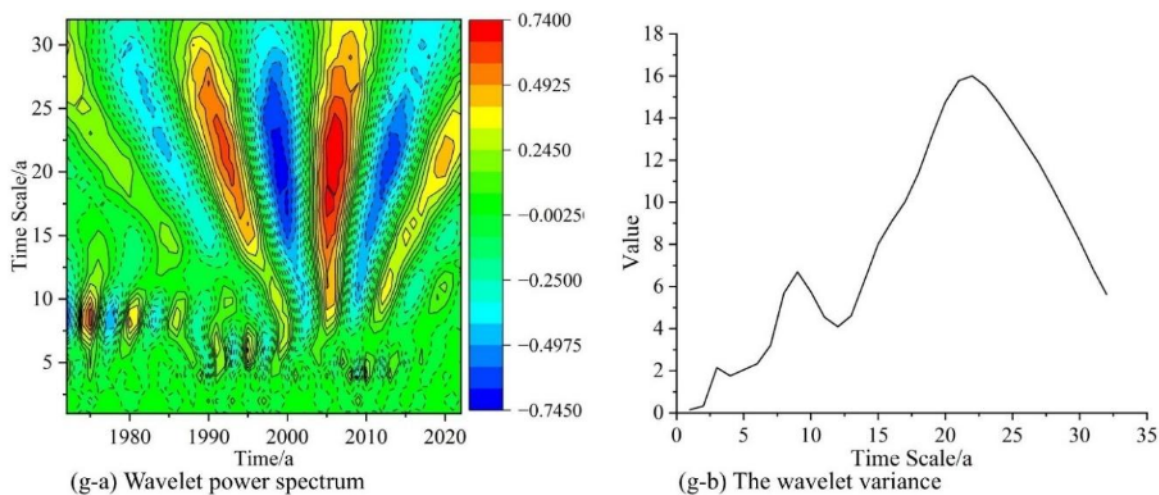
(e) Huangzhuang



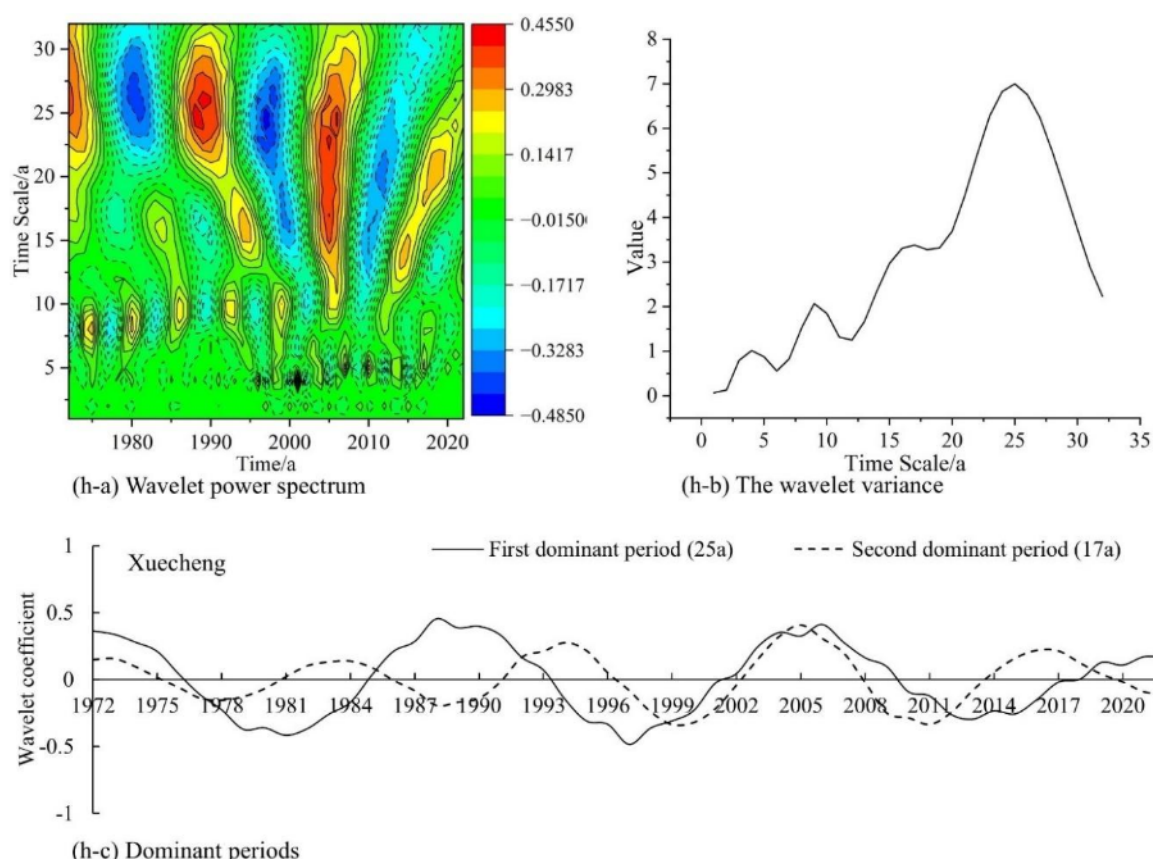
(f) Shuyuan



(g) Tengzhou



(h) Xuecheng

**Figure 5-14: Wavelet analysis of runoff volume at hydrological stations (Source: Author)**

The runoff was mainly concentrated in summer and autumn, accounting for about 80-98% of the annual runoff. Sunzhuang station had the largest runoff, even reaching 97.79%. Among them, the runoff from July to September accounts for 70.25-88.14% of the annual runoff. In spring and winter, the runoff was relatively small, both below 1 billion m^3 , accounting for 2.23-7.63% and 2.17-11.84%, and Sunzhuang station was basically cut off in winter. The values of the runoff at each hydrological station varied widely and were unevenly distributed spatially, with more in the southeast and less in the northwest, especially during July-September, when Houying and Yutai had the largest runoffs of 68.94 and 90.39 billion m^3 , respectively, and the lowest was Huangzhuang with only 14.78 billion m^3 .

Table 5-9: Multi-year average seasonal runoff volume in the NRB (Unit: Billion m^3)

Station	Spring	%	Summer	%	Autumn	%	Winter	%
Yutai	1.79	2.23	50.03	62.26	26.79	33.34	1.74	2.17
Sunzhuang	0.50	2.21	14.80	64.75	7.55	33.04	0.00	0.00
Liangshanzha	2.37	4.01	30.86	52.29	18.96	32.13	6.83	11.57
Houying	7.96	6.47	67.62	54.97	40.74	33.12	6.69	5.44
Huangzhuang	1.67	7.63	11.15	51.06	6.43	29.47	2.58	11.84
Shuyuan	5.74	6.26	56.14	61.23	20.39	22.24	9.42	10.27
Tengzhou	2.20	6.49	22.95	67.58	6.99	20.58	1.82	5.35
Xuecheng	0.55	3.01	12.96	70.67	4.17	22.75	0.66	3.57

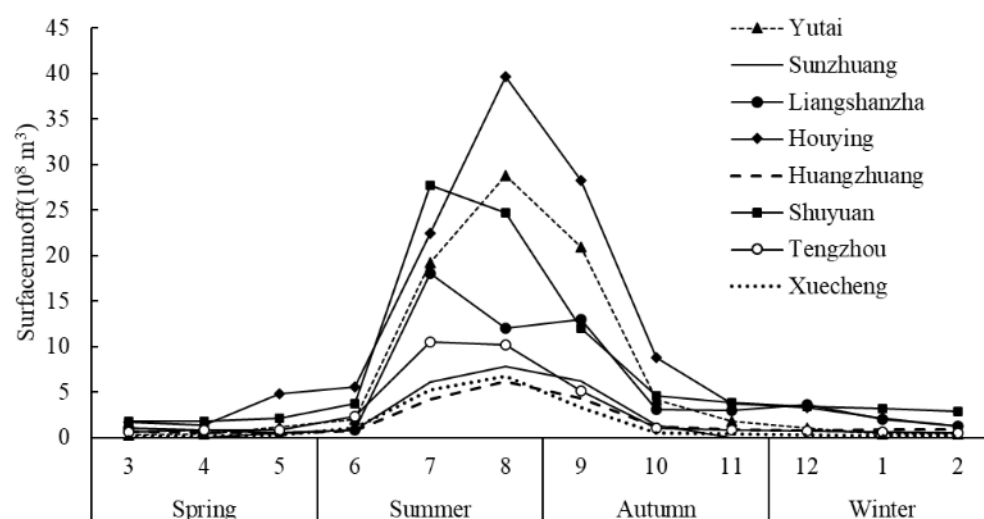


Figure 5-15: The multi-year average seasonal runoff at hydrological stations (Source: Author)

(2) Unevenness characteristic

The results are shown in Table 5-10 and Figure 5-16(c, d). Sunzhuang and Yutai exhibited the highest concentration of runoff, with C_d values of 0.86 and 0.81 and C_v values of 1.49 and 1.45, respectively, indicating that their runoff was more unevenly distributed throughout the year. In contrast, Huangzhuang had the lowest C_d (0.54) and C_v (1.02), suggesting a more even intra-annual distribution of runoff.

(3) Spatial distribution of runoff

Figures 5-16(a) and (b) show the uneven spatial distribution of runoff, with a decreasing trend from north to south. The spatial distribution characteristics of annual runoff and flood season runoff were the same. Among them, the Houying Station was the high-value center with an average annual runoff of 12.30 billion m^3 , while the Xuecheng Station was the low-value center with an average annual runoff of 1.8 billion m^3 .

Significant differences in runoff exist among stations. Figure 5-16(c) and (d) show that the runoff concentration center is precisely opposite to the precipitation concentration center, with runoff from the precipitation concentration center distributed relatively uniformly. Overall, runoff distribution in the southern region of the NRB was more concentrated, while the northern region was more uniform distribution.

Table 5-10: Unevenness characteristic of runoff at hydrological stations

Station	Flood season (billion m^3)	Whole year (billion m^3)	C_d	D	Peak runoff date	C_v	C_r
Yutai	7.10	8.04	0.81	213.41°	August 5th	1.45	0.61
Sunzhuang	2.10	2.29	0.86	210.03°	August 1st	1.49	0.63
Liangshanzha	4.38	5.90	0.59	217.85°	August 8th	1.15	0.48
Houying	9.59	12.30	0.68	214.38°	August 6th	1.19	0.48
Huangzhuang	1.55	2.18	0.54	216.09°	August 8th	1.02	0.43

Shuyuan	6.82	9.17	0.58	206.39°	July 29th	1.14	0.45
Tengzhou	2.81	3.40	0.69	200.51°	July 23rd	1.27	0.51
Xuecheng	1.63	1.83	0.78	205.27°	Jul 28th	1.43	0.59

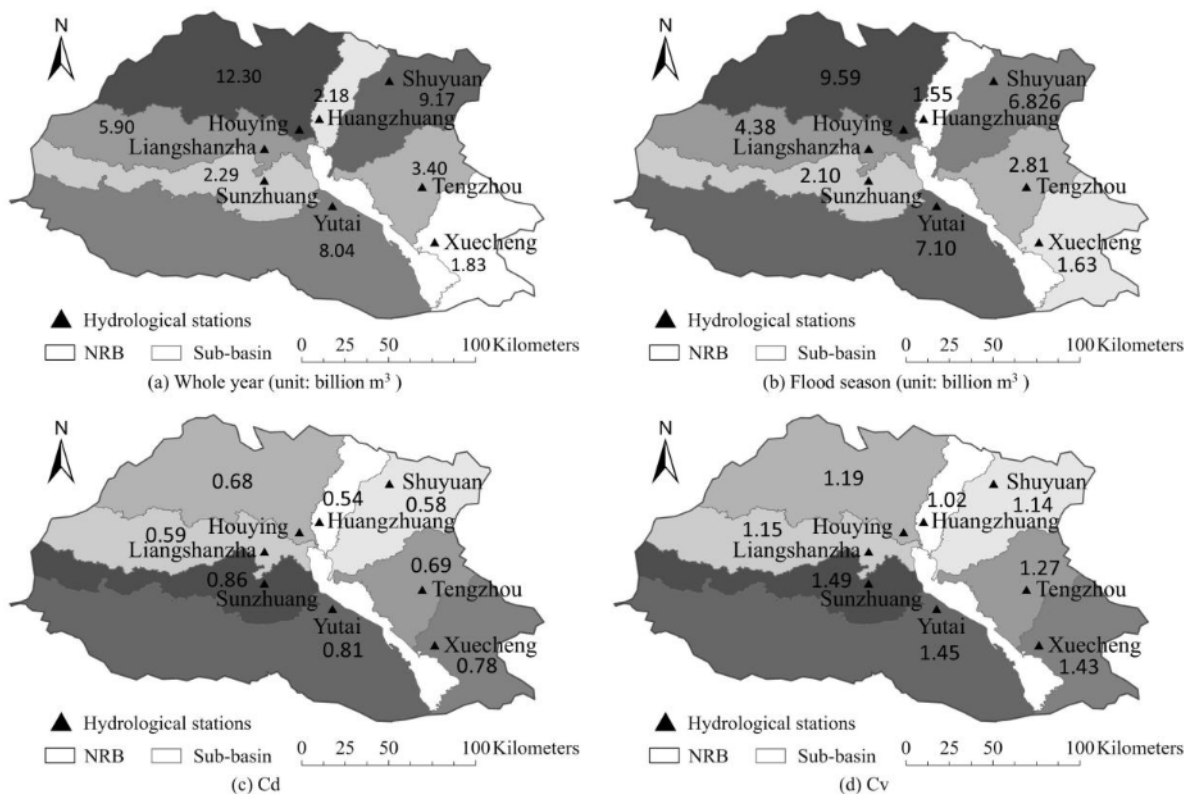


Figure 5-16: Spatial distribution of surface runoff (Source: Author)

5.2.2.4 Changes in runoff responses to heavy rainfall events

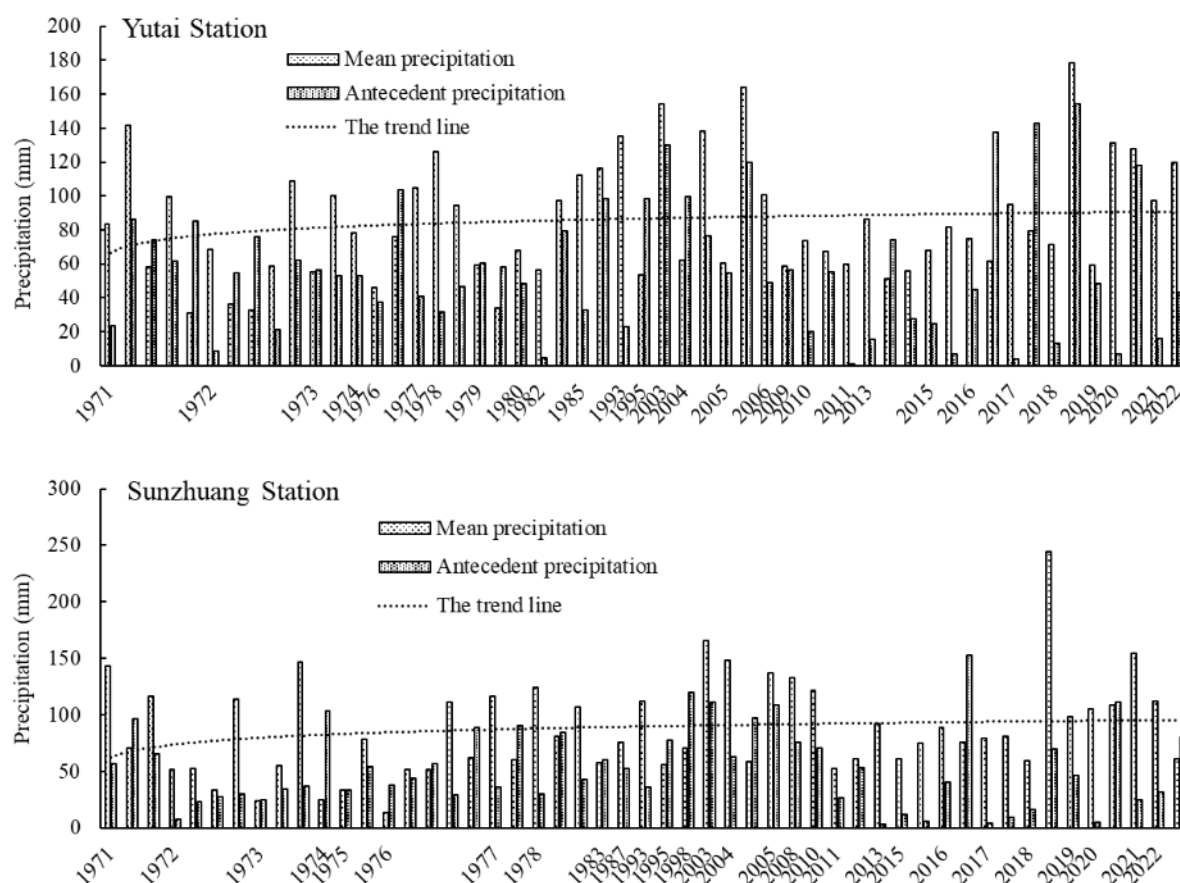
Each station experienced more than 50 heavy rainfall events (Figure 5-17). In the western NRB, Yutai, Sunzhuang, Liangshanzha, and Houying stations recorded 53 (1971-2022), 51 (1971-2022), 48 (1967-2022), and 55 (1964-2022) heavy rainfall events, respectively. In the eastern NRB, Huangzhuang Station recorded 55 heavy rainfall events during 1963-2022, Shuyuan Station recorded 56 during 1957-2022, Tengzhou Station recorded 46 during 1960-2022, and Xuecheng Station recorded 57 during 1962-2022.

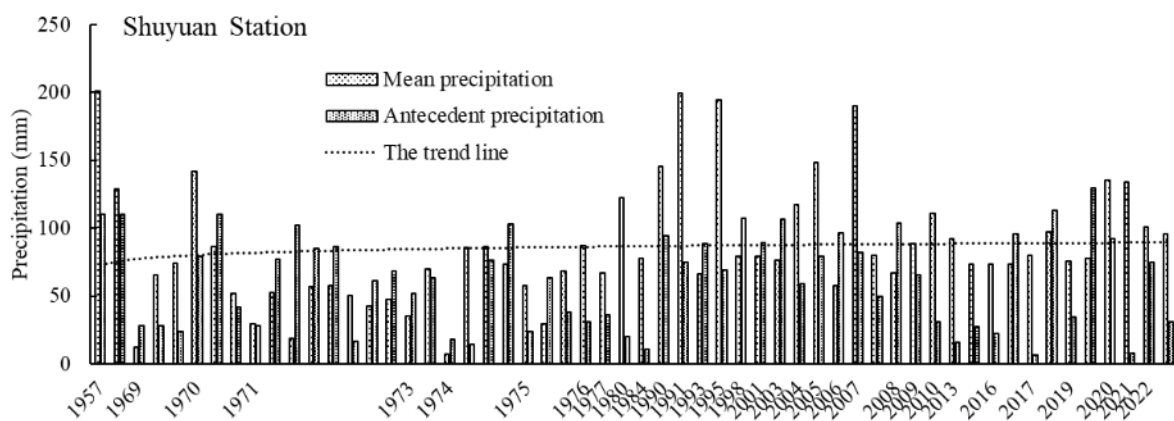
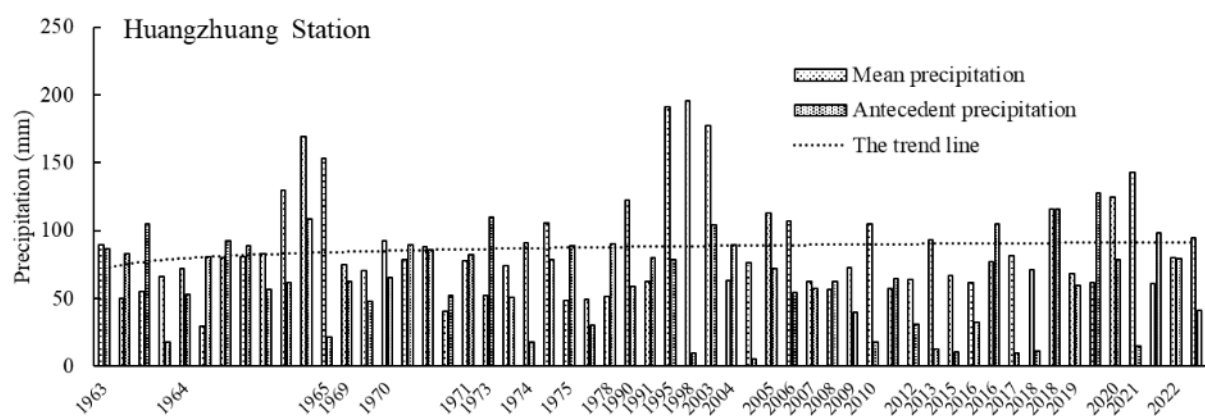
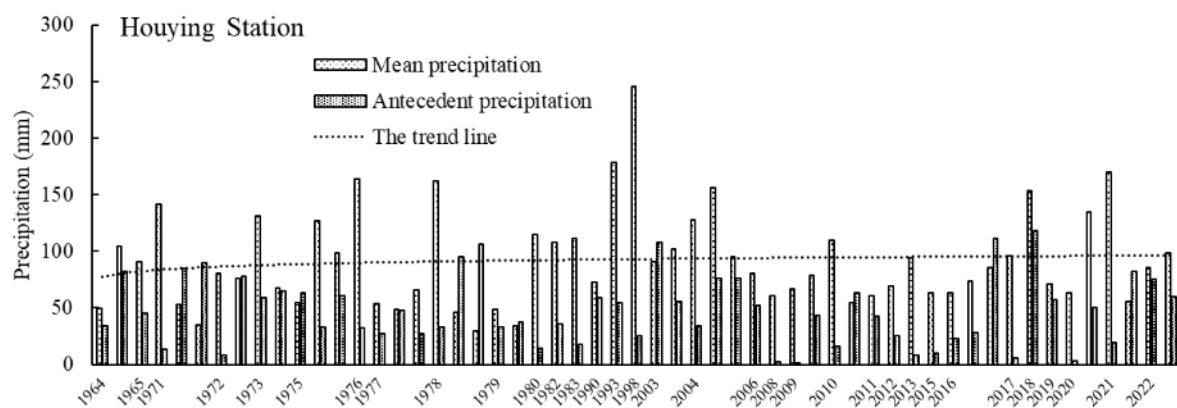
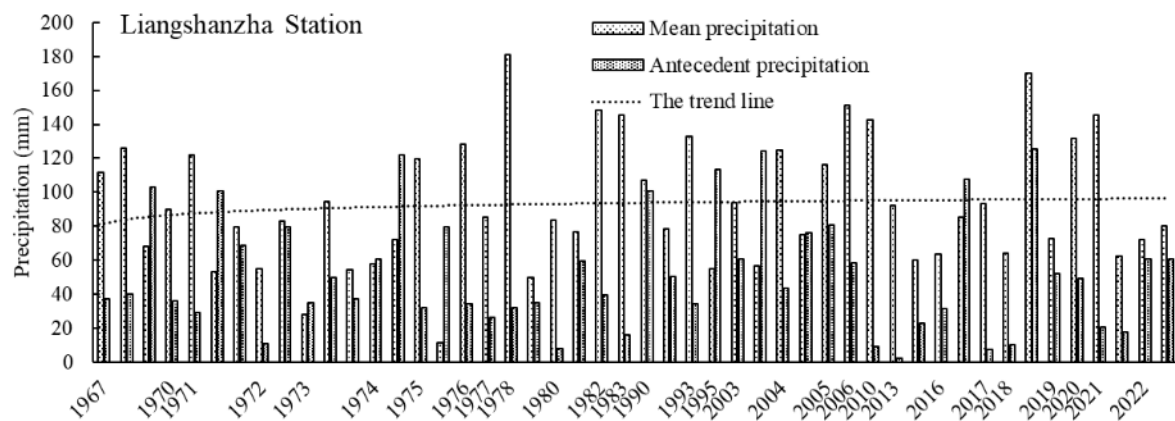
All the hydrological stations showed an increasing trend in heavy rainfall (Table 5-11). In particular, Sunzhuang and Shuyuan stations, which were located at the junction of urban and suburban areas, had U values of 2.27 and 2.25, respectively. Followed by Tengzhou station, which was located in the urban area, with U of 1.78, indicating a significant increase in heavy rain. Together with the higher flood season precipitation observed in urban than in suburban areas, these results suggest that the increase in heavy rainfall was more pronounced in areas affected by urbanization.

Antecedent precipitation generally showed weak decreasing or non-significant trends, suggesting that the increasing heavy rainfall was primarily associated with individual rainfall events rather than progressively wetter antecedent conditions. Runoff depth, however,

generally increased during heavy rainfall events. In the context of rapid urbanization and the conversion of permeable land to impervious area in the NRB, the increase in event runoff is consistent with the expected hydrological effects of urbanization, expansion of impervious surfaces reduces infiltration and increases the proportion of rainfall converted to surface runoff. Therefore, the both increase in heavy rainfall and runoff depth suggests that urbanization may have intensified event scale runoff generation through both changes in local rainfall characteristics and LULC transformation.

Peak flood flow, however, did not respond consistently to the increase in heavy rainfall and runoff depth. Four stations exhibited decreasing trends, one remained relatively stable, and only Liangshanzha Station showed a significant increase. This divergence indicates that increased runoff generation does not necessarily translate directly into higher peak flood. Peak flood flow is also affected by catchment characteristics and human regulation. In particular, many of the hydrological stations are located in the midstream and downstream of the NRB, where reservoirs and other water regulation projects constructed since the 1970s may have reduced peak flood. Thus, the observed event scale runoff response reflects the combined influence of urbanization, and water regulation rather than urbanization alone.





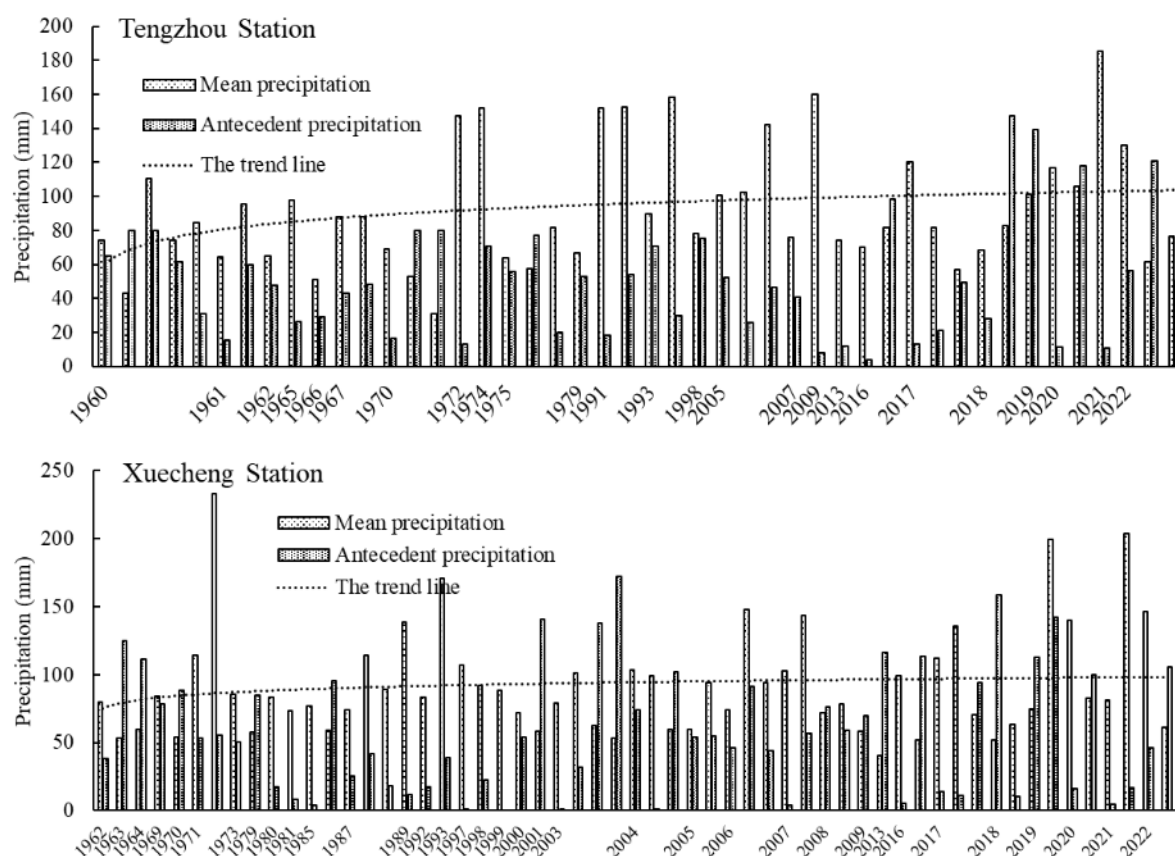


Figure 5-17: Heavy rainfall events at hydrological stations (Source: Author)

Table 5-11: Characteristics of heavy rain-runoff in the NRB

Station	Average precipitation (mm)	U	Antecedent precipitation (mm)	U	Peak flood flow (m ³ /s)	U	Runoff depth (mm)	U
Yutai	85.11	1.65	56.97	-0.97	348.00	-0.42	11.56	0.59
Sunzhuang	87.55	2.27	52.94	0.06	87.11	0.33	17.02	2.70
Liangshanzha	92.76	0.92	51.87	0.66	379.60	2.43	16.92	0.45
Houying	91.85	0.65	47.40	-0.98	191.12	-1.30	16.61	0.55
Huangzhuang	86.92	0.71	62.35	-1.45	161.36	-0.85	19.75	-2.24
Shuyuan	85.63	2.25	61.70	-0.98	585.86	0	39.17	1.39
Tengzhou	93.08	1.78	51.15	-0.68	197.81	-0.71	35.58	1.70
Xuecheng	92.94	0.86	58.30	0.46	-	-	-	-

5.2.3 Evaporation

5.2.3.1 Trend changes in evaporation

This research analyzed the trend change of evaporation in the NRB from 1960s to 2020. The evaporation fluctuated and decreased at the three meteorological stations and the NRB (Figure 5-18 and 5-19), and the MK test results were -6.02, -5.76, -8 and -4.76 in NRB, Xuzhou Station, Yanzhou Station, Dingtao Station, respectively. The decreasing trends were very obvious. Climatic conditions form the basis for changes in evaporation, while human activities have a significant impact on these changes. Between 1961 and 2002, evaporation decreased along with

reduced precipitation. After 2003, increased precipitation mitigated the downward trend in evaporation. The rise in human activities since the 1980s was the primary cause of the decrease in evaporation.

The maximum and minimum values of evaporation at Dingtao Station were 2376.70 mm and 573.80, respectively, a decrease of 75.86%, which was the largest among the three meteorological stations. The maximum and minimum values at Yanzhou station were 2072.30mm and 656.50mm respectively, a decrease of 68.32%. In contrast Xuzhou station had the smallest decrease, but also by 56%. The maximum and minimum values were 2279.00mm and 999.30mm. The decrease in evaporation might be caused by the increase in aerosols and other pollutants due to human activities in the context of global warming, resulting in a decrease in the amount of solar radiation and thus less evaporation from the evaporation dish. On the local scale, there was a wave peak in the 1970s and 1990s, respectively, with a small increase in evaporation.

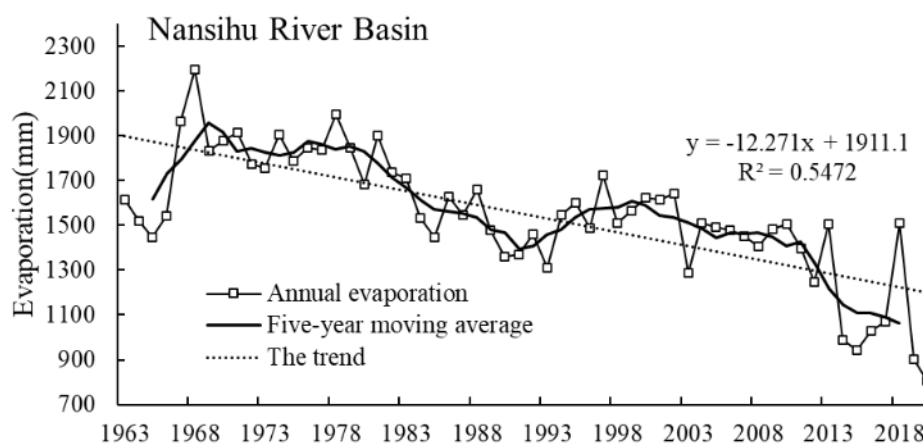
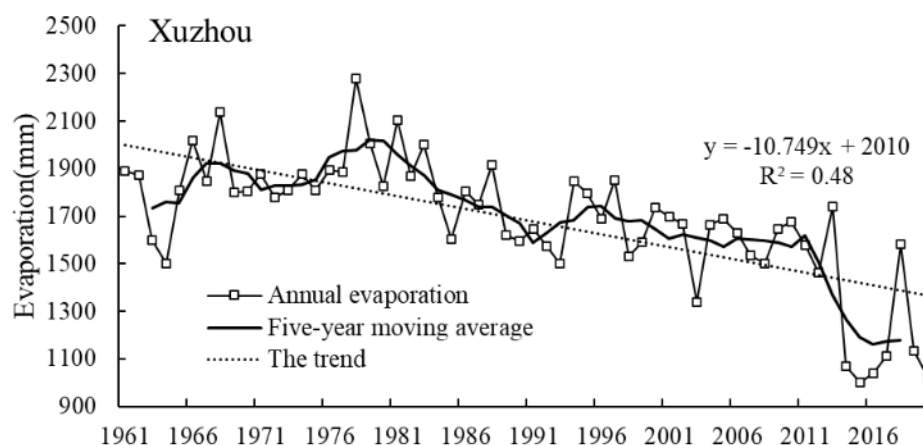


Figure 5-18: Evaporation Trends in the NRB (Source: Author)



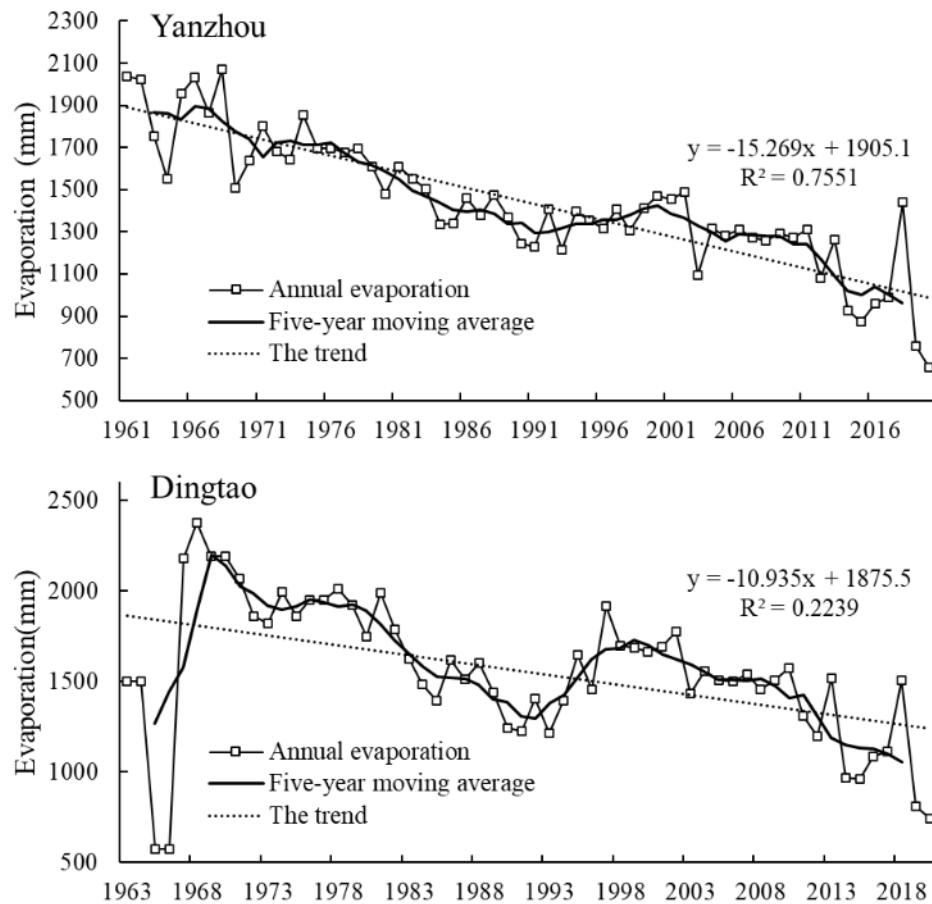


Figure 5-19: Evaporation trends at meteorological stations (Source: Author)

5.2.3.2 Cyclical variations in evaporation

Wavelet analysis of the multi-year average evaporation in the NRB showed clear periodic fluctuations (Figure 5-20(a)). 20-25a exhibited clear alternations between positive and negative phases across the full time scale, which was the dominant period; followed by localized small cycles of 15-18a and 5-10a.

Evaporation also did not have a uniform cycle and was nested in multiple time scales. There were three distinct peaks in the wavelet variance plot (Figure 5-20(b)), corresponding to 9a, 16a and 21a. The fluctuation at 21a was more stable and spanned the entire time scale, which was the first dominant period. 16a was a localized cycle affecting the 1963-1975 and 1995-2020. The second dominant period was 9a. On the 30a scale, the wavelet variance tended to rise linearly, and the next peak required longer time series data for verification. 4 oscillations occurred on 21a, with the abrupt change points being 1965, 1972, 1979, 1986, 1994, 2001, 2008, and 2014, each lasting 12-14 years. On 9a scale, 9 oscillations occurred.

The evaporation at the three meteorological stations was also nested in multiple time scales (Figure 5-21). The first and second dominant periods at Xuzhou station were 18a and 9a, respectively. The first and second dominant periods at Yanzhou station were 10a and 4a, respectively. The first and second dominant periods at Dingtao station were 22a and 9a, respectively. Yanzou station was subjected to relatively shorter cycles, which indicated that the area is more sensitive to the global and regional climate change.

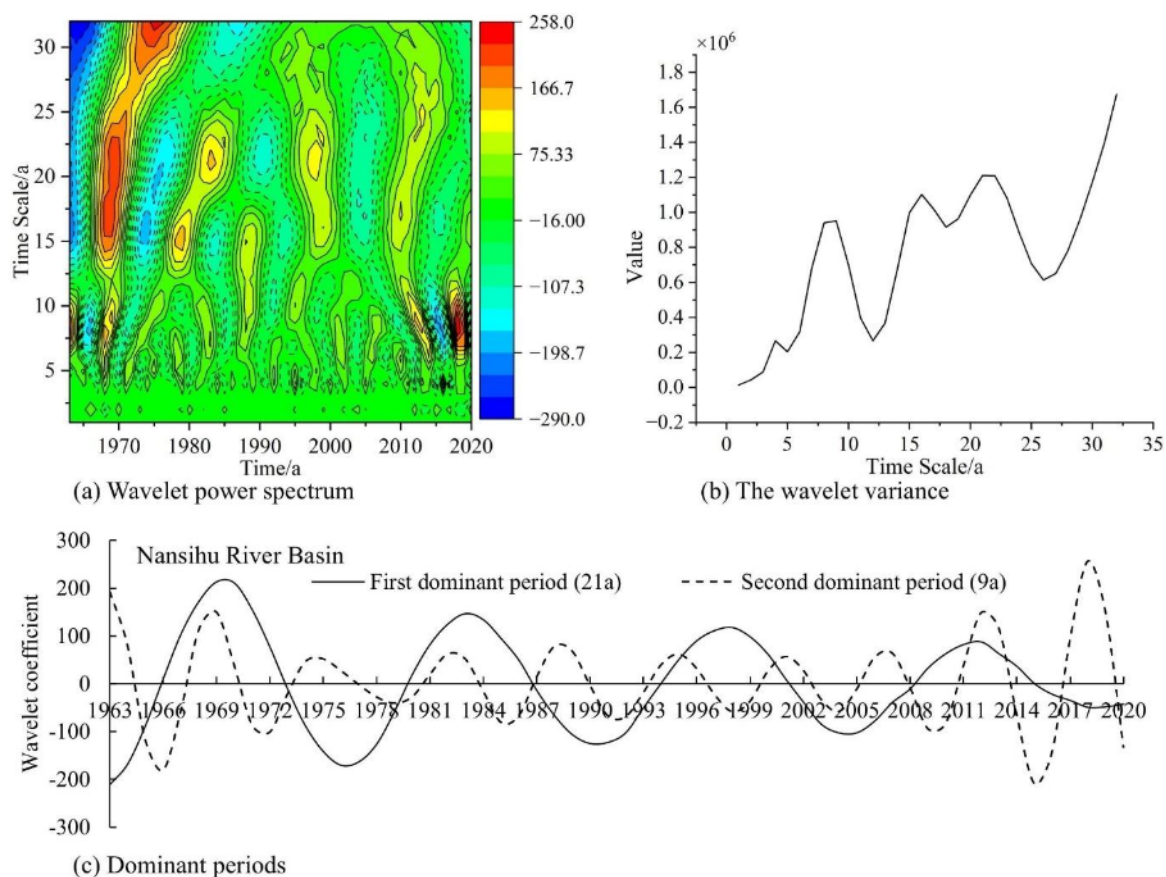
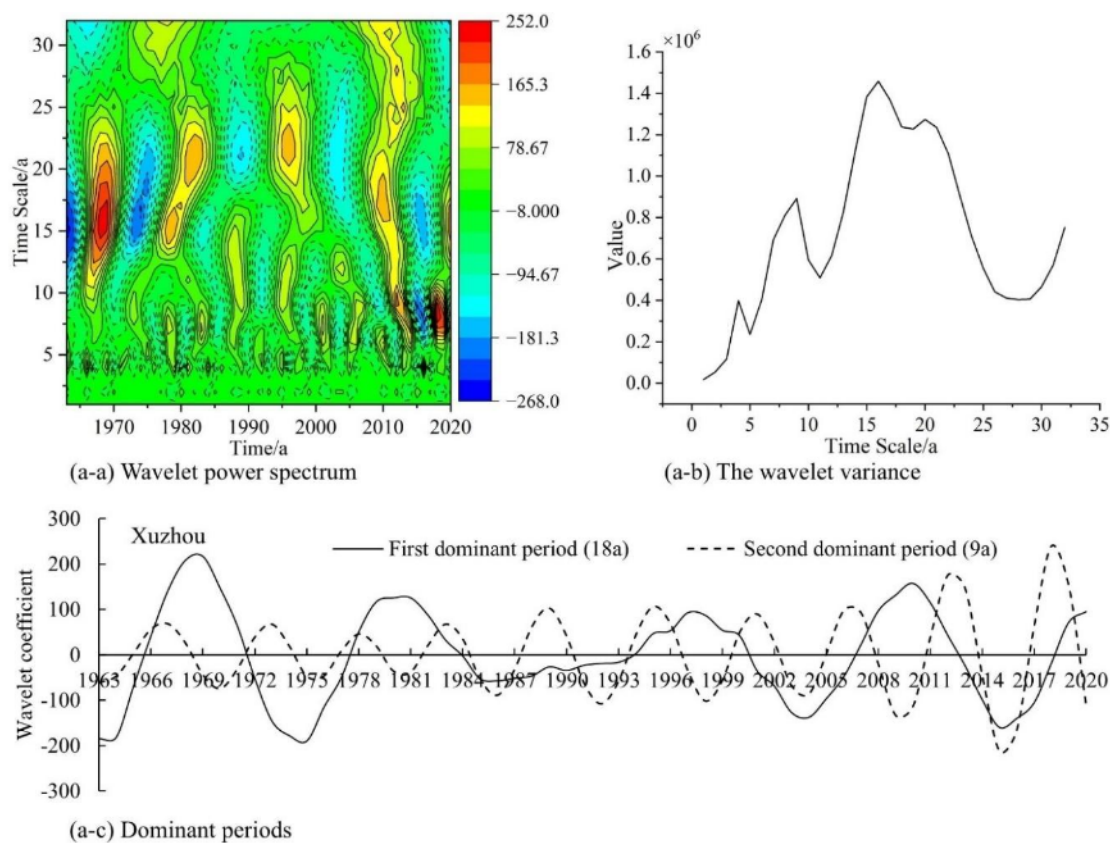
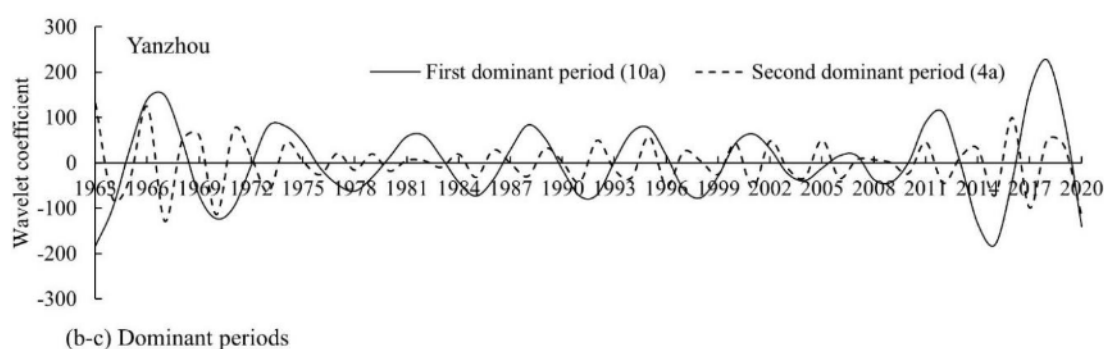
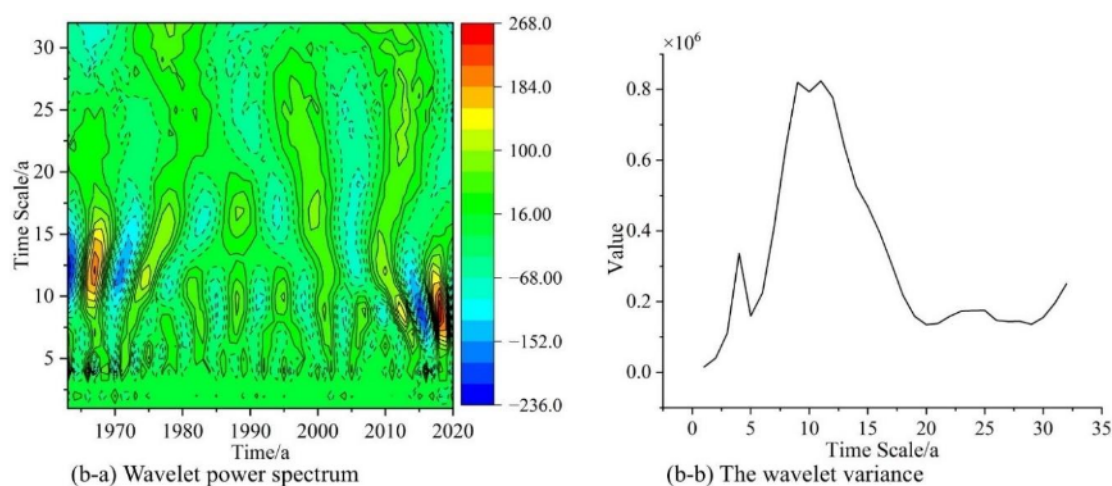


Figure 5-20: Wavelet analysis of annual evaporation in the NRB (Source: Author)

(a) Xuzhou



(b) Yanzhou



(c) Dingtao

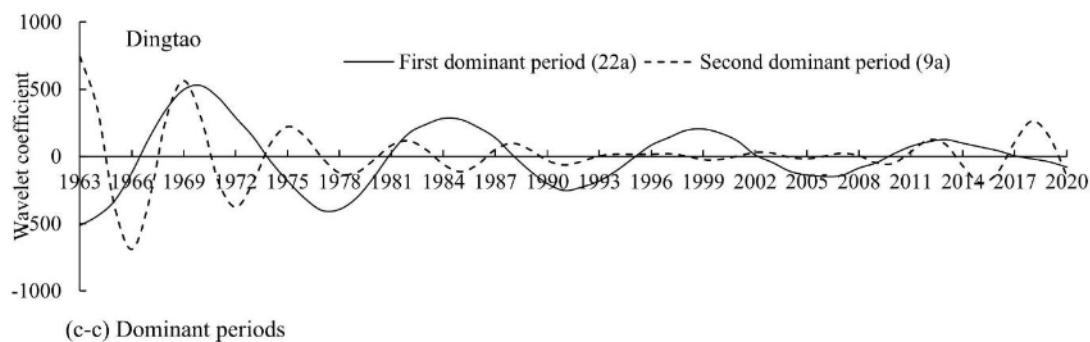
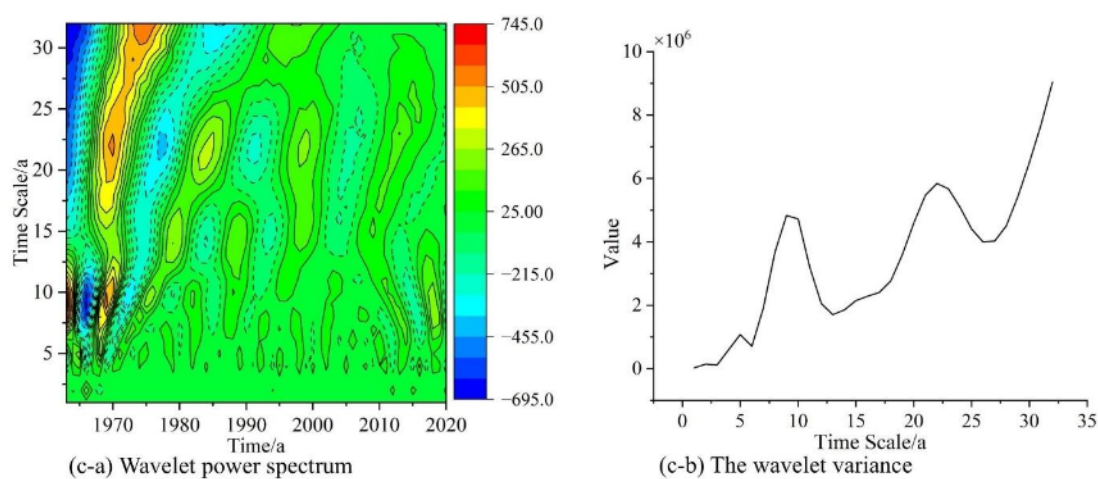


Figure 5-21: Wavelet analysis of evaporation at meteorological stations (Source: Author)

5.2.3.3 Intra-annual changes in evaporation

The intra-annual distribution of evapotranspiration in the watershed also varied considerably, while a consistent pattern was observed across the three meteorological stations (Figure 5-22). Among them, evaporation was highest in June, one month earlier than the peak of precipitation. This was due to the fact that June was the beginning of summer, the temperature raised and the sunshine time became longer, which was helpful for the production of evaporation. Peak evaporation dates were June 4th and June 5th. The evaporation in June accounted for 14.35-16.20% of the annual evaporation, and Dingtao's was the largest, 251.66 mm. The evaporation in December was the least, and Yanzhou was the least, 36.69 mm. The proportions in spring, summer, autumn and winter were 32.56-33.03%, 35.66-38.19%, 19.56-20.54%, and 9.22-10.88%, respectively (Table 5-12). The C_d and C_v showed that the distribution of evaporation was relatively even. Spatially, slightly larger in the southeastern part near Xuzhou (Table 5-13).

Table 5-12: The proportion of evaporation in each season

Station	Spring (mm)	%	Summer (mm)	%	Autumn (mm)	%	Winter (mm)	%
Xuzhou	553.76	32.92	599.83	35.66	345.52	20.54	182.99	10.88
Yanzhou	475.46	33.03	549.70	38.19	281.61	19.56	132.68	9.22
Dingtao	505.64	32.56	580.34	37.37	311.10	20.03	155.83	10.03

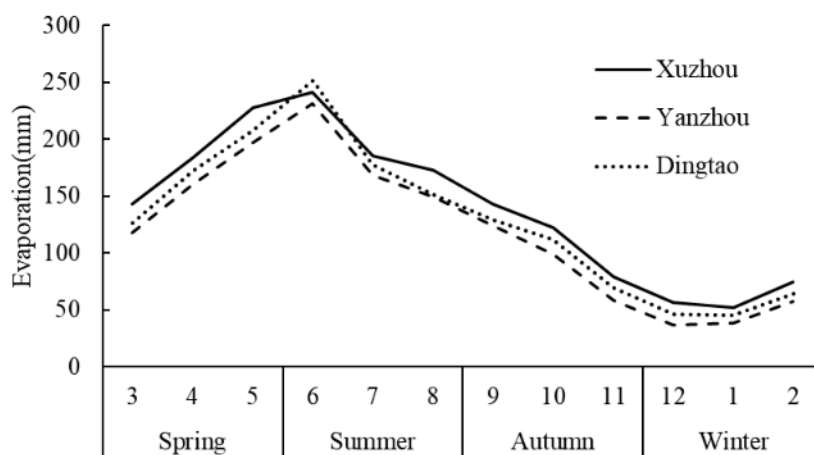


Figure 5-22: Average seasonal evaporation of the NRB (Source: Author)

Table 5-13: Unevenness characteristics of evaporation

Station	Flood season (mm)	Whole year (mm)	C_d	D	Peak evaporation date	C_v	C_r
Xuzhou	743.35	1682.10	0.30	152.90°	June 5th	0.44	0.19
Yanzhou	673.72	1439.44	0.35	153.24°	June 5th	0.51	0.22
Dingtao	709.86	1552.92	0.33	152.61°	June 4th	0.49	0.20

5.2.3.4 Urban-suburban differences in evaporation

Xuzhou station is located in the south of Xuzhou city, Dingtao station is located in Heze city, and Yanzhou station is located in the rural area outside the boundary of Yanzhou city. Therefore,

the average of the evaporation from Xuzhou and Dingtao stations is taken as the urban evaporation, and the evaporation from Yanzhou is taken as the suburban evaporation, and the difference between the urban and suburban evaporation is plotted (Figure 5-23).

It showed that since 1963-2020, the change of evaporation in the NRB had an overall decreasing trend, and the trend of urban and suburban areas was the same, urban evaporation was larger than suburban areas for many years. It increased before the 1970s, and then slowly decreased. Fluctuating changes in evaporation difference showed an overall upward trend, with an increasing trend before the 1970s and a relatively stable change after the 1970s. It mainly resulted from the development of urbanization, the increase of impervious surface, and the urban heat island effect, which led to the weakening of runoff infiltration and the increase of evaporation in urban areas; and in recent years, the difference between rural evaporation and urban evaporation showed a decreasing trend, and the difference was mostly around 200mm, but urbanization still influenced the change of evaporation.

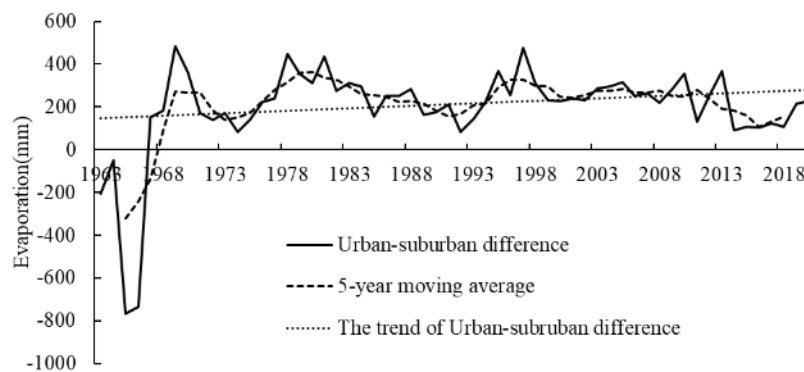


Figure 5-23: Urban-suburban differences in evaporation in the NRB (Source: Author)

5.3 Hydroecology in the NRB

This chapter evaluated the impacts of urbanization on watershed hydroecological functions from the perspective of ecosystem services. Urbanization leads to significant LULC changes, which can further alter hydrological processes and ecological conditions. To assess these impacts, three indicators were selected: water yield, carbon storage, and habitat quality. Their temporal changes, spatial distributions, and responses to LULC change were analyzed. Through this assessment, ecologically vulnerable areas and areas with weak ecological functions can be identified, providing an ecological basis for watershed ecological protection strategies.

5.3.1 Water yield

5.3.1.1 Simulation results of water yield in the NRB

Spatially (Figure 5-24), at the regional scale, the eastern part exhibited greater water yield than the western part, consistent with the spatial pattern of precipitation. These results suggest that precipitation played a dominant role in the spatial distribution of water yield. When different LULC types were considered across the NRB, the majority of low value areas were in the eastern mountainous area, primarily due to its extensive vegetation and high infiltration

capacity. Minimum water yield values were observed around Nansihu Lake, while impervious areas showed relatively high water yield.

Average water yield in the NRB from 2000 to 2022 was 268.22 mm. It showed a fluctuating downward trend with an overall decrease of approximately 33.51% (Table 5-14). This indicated a decline in water conservation function in the NRB. This decreasing trend is closely correlated with changes in precipitation during the same period, but the decline is more significant. This indicates that, in addition to climate change, other factors may be intensifying the reduction in water yield (W. Zhang et al., 2025).

Table 5-14: Water yield and precipitation in the NRB

Year	Water Yield (mm)		Precipitation (mm)	
	Max	Mean	Max	Mean
2000	561.76	283.12	849.80	754.47
2005	692.36	330.98	944.10	813.61
2010	538.36	237.64	776.20	689.40
2015	553.64	269.28	829.10	730.58
2022	628.78	220.06	874.00	682.80

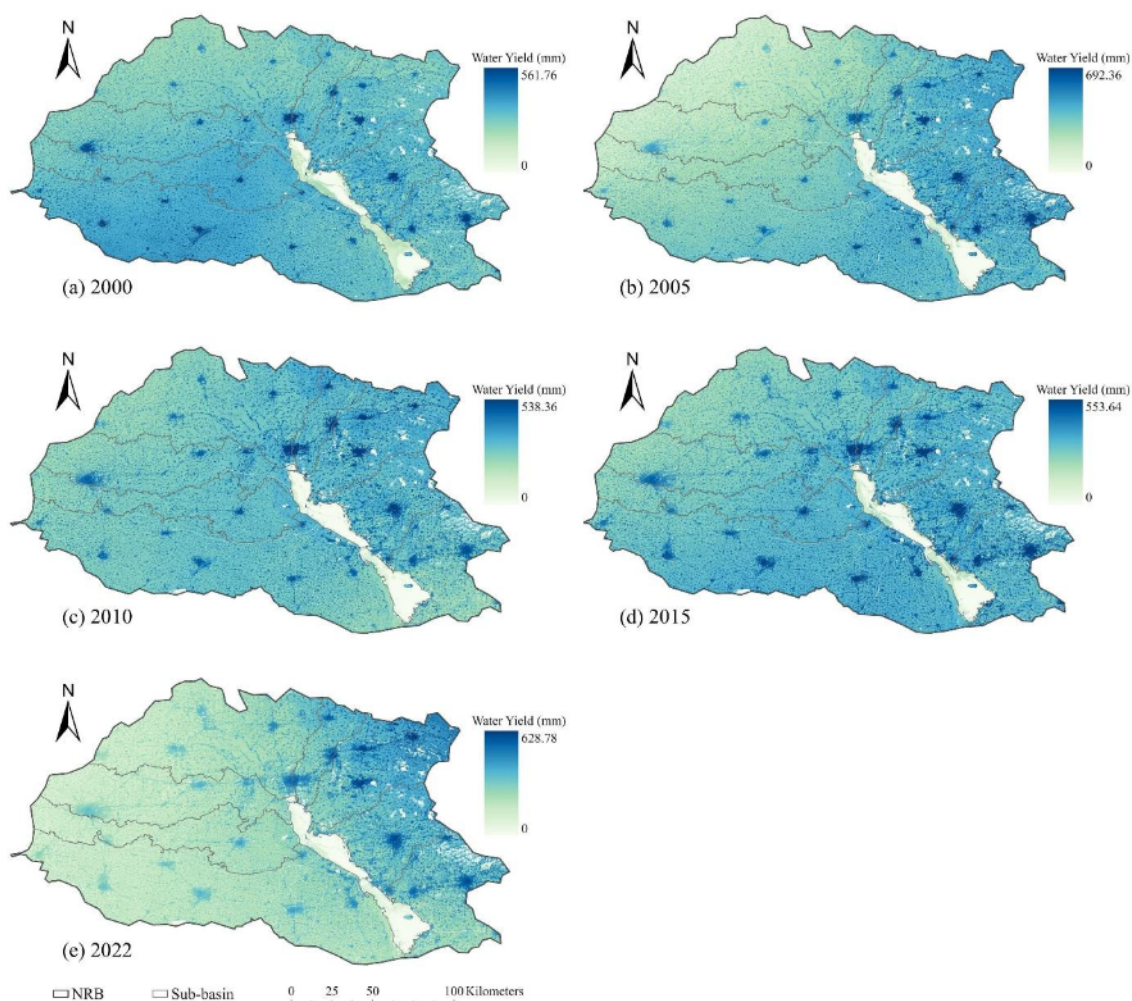


Figure 5-24: Spatial distribution of water yield in the NRB from 2000 to 2022

(Source: Author)

5.3.1.2 Changes of water yield in the NRB

Analysis of spatial trends in water production across different periods reveals:

2000-2005 (Figure 5-25(a)): Water yield increased in eastern area while remaining relatively stable in western area.

2005-2010 (Figure 5-25(b)): Water yield decreased in eastern area, while increasing or stabilizing in western area.

2010-2015 (Figure 5-25 (c)): Overall water yield decreased, with the rate of decline gradually slowing from north to south.

2015-2022 (Figure 5-25 (d)): A decreasing trend from east to west.

The greatest increase was from 2000 to 2005 and the largest decrease was from 2005 to 2010, with 581.68 mm and -648.02 mm, respectively. The overall trend from 2000 to 2022 (Figure 5-26), the greatest reduction occurred in the western plains (-200 to -100 mm), while the central area including the Nansihu Lake decreased by -100 to 0 mm, and the northeast corner of the basin increased significantly by over 50 mm. This spatial variation is a response to spatial variations in the underlying surface.

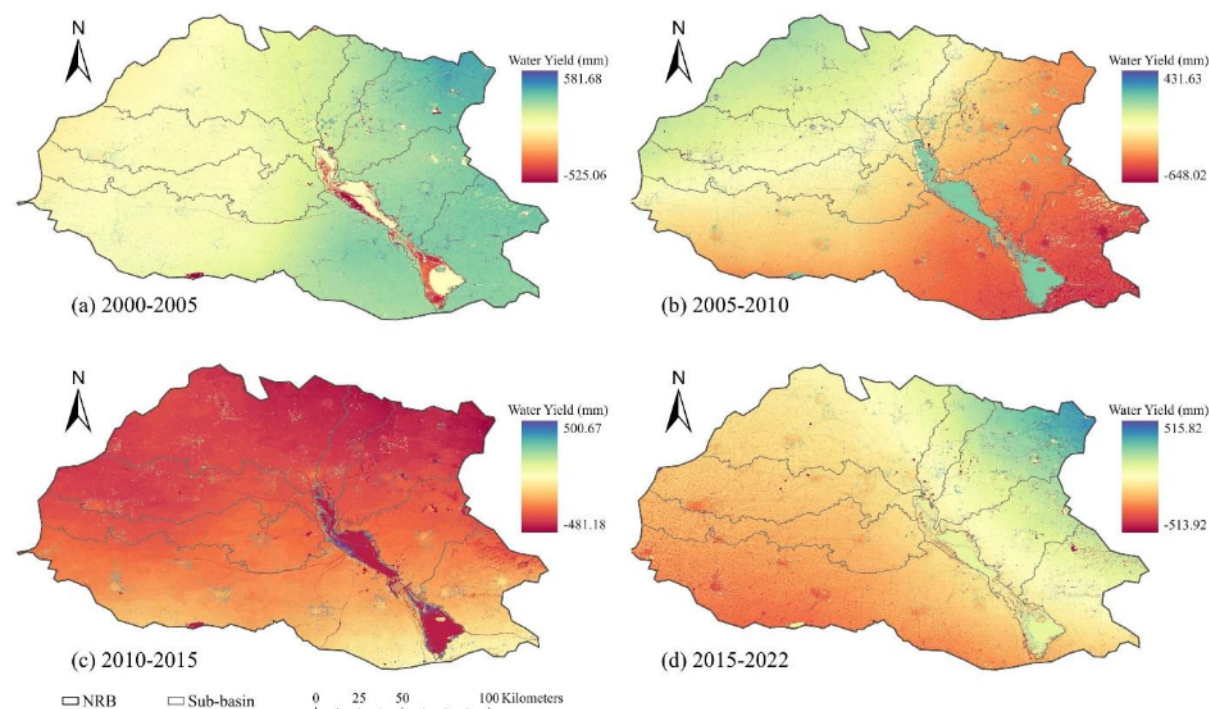


Figure 5-25: 5-year change of water yield (Source: Author)

5.3.1.3 Response of water yield to LULC changes

As LULC changes represent the spatial manifestation of urbanization in this study, the response of water yield to LULC change was examined to identify how land surface transformation associated with urbanization influenced the spatial distribution of water yield. The 6 LULC types were categorized into two groups based on the degree of human disturbance.

Natural areas: forest, grassland and water, which are minimally influenced by human activities and maintain a natural surface state.

Non-natural areas: cropland, bare land and impervious areas, which had been developed and had lost their original natural surface state.

Water yield from water was recorded as 0. With a single vegetation type and a simplified ecosystem structure, cropland is heavily influenced by human activities. Therefore, it is classified as a non-natural area.

Water yield of non-natural areas was about three times that of natural areas (accounting for approximately 75% and 25% of total water yield, respectively) (Figure 5-27). The difference was most pronounced in 2010, with 79% and 21% respectively. This shows that the land surface altered by human activities has significantly enhanced its runoff generation capacity. Since urbanization is primarily characterized by the expansion of impervious surfaces and the transformation of natural land into developed land, non-natural areas, can be considered as the spatial manifestation of urbanization processes. Therefore, the significantly higher water yield observed in non-natural areas reflected the impact of urbanization on water yield.

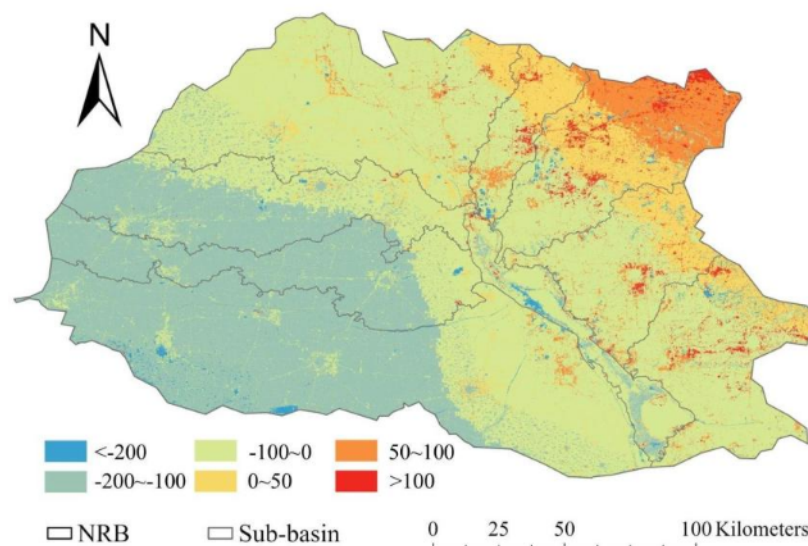


Figure 5-26: The change of water yield in the NRB (Source: Author)

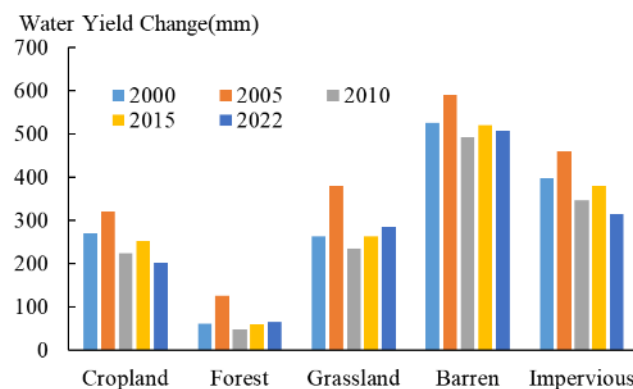


Figure 5-27: Changes in water yield for LULC types (Source: Author)

Among the specific LULC types, forest showed the lowest water yield (49.04-127.11 mm), reflecting its strong interception, infiltration, and evapotranspiration capabilities. Meanwhile, bare land showed the highest yield (493.82-591.59 mm) due to its lack of vegetation cover and weak infiltration. Impervious areas had the second highest water yield (315.15-459.07 mm). Since the replacement of pervious surfaces with impervious ones prevents absorption and infiltration, leading to excessive runoff and an increased total water yield. And this process represented a key mechanism through which urbanization increases water yield. Cropland and grassland produced nearly equal water yield, with average values ranging from 255-286 mm. However, due to the uniform vegetation structure of cropland, its hydrological regulation capacity is significantly lower than that of grasslands.

5.3.2 Carbon storage

5.3.2.1 Simulation results of carbon storage in the NRB

The distribution of carbon storage intensity in the NRB (Figure 5-28), changed significantly during 2000-2022. The value of carbon storage density was from 3.50 to 29.85 t/ha. Carbon storage intensity was high in the east and low in the west, and the highest carbon storage intensity was in the forest distributed in the eastern part. The carbon storage intensity of the water bodies and urban agglomerations was low. Areas with low carbon storage density expanded over the years.

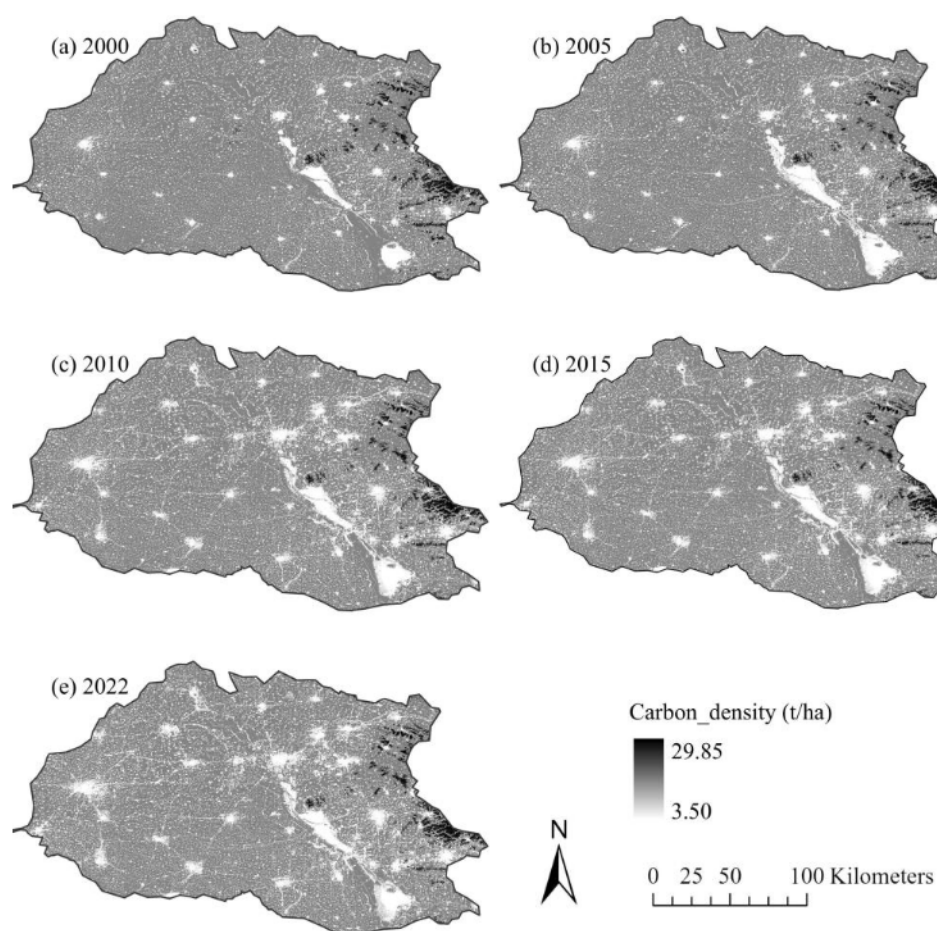


Figure 5-28: Carbon storage density in the NRB (Source: Author)

The carbon storage in the last 20 years showed a decreasing trend with the maximum in 2000 and the minimum in 2022 with a decrease of 7.45%. The carbon storage in 2000, 2005, 2010, 2015 and 2022 was 414.03, 402.63, 394.56, 389.79, and 383.20 (unit: 10^6Mg), respectively.

5.3.2.2 Changes of carbon storage in the NRB

By subtracting two maps of carbon storage intensity for two different years to obtain its changes. Figure 5-29 is the change of carbon storage in 2000-2022. It showed that carbon storage remained stable over much of the NRB. Carbon storage density in the area around the Nansihu Lake decreased between 2000 and 2005, increased between 2010 and 2015. The other two time periods (2005-2010 and 2015-2022) remained basically stable. The main reason was the change in LULC type. In the urban agglomeration area, both time periods were decreasing, which was due to urban expansion. Carbon storage density in the east mountainous area increased among three time periods, 2005-2010, 2010-2015 and 2015-2022. This is attributable to the policy of returning farmland to forests.

The change of carbon storage density corresponds well with the change of LULC, and the area shifted from the non-natural LULC type to the natural LULC type, carbon storage density increased.

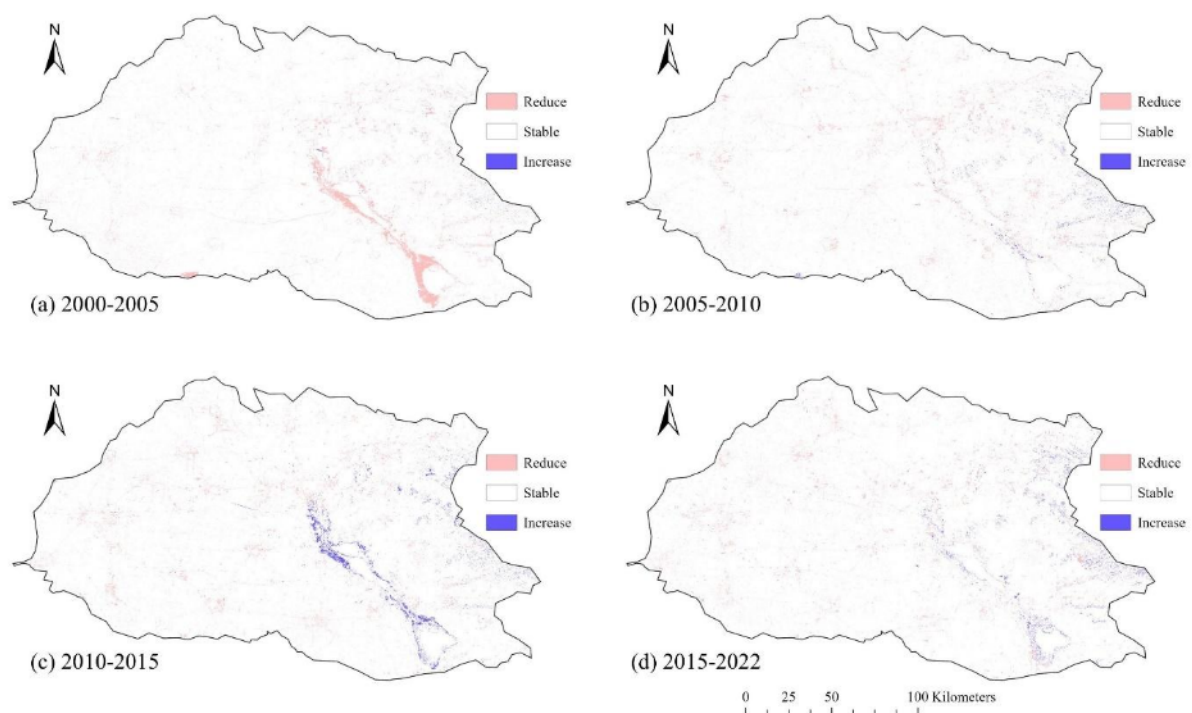


Figure 5-29: The change of carbon storage density (Source: Author)

5.3.2.3 Response of carbon storage to LULC changes

The response of carbon storage to LULC change was therefore examined to assess how LULC transformation associated with urbanization was related to changes in carbon storage. Table 5-15 showed the amount of carbon storage and change in LULC types in different years. It showed that non-natural area stored much more carbon than natural area, which was about 21 times.

Cropland accounted for a large part of the carbon storage, which was about 90% of the total carbon storage in the NRB, and it was the main source of carbon storage in the NRB. The mainly reason was that the NRB is a typical agricultural basin, with cropland accounting for over 70% of the total area. The carbon storage of cropland showed a decreasing trend, especially in the period of 2000-2010, decreasing by 23.81%, and the decreasing trend slowed down in the period of 2010-2022, but the decreasing trend was still obvious compared with other LULC types. This is mainly due to the fact that, during urbanization, urban expansion encroaches upon cropland and natural land, leading to a reduction in their area. This also explains why, excluding cropland, the carbon storage of non-natural land types such as impervious surfaces and bare land shows an increasing trend of 49%. On the contrary, the carbon storage of nature area showed a slow decreasing trend with a decrease of 5.29%.

Overall, these results suggest that urbanization reshapes the spatial distribution of carbon storage by replacing high-carbon-density land (such as cropland and natural vegetation) with low-carbon or non-carbon surfaces, thereby reducing the ecosystem's carbon storage capacity.

Table 5-15: Carbon storage and its changes on LULC types from 2000 to 2022 (Unit: 10^6Mg)

LULC	Crop land	Forest	Grass land	Water	Bare land	Impervious land	Natural Area	Non-Natural Area
2000	376.49	6.18	9.78	2.51	0.01	19.07	18.46	395.57
2005	364.05	5.88	7.64	4.33	0.01	20.72	17.85	384.78
2010	352.69	6.46	7.33	4.57	0.03	23.48	18.37	376.2
2015	346.07	7.4	6.31	3.82	0.02	26.16	17.54	372.25
2022	337.22	8.86	4.7	3.93	0.01	28.5	17.48	365.72
2005-2000	-12.44	-0.29	-2.14	1.816	0	1.65	-	-
2010-2005	-11.36	0.58	-0.31	0.247	0.03	2.75	-	-
2015-2010	-6.62	0.94	-1.02	-0.75	-0.02	2.69	-	-
2022-2015	-8.85	1.45	-1.62	0.11	-0.01	2.33	-	-

5.3.3 Habitat quality

5.3.3.1 Temporal changes in habitat quality

Habitat quality took the value of 0-1. From 2000 to 2022, habitat quality in the NRB declined from 0.25 to 0.22, and overall habitat quality was poor and continued to deteriorate. There was a 12% decline over 20 years, and the downward trend was not very significant. In this research, habitat quality was categorized into five classes, very poor (0-0.2), poor (0.2-0.4), moderate (0.4-0.6), good (0.6-0.8) and very good (0.8-1).

Habitat quality was low in most areas of the NRB, with very poor and poor areas accounting for 95% of the total area, good and very good areas accounting for only 5%, and moderate habitat quality areas accounting for less than 0.5% (Table 5-16). There was a significant

difference in the area of high and low habitat quality. The area of very poor habitat quality areas continued to grow, with a total increase in area of 2,117.79 km² from 2000 to 2022, increasing from 15.10% to 22.57%. The area of poor habitat quality areas had the highest percentage, but showed a decreasing trend, with a total decrease of 2,391.44 km², from 80.79% to 72.36%. The area of moderate habitat quality experienced a fluctuating trend, increasing initially, decreasing thereafter, and increasing again, with the maximum value being 97.60 km² in 2010 and the minimum value being 33.32 km² in 2015. The change was slightly complicated, but due to the small area occupied, the change was not significant and had little impact on the overall habitat quality of the watershed. The area of good habitat quality areas rose by 476.32 km², from 2.5% to 4.18%. The area of very good habitat quality area first increased and then decreased, the area overall decreased by 252.15 km², increased by 1,051.76 km², and the proportion decreased to 0.59%.

Table 5-16: Areas of different levels of habitat quality in the NRB (Unit: km²)

Habitat Quality \ Year	2000	2005	2010	2015	2022
Very poor	4282.34	4652.94	5273.67	5878.38	6400.13
Poor	22908.12	22151.34	21460.04	21064.60	20516.68
Moderate	36.01	76.43	97.60	33.32	85.49
Good	709.43	976.89	1015.74	1067.62	1185.75
Very good	419.58	497.89	508.43	311.57	167.43

5.3.3.2 Spatial distribution of habitat quality

The high values of habitat quality were distributed in the central lake area and the eastern hilly area, while the low values were distributed in the western plains area, showing a general trend of high in the east and low in the west (Figure 5-30). This was mainly due to the western plains area was mainly an agricultural cultivation area with a high percentage of cropland. Cultivated land in this region is characterized by monoculture vegetation and weak soil and water conservation. These factors led to intensive agricultural activities, which caused serious surface pollution.

Moreover, urbanization invaded the natural ecological environment, leading to fragmentation of the ecological environment and degradation of ecological functions, which led to a decline in the quality of the habitat. As for the eastern hilly area, due to the high altitude and rugged terrain, the surface was mainly covered by forests and grasslands, and forest reserves had been established in some areas. Therefore, disturbance from human activities was relatively low here and habitat quality is relatively high.

The Nansihu Lake was separated into upper and lower sections by Erjiba Dam. Habitat quality in the lower Lake improved significantly from 2000 to 2005, and remained good for more than a decade afterwards. This was because the lake area was rehabilitated since the establishment of the nature reserve in 1990 and had been well maintained for a long period of time.

However, since 2015 there had been a slight decline in habitat quality around the Nansihu Lake. In addition, there were some obvious banded areas of low habitat quality distributed along

roads. This was due to roads fragmenting habitat patches, fragmenting habitat areas, or leading to permanent loss of parts of the habitat, decreasing available habitat space, affecting the survival of surrounding species, and leading to a decrease in biodiversity and ecosystem stability. Figure 5-30(e), in 2022, in the northern part of the NRB, the habitat quality of the surrounding area was significantly reduced due to the construction of highway G30.

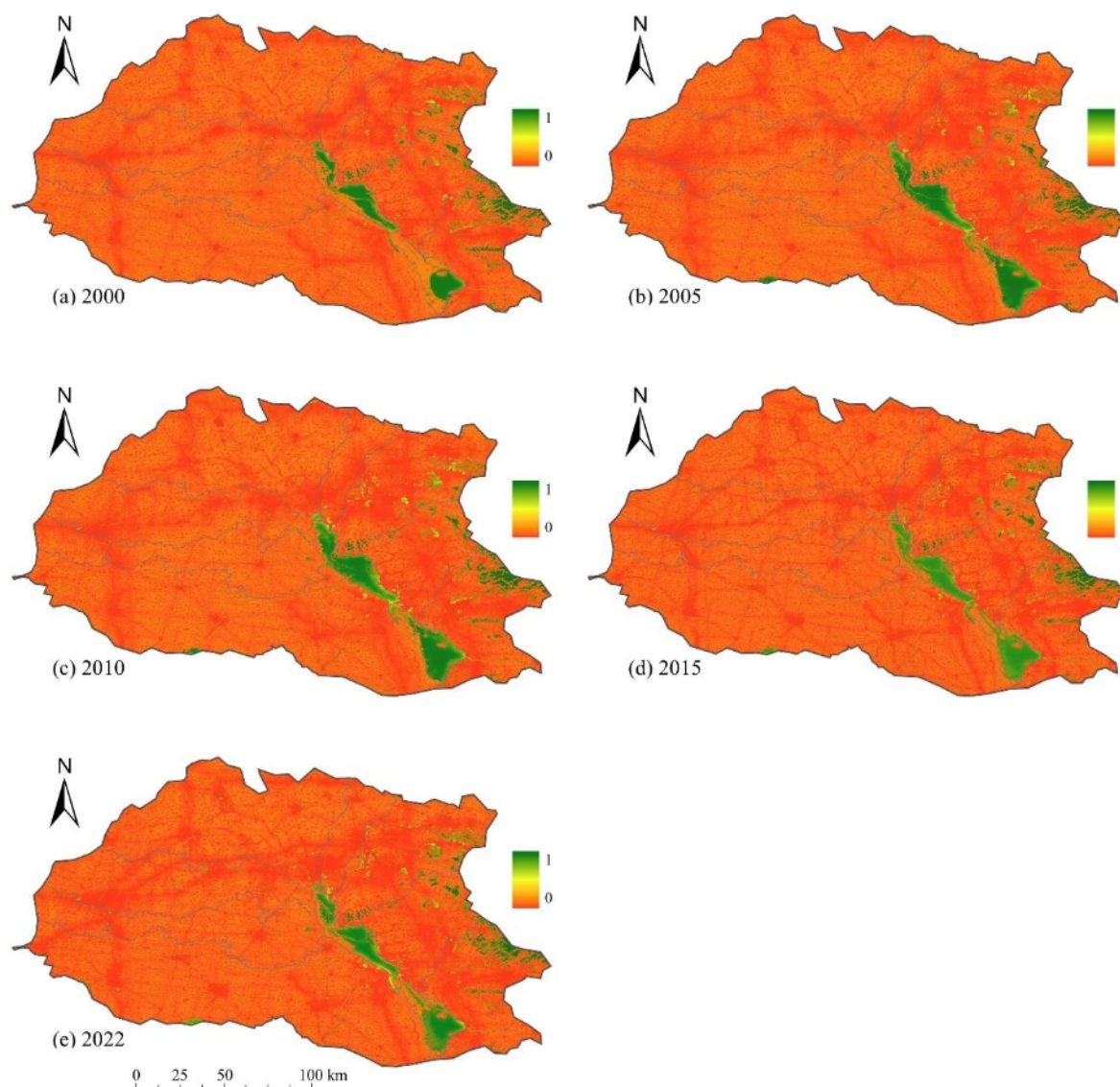


Figure 5-30: Spatial distribution of habitat quality in the NRB from 2000 to 2022 (Source: Author)

5.3.3.3 Changes in habitat quality

Changes in habitat quality were categorized into 5 levels: high declined, declined, unchanged, Improved and high improved (Figure 5-31). Habitat quality remained unchanged in most areas of the NRB.

The areas of declining habitat quality were mainly located around urban agglomeration, which was due to urban expansion. As urbanization progresses, natural and semi-natural habitats are increasingly converted into built-up land, leading to habitat loss, fragmentation, and reduced

ecological connectivity. The decline from 2010 to 2022 was more noticeable than the decline from 2000 to 2010, with a greater range of changes. Areas with rising habitat quality were primarily distributed across hilly and mountainous terrain in the eastern part of the NRB, which was due to the relatively low human activities in the hilly and mountainous areas, and the successive establishment of some ecological reserves, such as the Confucius Lake National Wetland Park in Qufu City, and the Zoucheng Taiping National Wetland Park, which effectively protected the local ecological environment, thus improving the quality of the habitats. Habitat quality in the Nansihu Lake area was highly improved during the period 2000-2010, and the ecological environment was effectively protected due to the establishment of the protected area. However, during the period 2010-2022, it high declined or declined.

The change in habitat quality that occurred at the boundary of the Nansihu Lake area was because the area of the lake area was also affected by precipitation. In abundant water years, the habitat quality increased as the lake area became larger, while in dry water years, the habitat quality decreased as the lake area decreased and converted to agriculture land or other types of land. Between 2010 and 2022, there was a significant decrease in habitat quality in Shanting District, which is located in the southeast corner of the NRB, which might be related to the rapid urbanization, the destruction of the original natural ecosystems, and the urban expansion that led to changes in LULC and increased landscape fragmentation.

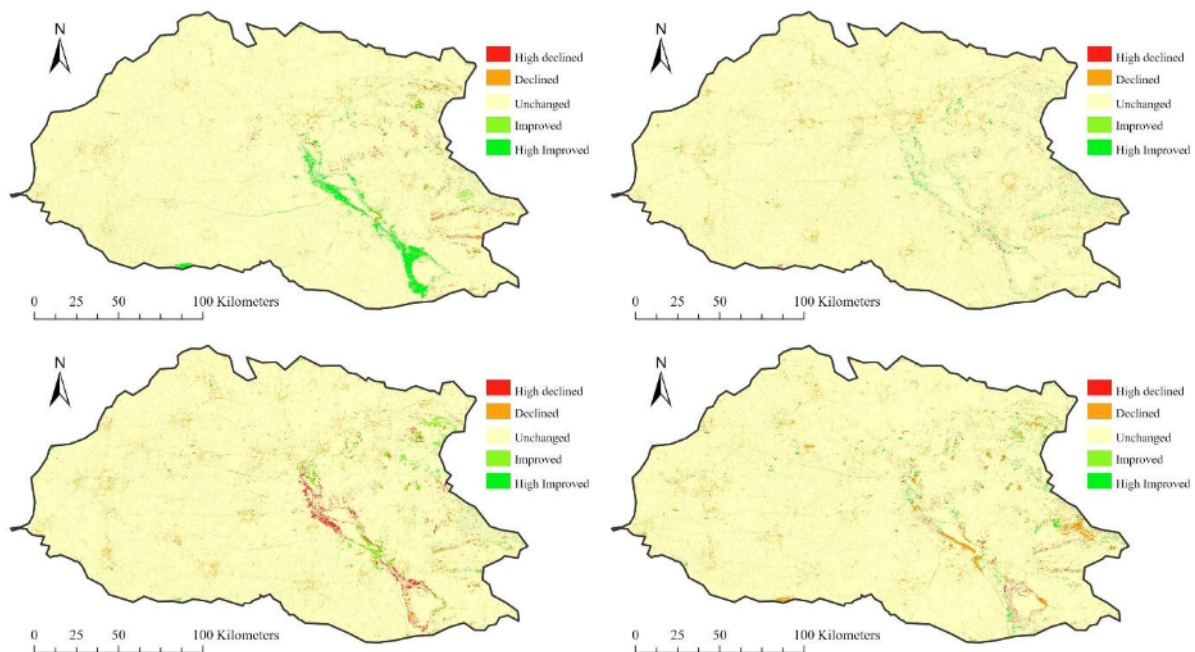


Figure 5-31: Changes in habitat quality in the NRB (Source: Author)

5.4 Water security in the NRB

This chapter evaluated water security at the watershed scale by identifying areas exposed to major water-related risks. Water security in a watershed involves three key aspects. First, maintaining good connectivity between rivers and lakes is essential for sustaining a healthy hydrological cycle and ecological functions. Second, stormwater flooding poses significant risks to human life and property. Third, surface water pollution threatens both environmental

quality and public health. Therefore, this chapter assessed water security from three perspectives: ecological protection, flood risk, and surface water pollution. Through these analyses, areas with high water-related risks were identified, and a watershed water security pattern was established.

5.4.1 Water source protection

Water conservation maintains the water content of the soil near rivers, increases stored water and regulates the hydrological cycle; it maintains the health and stability of the hydroecology of the watershed and ensures a sustainable supply of water resources for productive and living activities. Appropriate restricted areas should be established around the river system to minimize the occupation and disturbance of water bodies and their surrounding ecologically sensitive areas by human activities. In this research, buffer zones of different widths were designed for linear rivers and areal water bodies, respectively, to delineate the boundary of water source protection in NRB.

(1) Linear water bodies

Linear water bodies include naturally or artificially formed rivers, streams, estuaries, canals, and ditches. They are typically linear in character, with water bodies flowing along long and narrow channels. The main types of linear water bodies in NRB are rivers and canals, the longest of which is the Beijing-Hangzhou Grand Canal, which runs north-south through NRB, dividing the NRB into the eastern part and western area. Next are Dongyu River, Wanfu River and Si River. Linear water bodies data were downloaded from the website Open Street Map. According to the width of the river, the rivers were divided into two classes of Level I ($\geq 5\text{km}$) and Level II ($< 5\text{km}$), respectively, with buffer zones of 1000m and 500m were set respectively.

The protection map of linear water bodies is shown below (Figure 5-32). The width of the rivers was not considered and can be compensated by the surface watershed.

(2) Areal water bodies

Areal water bodies are large bodies of water with significant water surface width and area, and include lakes, reservoirs, wetlands, ponds, and oceans. Areal water bodies in NRB are mainly lakes and reservoirs. The majority of these are Nansihu Lake and a few reservoirs in the eastern part. The rest are some isolated ponds. Areal waters store large amounts of surface water and are an important source of water withdrawals for human activities. These two parts overlaid and merged were the surface watershed of NRB. Different sizes of surface waters have different levels of function, and therefore different buffer zones were established for protection. The functions of small-sized waters were mainly to maintain local ecological balance, replenish groundwater and purify water quality, while large-sized waters play a role in climate regulation, flood control and reducing the threat of floods, and provide a stable water source for industrial production, agricultural irrigation and residential life.

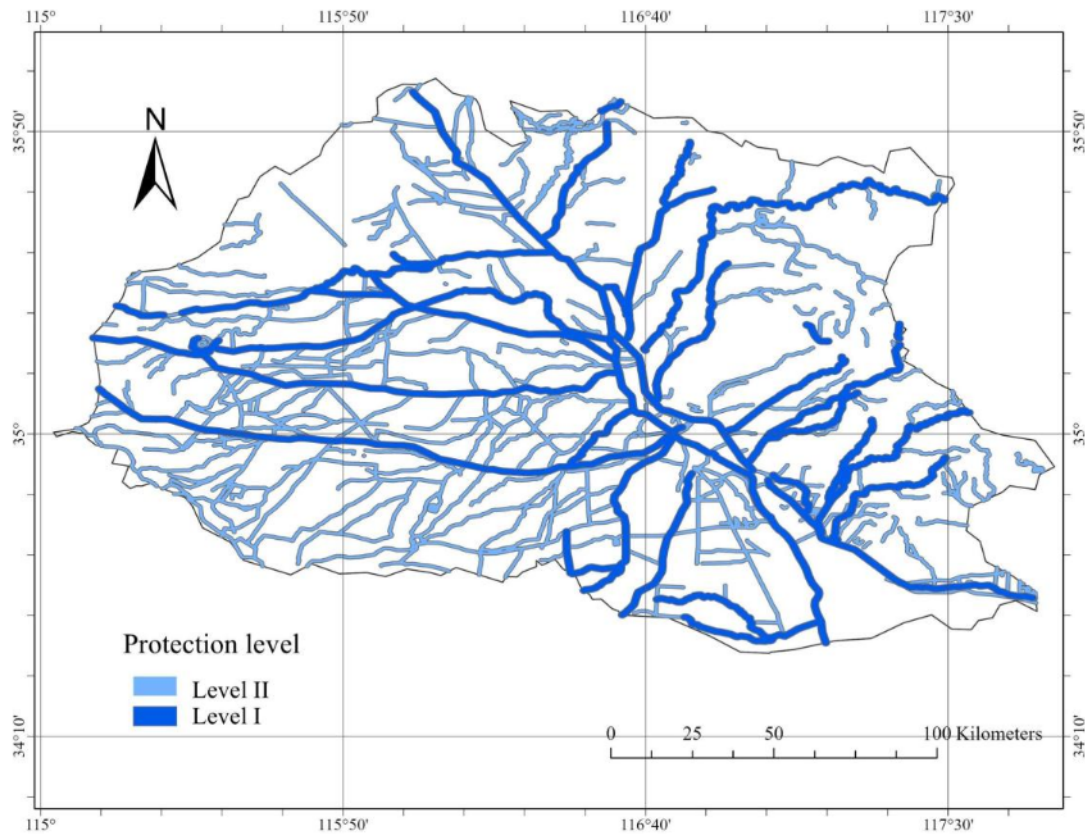


Figure 5-32: Linear water protection map in the NRB (Source: Author)

According to the size of water area, water area was classified into three categories ($1\text{ha} < \text{area} < 50\text{ha}$, $50\text{ha} < \text{area} < 5000\text{ha}$, $\text{area} > 5000\text{ha}$), and the buffer zones were established with 200 m, 500 m, and 1000 m respectively, which are designated as water source protection zones (Figure 5-33).

(3) Water source protection

The final source protection area for the NRB was an overlay of the linear water protection area and the areal water protection area (Figure 5-34). For the overlap, the values were calculated according to the higher protection level.

Expansion of construction land can increase development pressure around rivers and other surface water bodies, potentially reducing natural buffer functions and increasing the exposure of water sources to urban runoff and pollutant inputs. The identified protection zones therefore indicate areas where future urban expansion and land conversion should be more strictly controlled. From a water security perspective, maintaining natural or semi-natural land within and around these protection areas can help reduce potential conflicts between urban development and water source protection.

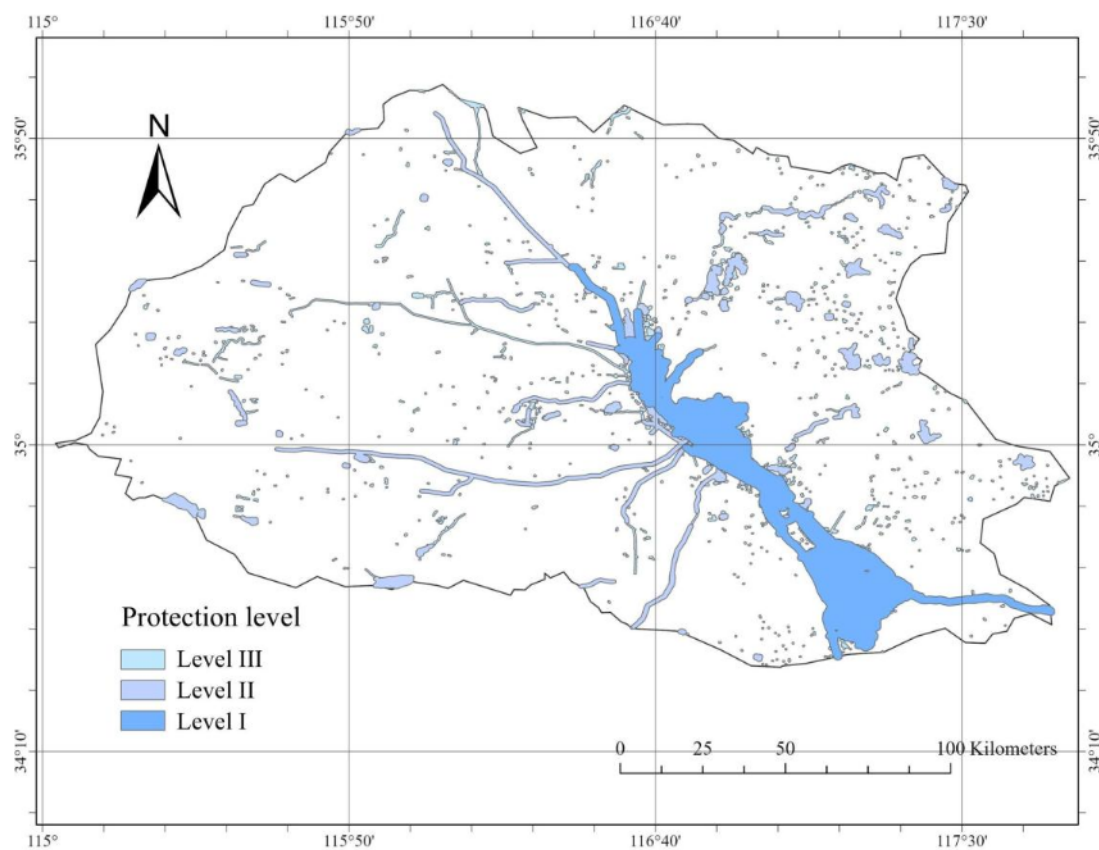


Figure 5-33: Areal water protection map in the NRB (Source: Author)

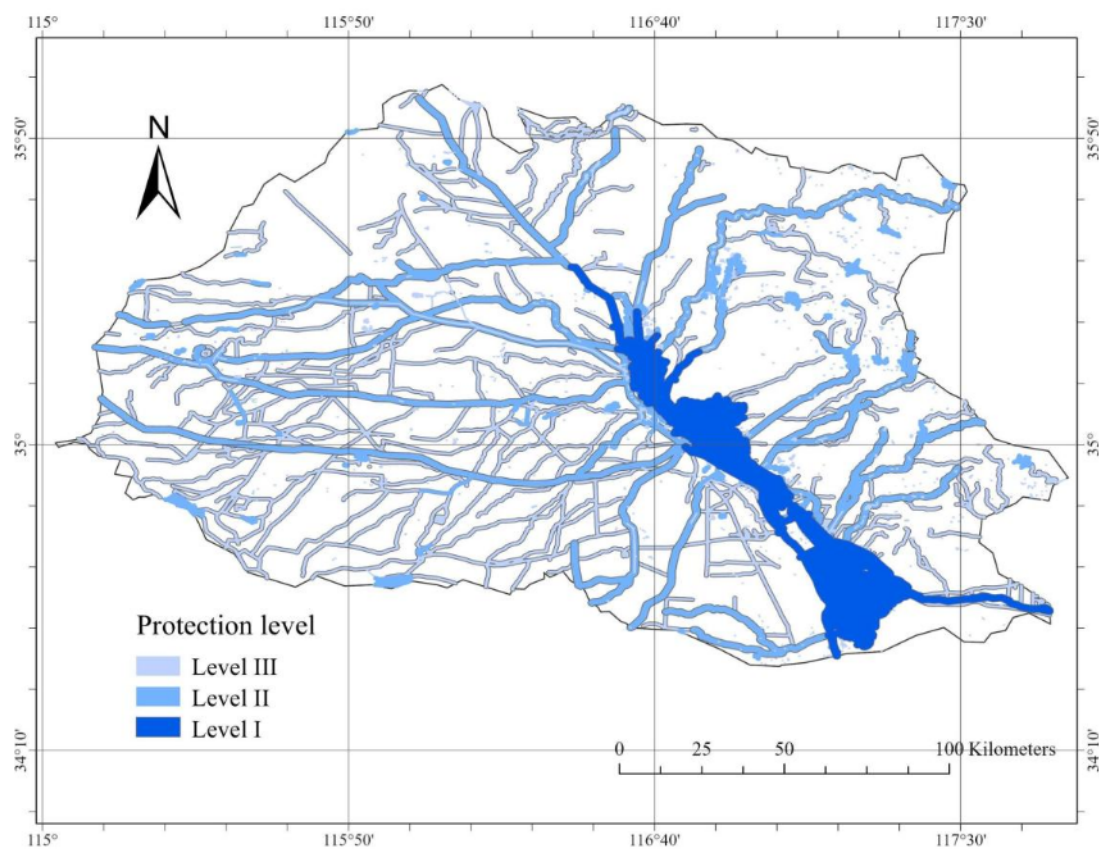


Figure 5-34: Water system protection map in the NRB (Source: Author)

5.4.2 Flood inundation risk

The inundation depths of sub-watersheds with P 10a, 20a, 50a, 100a and 200a in 2000, 2010 and 2022 were calculated respectively (Table 5-17). Figure 5-35 was the rainfall inundation risk area in NRB, and it can be seen that the high risk area was distributed around Nansihu Lake area, especially the north side of the lake area, where the topography is relatively low. Due to the limited resolution of the DEM data, the differences in simulated inundation depth under different scenarios were relatively small, resulting in only minor distinctions among the inundation risk zones.

Table 5-17: Depth of inundation for different P in the sub- watershed (Unit: m)

Dongyu	10a	20a	50a	100a	200a	Water level difference
2000	31.98	32.23	32.62	32.96	33.15	1.17
2010	32.07	32.33	32.75	33.05	33.23	1.16
2022	32.15	32.43	32.89	33.12	33.31	1.16
Wanfu	10a	20a	50a	100a	200a	
2000	33.27	33.53	33.92	34.05	34.11	0.84
2010	33.33	33.61	34.01	34.07	34.14	0.81
2022	33.42	33.71	34.03	34.1	34.17	0.75
Shihe	10a	20a	50a	100a	200a	
2000	34.46	35.01	35.26	35.48	35.73	1.27
2010	34.71	35.09	35.37	35.62	35.87	1.16
2022	34.86	35.15	35.43	35.7	35.98	1.12
Guangfu	10a	20a	50a	100a	200a	
2000	33.01	33.18	33.46	33.72	33.99	0.98
2010	33.12	33.33	33.67	33.96	34.14	1.02
2022	33.21	33.45	33.82	34.07	34.24	1.03
Liangqiyun	10a	20a	50a	100a	200a	
2000	35.18	35.49	36.01	36.17	36.36	1.18
2010	35.26	35.61	36.06	36.24	36.43	1.17
2022	35.39	35.78	36.14	36.33	36.59	1.2
Panlong	10a	20a	50a	100a	200a	
2000	26.65	27.15	27.62	28.01	28.25	1.6
2010	26.88	27.28	27.78	28.11	28.37	1.49
2022	27.02	27.36	27.88	28.18	28.44	1.42
Shizi	10a	20a	50a	100a	200a	
2000	32.04	32.37	32.91	33.15	33.36	1.32
2010	32.18	32.55	33.05	33.26	33.49	1.31
2022	32.24	32.64	33.1	33.32	33.56	1.32
Zhuzhaoxin	10a	20a	50a	100a	200a	
2000	33.06	33.33	33.79	34.09	34.31	1.25
2010	33.15	33.46	33.95	34.18	34.42	1.27
2022	33.27	33.62	34.08	34.31	34.56	1.29

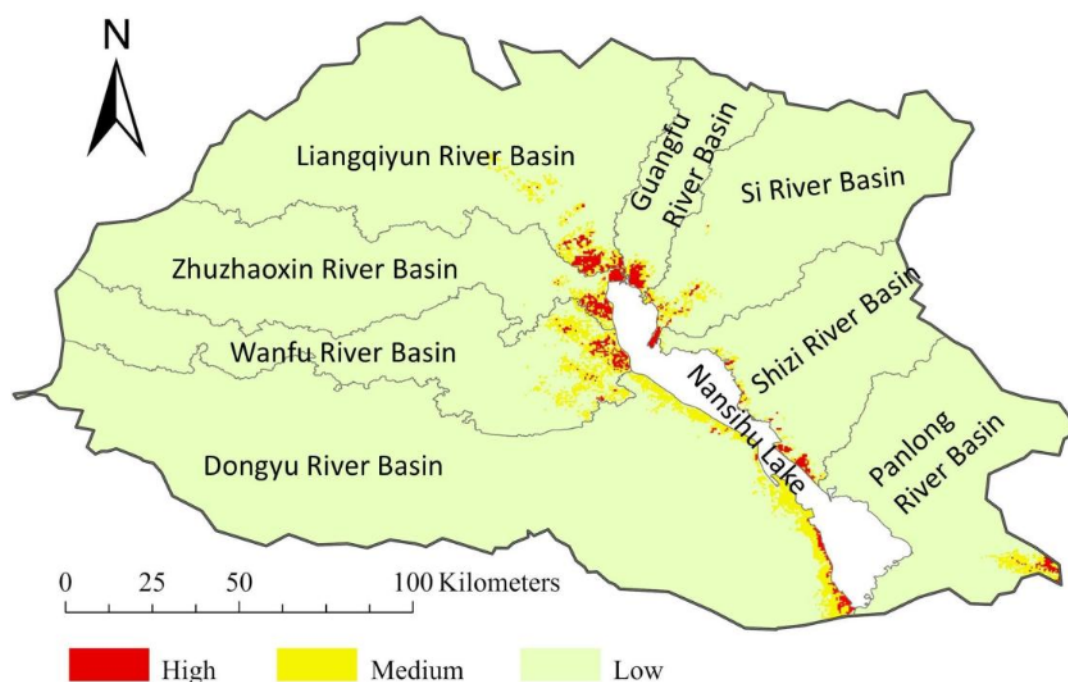


Figure 5-35: Flood inundation risk map for the NRB (Source: Author)

5.4.3 Water pollution

The monitoring and analysis of water quality can identify heavily polluted areas and help determine the distribution of troubled water bodies and their changing trends. Through accurate monitoring, effective protection and sustainable use of the water environment can be achieved, thereby safeguarding the health and safety of human society and the ecosystem.

5.4.3.1 Intra-annual changes in water quality

Table 5-18 shows the percentage of days throughout the year for which various water quality was recorded at 25 river cross sections in the NRB in 2023, as well as the reclassified water quality class. 20% of the stations had good quality, 48% had moderate quality, and 32% had poor quality. Urbanization can increase potential pollution pressure through population concentration, expansion of construction land, increased wastewater generation, and urban runoff.

The spatial distribution of water quality did not have any obvious characteristics, in the center of the watershed, the west border and the southeast corner of the distribution of poor water quality monitoring points (Figure 5-36). The source of pollution in the western part was mainly the widely distributed agriculture; the source of pollution in the eastern part was mainly the industrial pollution, with some coal, paper and chemical industries distributed in the nearby area, and of course, there was pollution from the residents' lives in both the eastern and western areas.

Total annual levels of major pollutants were not significantly different between Eastern area and Western area in 2023, COD_{Mn} (657.67mg/L, 712.78mg/L), $\text{NH}_3\text{-H}$ (17.45mg/L, 25.24mg/L), TP (11mg/L, 12.39mg/L), TN (611.57mg/L, 420.92mg/L). Except for TN, the other three pollutants were slightly higher in the western part than eastern part. In

eastern part, the highest COD_{Mn} was Dongshifo of Guangfu River (67.73 mg/L), the lowest was 310Gongluqiao of Wu River (35.97 mg/L); the hight NH₃-H was Jiazhuangzha of Dasha River in Yicheng (4.29 mg/L), the lowest was Shizihedaoqiao of Dasha River in Xuecheng (0.68 mg/L) and 310Gongluqiao of Wu River (0.68 mg/L); the highest TP was Linjiaba of Beijing-Hangzhou Great Canal (1.46 mg/L), the lowest was Shizihedaoqiao of Dasha River in Xuecheng (0.43 mg/L); the highest TN was Jiazhuangzha of Dasha River in Yicheng (119.12 mg/L), the lowest was Yingou river mouth of Si River (17.98 mg/L).

In western part, the highest COD_{Mn} was Nanqiao of Muzhu River (79.93 mg/L), the lowest was 42.80mg/L; the highest NH₃-H was Fanli of Xiaoqing River (4.99 mg/L), the lowest was Huashanzha of Dasha River (0.49 mg/L); the highest TP was Nanqiao of Muzhu River (1.71 mg/L), the lowest was Liji of Beijing-Hangzhou Great Canal(0.56 mg/L); the highest TN was Fanli of Xiaoqing River(98.01 mg/L), the lowest was Huashanzha of Dasha River (11.75 mg/L).

Table 5-18: Water quality in the NRB

Cross section	I (%)	II (%)	III (%)	IV & V (%)	Class
Niu Zhuang Zha	0	51.90	43.88	4.22	1
Lao Yun He Wei Shan Duan	0.10	39.80	54.53	5.57	1
Ma Lou	0	27.02	64.95	8.03	1
Shi Zi He Da Qiao	0	49.74	42.20	8.06	1
Wu Cha He Kou	0	64.77	26.11	9.12	1
Hua Shan Zha	0	3.16	85.87	10.97	2
Xin Xue He Ru Hu Kou	0	42.01	46.99	11.00	2
Er Ji Ba	0	4.09	82.39	13.52	2
Li Ji	0	12.93	70.70	16.37	2
Xi Yao	0	0.00	76.42	23.58	2
Fan Li	0	24.82	50.64	24.54	2
Yin Gou (Ru Hu Kou)	0	12.63	61.78	25.59	2
Xu Zhai	0	6.63	65.38	28.00	2
Xi Shi Fo	0	6.51	64.86	28.63	2
Gao He Qiao (Old Wan Fu He Kou)	0	13.41	56.29	30.30	2
Yan Zhou Nan Da Qiao	0	9.38	59.93	30.68	2
Yu Tun	0	2.76	65.18	32.06	2
Lin Jia Ba	0	7.46	55.43	37.11	2
Jia Zhuang Zha	0	5.47	53.03	41.49	3
Dong Shi Fo	0	1.77	56.18	42.04	3
310 Gong Lu Qiao	8.60	32.61	16.31	42.48	3
105 Gong Lu Qiao	0	2.83	53.57	43.60	3
Xiang Zi Miao	0	0.58	52.67	46.75	3
Qun Le Qiao	0	2.21	49.23	48.56	3
Nan Qiao	0	3.66	21.21	75.13	3

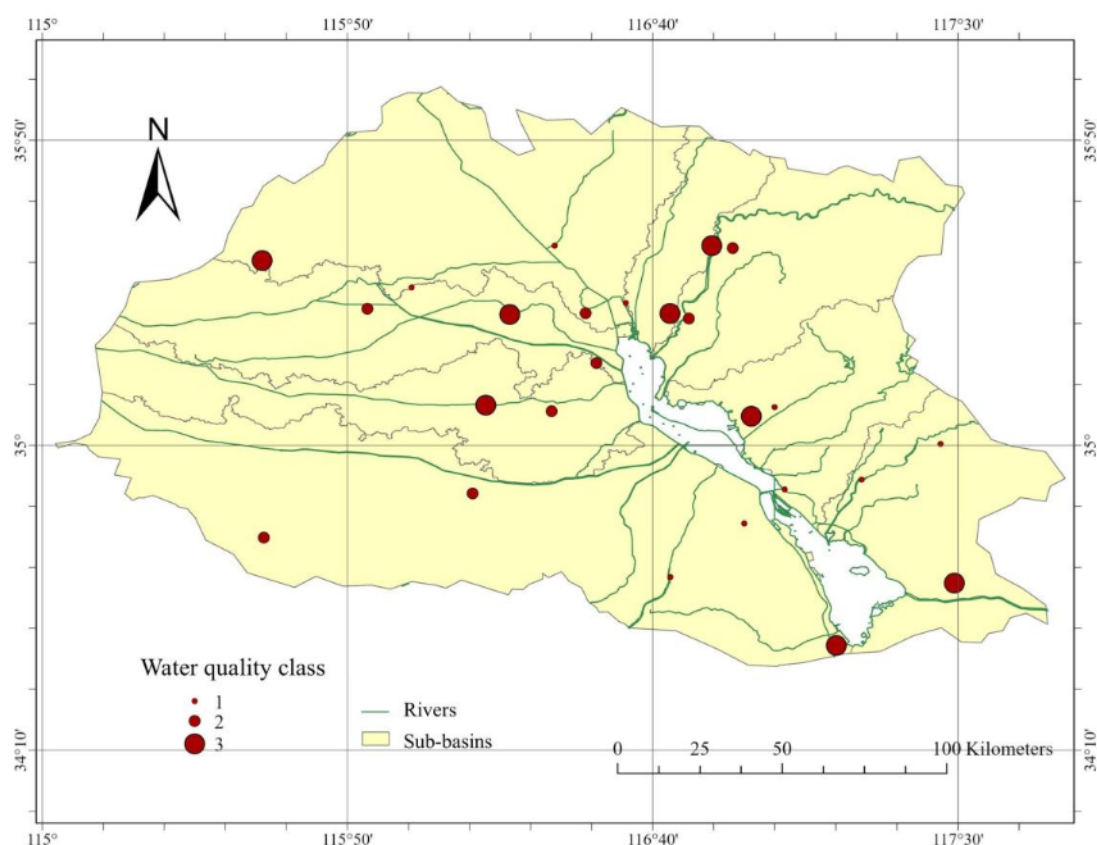


Figure 5-36: Water quality class distribution in the NRB (Source: Author)

The CPI for the eastern part was greater than the western part, 67.93 and 52.24, respectively. The graphs below showed the CPI for the five more polluted cross sections in the eastern area and the western, respectively (Figure 5-37). In the eastern part, 310Gongluqiao and Jiazhuangzhahad largest CPI, which was 12.49 and 11.79, respectively. In the western part, Fanli and Nandaqiao were the largest, which was 9.63 and 7.31. The CPI for TN was the largest and far exceeded the other three pollutants, which maenad that TN was the main pollutant in NRB. One of the reasons for this was that the NRB has a high level of agricultural production activities, which was the main source of TN, and the application of chemical fertilizers (e.g., urea, ammoniacal nitrogen fertilizers) and mismanagement of livestock and poultry manure can lead to a large amount of nitrogen entering the water body through surface runoff. During the rainy season, nitrogen fertilizer residues were more likely to be washed into rivers.

5.4.3.2 Seasonal changes in water quality

The eastern part, the western part and Nansihu Lake were each selected as the best and the worst water quality cross sections, and their monthly average pollution concentrations were calculated. The Eastern area was chosen as 310Gongluqiao (the worst) and Shizihedaqiao (the best); the western part was chosen as Fanli (the worst) and Huashanzha (the best); and there was only one monitoring cross section in the Nansihu lake, Erjiba. The results were shown in the Figure 5-38.

CODMn concentrations fluctuated between 1-6 mg/L, with an overall trend of lower concentrations in the 310Gongluqiao cross section. It was highest in April and decreased

significantly between June and October, showing significantly lower values. The overall level of concentrations in the Huashanzha cross-section was higher and peaked in summer (July-September), which may be related to seasonal rainfall or increased pollutant discharges from upstream sources. Concentration levels in the Erjiba and Fanli cross-sections were relatively stable, but there were some fluctuations. This showed that it is influenced less by point or surface sources.

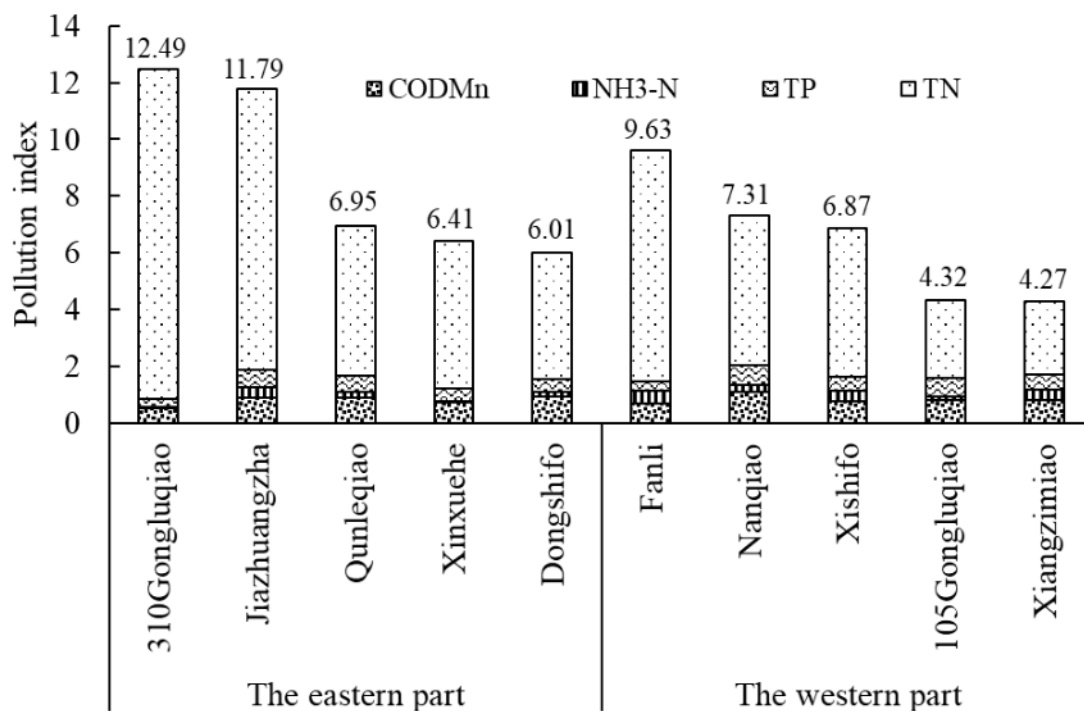


Figure 5-37: SPI of the eastern part and the western part in the NRB (Source: Author)

For $\text{NH}_3\text{-N}$ concentration, it was high in Fanli overall, with significant peaked especially in June and September, possibly due to concentrated discharges from increased pollution sources or seasonal factors, such as runoff from irrigated agriculture and fertilizer application that converged into the river. $\text{NH}_3\text{-N}$ concentrations in the other three cross-sections were low, mostly below 0.1 mg/L. 310Gongluqiao had a significant peak in July, close to 0.4 mg/L, was presumed to be related to specific pollution events, such as concentrated releases from industrial or domestic discharges, and the subsequent decline might be related to pollutant dilution or treatment measures.

For TP concentration, 310Gongluqiao showed a significant peak in July, with was much higher than the other cross sections, showing that there might be a strong input of pollution at this time of year. Fanli had a slightly higher concentration overall, showing slow fluctuations throughout most of the year, but no significant abnormal peaks. Concentrations at the other three cross sections were all low overall and remained flat throughout the year. For TN concentration, 310Gongluqiao were highly seasonally influenced, with high and fluctuating values. It reaches its highest value in January, then declines rapidly to near zero in May, but picks up gradually from June, reaching high concentrations again in November and December.

Concentrations in Fanli were relatively stable throughout the year, fluctuating between 5 and 12, it showed persistent pollution inputs. The other three cross sections were generally low and

fluctuated over a small range, indicating relatively stable water quality. Water quality monitoring is particularly important to identify priority areas for water quality management during times of high seasonal pollutant concentrations.

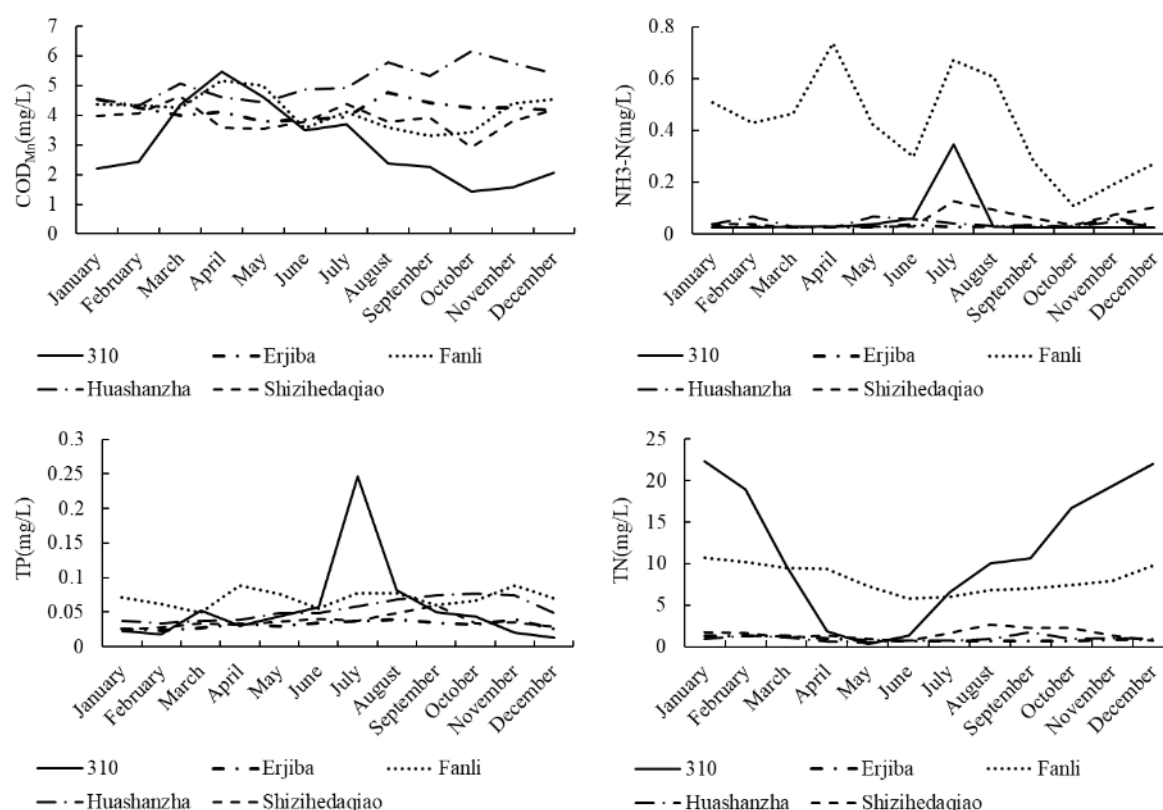


Figure 5-38: Seasonal variations in pollutant concentrations (Source: Author)

5.5 Rainwater management in the NRB

Based on the findings of the previous chapters and the key tasks identified in chapter 4.6, this chapter proposed recommendations for rainwater management in the NRB. The proposed strategies address the major hydrological, ecological, and water security problems identified in the basin. The aim is to move beyond traditional city-focused rainwater management and develop a more integrated approach at the watershed scale, considering water quantity, water quality, ecological protection, and upstream-downstream interactions.

5.5.1 Climate-adaptive rainwater management

Chapter 5.2 provided long-term hydrological monitoring data and heavy rainfall events data. Based on these long-term observations and changing hydrological conditions, more flexible and adaptive management strategies can be developed to better respond to climate variability and extreme events.

Different management strategies should be adopted for wet and dry years. During wet years, priority should be given to flood prevention, peak flow reduction, stormwater detention, and inundation control. During dry years, the focus should shift toward rainwater harvesting and reuse, ecological water replenishment, and water supply security. In this way, rainwater can be managed not only as a potential flood risk but also as a valuable water resource.

Overall, climate adaptation should shift from a single flood-control approach to adaptive management of the entire hydrological cycle. By integrating long-term monitoring, flood control, water storage, rainwater utilization, and ecological water needs, the river basin can respond more flexibly to both water excess and water shortage under changing climatic conditions.

5.5.2 Decentralized rainwater management

When faced with water shortage and urban flooding, the most immediate consideration is the construction of dams, floodgates and reservoirs to hold back the water or the construction of more drainage networks to drain the water away. Although water conservancy projects serve social functions like water withdrawal and flood control, large-scale construction also disrupts the natural hydrological situation and hydrological cycle of the watershed.

Scientific rainwater management should start from the perspective of the entire watershed, assess the overall hydrological cycle function and hydroecology function of the watershed, integrate the upstream-midstream-downstream flood storage function, and adopt decentralized and small-scale facilities, so that each functional area of the city can independently absorb and store rainwater, reduce or replace the traditional centralized mode, and minimize the reliance on public municipal pipeline networks.

To accomplish this, the first step is to analyze the LULC structure, identify and analyze which LULC types are likely to cause floods, and which have the potential to prevent floods. Then make full use of the LULC types with flood control potential to build a large number of small, decentralized water storage facilities, so as to regulate floods according to the laws of nature, and constitute a networked, decentralized management system in the entire watershed.

According to chapter 5.1.3, the most widely distributed LULC types in the NRB are cropland and impervious area. Rainwater management of these two types of LULC is extremely important, especially for impervious area, which is the main source of a large amount of surface runoff. Cropland has a singular vegetation and fragile ecosystem, which is one of the main causes of soil erosion. Within cropland, make full use of agricultural facilities such as ridges and terraces so that rainwater stays in place as long as possible, which not only reduces the scouring of the soil by rainwater runoff, but also significantly reduces the demand for additional water for agricultural irrigation. Moreover, conservation farming techniques, such as cover cropping, crop rotation and intercropping, are being promoted to improve soil structure and enhance the soil's ability to absorb and retain water.

In urban areas with high building density, small and decentralized infiltration spaces are built by making full use of urban green spaces. A complete infiltration and storage system includes collection system, which collects rainwater from roofs, roads and other impervious surfaces; infiltration system, which makes rainwater infiltrate into the ground and recharge the groundwater, and it consists of infiltration wells, infiltration pits and infiltration trenches, etc.; and storage system, which stores rainwater temporarily or for long term to regulate water utilization when necessary, and it consists of surface water storage and underground water storage.

For natural types of land, such as forests and grasslands, the resilience and stability of ecosystems can be effectively enhanced by increasing the diversity of tree species, especially by prioritizing native and suitable species. This diversified vegetation structure is not only better able to defend against extreme weather events, but also provides a rich habitat resource for native plants and animals. In addition, to restore and connect damaged ecological corridors, especially in areas where ecosystems have been fragmented due to urban expansion, it can provide connectivity for wildlife migration and reproduction and further protect biodiversity and the overall functioning of ecosystems. For natural river systems, increasing their storage space and curvature can effectively slow down the flow rate of floodwaters, allowing rainwater to have a longer residence time in the river channel and reducing the impact of flood flows downstream. This not only helps to restore the natural connectivity of rivers but also enhances the stability of riparian ecosystems and promotes groundwater recharge.

5.5.3 Establishment of protected areas

A detailed study of potential protected areas is critical, this process involves a comprehensive assessment of the ecosystem services of the study area, such as the contribution of these areas to water conservation, biodiversity, and carbon capture. Based on the results in chapter 5.3, the ecologically sensitive areas within the NRB primarily include the Nansihu Lake and the eastern hilly areas. This is mainly disturbed by human activities, such as deforestation, urban expansion and tourism development, leading to fragmentation of the ecosystem and degradation of ecological functions.

To develop effective conservation measures, studies also need to focus on natural factors such as the geological features, hydrological conditions and soil structure, as well as their cultural and historical values, in order to determine the boundaries, functional zoning and conservation objectives of protected areas.

Based on these studies, specific areas of both ecological and human social importance, such as critical water source protection areas and biodiversity conservation areas, can be delineated. Within these protected areas, development activities that may cause damage to the ecosystem, such as large-scale land reclamation, industrialized production and unsustainable tourism activities, should be strictly limited. At the same time, ecological restoration of protected areas should be strengthened, focusing on the restoration of their natural vegetation, ecological corridors and wetland functions in order to improve the integrity of the ecosystem. At present, a number of protected areas have been established in the eastern part and in the lake area, such as, the Nansihu Provincial Protected Area, the Confucius Lake National Wetland Park in Qufu City, the Taiping National Wetland Park in Zoucheng City, and the Weishan Lake Wetland Park, among others. To a certain extent, these protected areas have mitigated the trend of ecological degradation and have performed such functions as soil and water conservation, species protection and ecological education.

However, future conservation efforts still need to be further optimized, for example, by strengthening the legal protection of protected areas, improving the ecological compensation mechanism, raising the professionalism of management, and promoting the construction of scientific research and monitoring systems in protected areas. In addition, educating the public and deepening awareness of ecological conservation are important aspects of long-term

conservation. Through extensive publicity and community participation activities, people's conservation autonomy can be stimulated, forming a positive cycle of joint efforts by the Government, society and individuals, thus realizing the long-term maintenance of ecological balance.

5.5.4 Separation of rainwater and sewage and Sewage reuse

Regardless of whether a separate or combined system is employed, the fundamental logic of traditional drainage systems relies on pipe networks to collect and discharge rainwater. The “rainwater-sewage separation” approach proposed in this research does not achieve separation through the installation of independent rainwater drainage networks. Instead, it emphasizes integrating rainwater into the natural water cycle from the moment it reaches the ground. By restoring the natural pathways of rainwater runoff, rather than simply installing more pipe systems, the aim is to manage and recycle rainfall through processes such as evaporation, infiltration, and natural runoff.

However, this does not mean that rainwater management needs to be done in such a way that all rainwater is retained, but rather that a scientific and reasonable balance needs to be found between “total discharge” and “zero discharge” to avoid going to any extreme mode. If rainwater is simply intercepted, it will definitely cause water shortage downstream, and the hydrological cycle of the whole basin will be affected. Scientific rainwater management should fully comply with the laws of the natural hydrological cycle of the watershed, to achieve coordination and balance between the discharge, storage and utilization of rainwater, with “storage as the mainstay and drainage as a support” as the core principle.

Specifically, rainwater storage should be prioritized through green infrastructure and natural ecosystems, and emissions should be controlled through rationally planned engineering facilities to ensure the sustainable use of water resources. Rainwater storage is not only for rainwater reuse, but also carries multiple ecological functions. For example, it is a buffer zone for evaporation and infiltration of urban rainwater, a source zone for surface runoff, and a power source for the natural hydrological cycle, directly affecting the dynamic balance of the hydrological cycle. Storage should account for about 50 percent of rainwater, enabling rainwater to participate in the hydrological cycle in its natural way.

Pollution in the NRB is mainly caused by non-point source pollution. Wastewater is treated mainly through municipal wastewater treatment plants and centralized industrial wastewater treatment plants. However, in order to save production costs, some enterprises still discharge production wastewater directly without treatment, and this kind of smuggling and leakage should be supervised and punished more intensively by the government. Moreover, the phenomenon of rural sewage being discharged directly or spilled is also common, while urban sewage is usually piped to treatment plants for centralized treatment. This requires increased public education to raise awareness of the importance of “Treating Sewage Before Discharging”.

Although China's wastewater treatment penetration rate is expected to reach 80% by 2030, the pollution load of urban wastewater on the water environment has not significantly diminished. This is because although the volume of sewage treatment is increasing, the total volume of

discharge is also increasing at the same time, resulting in a limited reduction in the total pollution load. Therefore, increasing the sewage treatment penetration rate alone will not completely solve the water pollution problem. The fundamental solution to the problem requires promoting the effective utilization of reclaimed water.

In the municipal field, reclaimed water can be used for road sweeping, garden irrigation and landscape water; in the industrial field, it can be used as cooling water, process water and washing water; in agriculture, it can be used for farm irrigation and agricultural water replenishment; in addition, reclaimed water can be used for environmental protection such as wetland restoration and ecological replenishment of rivers, as well as non-drinking uses in daily life, such as flushing toilets and washing cars. This reuse method not only effectively relieves the pressure on natural water resources and lowers the use of clean water resources while decreases the environmental effects of untreated sewage discharge. On the one hand, this method meets the requirements of the natural purification function of water bodies, so that the reclaimed water discharged into natural water bodies becomes part of the downstream urban water resources. On the other hand, through wastewater regeneration, it reduces the total amount of water demanded by the society, achieves the recycling and efficient utilization of water resources, and promotes sustainable development.

5.5.5 Integrated watershed management

To ensure the protection of the ecological functions of watershed systems and their hydrological flow characteristics, use the entire watershed as the unit of management rather than the administrative division. This involves the integrated management of all aspects related to water resources, including the balance between water quantity and quality, the optimization of water supply and drainage systems, and the coordination of surface and groundwater. By integrating the needs and conditions upstream and downstream of the watershed, a holistic layout is planned, and management programs are jointly developed and implemented to work towards restoring the natural pathways of rainwater.

The NRB involves 37 counties and districts in four provinces, with complex provincial boundaries, unclear territorial demarcation, and unbalanced regional economic development. Each region has developed its own ecological restoration program and water pollution control program, and they are all working on their own, with different standards.

Therefore, rainwater management in the watershed should be involved in the integrated management of the watershed, and the watershed should be the basic management unit to ensure the sustainability of the ecological function of the water system and the basic hydrological flow function within the watershed. The system should integrate urban and rural water supply, water conservation, wastewater treatment and reuse, urban rainwater management and water resource protection, so as to achieve integrated management of water quantity and quality, water resources and rainwater, and wastewater reuse in the watersheds, and to balance the coordinated development of upstream and downstream watersheds and between different cities.

This integrated management model not only helps to promote the appropriate development, utilization and protection of water resources, but also supports effective responses to flooding

and water environment degradation. It is recommended to establish a specialized department responsible for integrated watershed-based management of water resources and the water environment. Its main responsibilities should include planning for the healthy circulation of water systems in the basin, determining the functions of water bodies and standards for pollutant discharges in each section of the river. It should also coordinate the scale of water intake and the quality standard of recycled water discharge among provinces, cities and counties, and establish a charging system for water sources, water supply and sewage treatment, as well as a hydroecology compensation mechanism. Only when these responsibilities are effectively fulfilled can it be ensured that the process of urbanization at the watershed scale is coordinated with the development of the watershed hydrological cycle, thereby supporting the long-term health and sustainable functioning of the watershed water system.

6 Conclusion

Chapters 1 and 2 presented the theoretical background, key concepts, and methodological approaches related to the hydrological effects of urbanization and stormwater management. They also presented the research objectives and research questions. Chapter 3 described the physical and socioeconomic characteristics of the study area. Socio-economic data, climatic data and spatial data related to the research were also introduced. Chapter 4 described the research methodology in detail. Chapter 5 presented the results of the research based on the research methodology in Chapter 4. As a synthesis of the research, this chapter presents the main findings of the study, answered the questions posed in Chapter 1, and provided recommendations for future research.

6.1 Methodology Contributions

With global climate change and rapid urbanization, the natural hydrological cycle has been significantly altered, and cities are facing increasingly serious problems of flooding, water scarcity and ecological degradation.

Taking the NRB as a case study, this research presented a watershed-based rainwater management strategy focusing on the restoration of the natural hydrological cycle function. A comprehensive assessment was carried out in four aspects: urbanization level, hydrological effect, hydroecological functions and water security function. The research shows that urbanization has led to the rain island effect and an increasing trend in heavy rainfall, and that disturbances caused by human activities have further affected the hydrological cycle and ecosystem service functions of watersheds, including the decline of water conservation capacity, carbon storage and biodiversity. Based on the results of the assessment, the research proposes a rainwater management plan for the watershed. It emphasizes the integration of upstream and downstream flood storage functions, the promotion of decentralized facilities to reduce reliance on municipal networks, and the restoration of hydro-ecological functions through the protection of ecologically sensitive areas and the implementation of the “separation of rainwater and sewage”. It is recommended that an integrated management organization be established on a watershed basis to achieve scientific rainwater management and water resource management. This research provided a reference framework for sustainable water management in rapidly developing river basins.

The research questions are addressed below on the basis of the study findings.

1) Why should the hydrological effects of urbanization be addressed with integrated watershed management?

The problem of “rainwater flooding” is not only a matter of excessive surface runoff, but also a disruption of the functioning of the entire hydrological cycle. The increase in impervious surfaces in the process of urbanization has resulted in a reduction in the capacity of soils to absorb and filter rainwater, generating large amounts of surface runoff, weakening the natural recharge of groundwater, and disrupting the balance of the natural hydrological cycle. This disruption of the natural hydrological cycle function not only aggravates urban flood risk, but also has long-term negative impacts on ecosystems. Considering the problems and challenges

that still exist in stormwater management, this research rethought and redesigned urban water management strategies to develop a more sustainable and comprehensive stormwater management approach from the perspective of the entire watershed, centered on the restoration of natural hydrological cycle processes.

It includes the following aspects:

- ① To ensure the overall ecological function of the watershed, to treat the watershed as an indivisible whole, to take into account in an integrated manner the integrity of its natural system and the coordination of its ecological functions, and to comprehensively assess the upstream, midstream and downstream of the watershed, so as to ensure that development activities in the upstream areas will not negatively affect the ecological environment and water safety in the middle and downstream regions.
- ② To ensure ecological priority by prioritizing areas of high ecological value or ecological sensitivity, establishing protected areas, and reducing or prohibiting human interference.
- ③ Synchronize urban development with rainwater management. Abandon the previous model of “development first, then restoration”, and make rainwater management an important part of urban development, so that urban development and rainwater management can be synchronized.
- ④ Decentralized water management. Reduce the reliance on water conservancy projects and flood control projects, and instead decentralize rainwater management measures to all corners of the city, making full use of the city's green space, soil, rivers, roads, drains and other natural and artificial elements.

To develop watershed-scale stormwater management strategies, a thorough and detailed understanding of the process of urbanization within the watershed and the impact of urbanization on the hydrologic cycle should be developed. This included analyzing how urban expansion had changed land cover and increased impervious surfaces, and how these changes had led to increased surface runoff and decreased groundwater recharge. At the same time, there was a need to examine how urbanization has altered rainfall-runoff processes and how these changes increased flood risk and affected water quality and ecosystems throughout the watershed. Each of the following four research questions corresponds to one of the four assessment dimensions.

2) Which key indicators should be used to assess the level of urbanization? How can these indicators be used to characterize the mechanisms through which urbanization affects hydrological processes at the watershed scale?

The level of urbanization at the watershed scale can be characterized by combining population, economic structure, and LULC change. Among these indicators, population growth and urban spatial expansion reflect the concentration of population and urban development, while the transition of the industrial structure from primary toward secondary and tertiary industries represents the socioeconomic transformation accompanying urbanization. Based on these indicators, the major cities within the NRB showed substantial growth in the urban population, continuous expansion in city size, and a shift in economic structure toward tertiary industries, indicating an accelerating process of urbanization within the NRB.

LULC change provided the most direct link between urbanization and watershed hydrological processes. The NRB experienced a continuous decrease in cropland and an increase in impervious surfaces, with cropland constituting a major source of newly developed impervious area. This transformation alters the physical characteristics of land surface by increasing impervious areas and reducing the capacity of the land surface to intercept and infiltrate rainfall. Consequently, rainfall is more rapidly converted into surface runoff, potentially increasing runoff generation and flood risk. Population growth and economic restructuring primarily represent socioeconomic drivers of urban expansion, whereas the associated conversion of land cover and increase in impervious surfaces directly alter hydrological processes. Rather, they represent the socioeconomic drivers underlying the demand for urban expansion and associated LULC conversion.

The LULC analysis also has direct implications for rainwater management. Different LULC types have different capacities for runoff generation, infiltration, retention, and flood regulation. Identifying LULC transitions and distinguishing runoff-generating areas from LULC types with greater flood-regulation potential therefore provides a basis for spatially targeted rainwater management. Rather than relying exclusively on conventional drainage infrastructure, watershed management can make greater use of the hydrological functions of existing LULC types and prioritize the protection of areas with high retention and infiltration potential.

The third research question concerned the methods and scales required to assess the hydrological effects of urbanization.

3) Which methods should be used to assess the characteristics of hydrological-cycle components, and which temporal and spatial scales should be considered?

This research showed that precipitation, surface runoff, and evaporation should be assessed across multiple dimensions, including long-term trends, cyclical variations, intra-annual distribution, and responses to heavy rainfall events. These dimensions represent different temporal, spatial, and event-based characteristics of the hydrological cycle.

The long-term trend analysis showed that precipitation increased overall, whereas surface runoff and evaporation decreased. Of particular importance were the contrasting trends in precipitation and surface runoff. Increasing water withdrawals associated with domestic, industrial, and agricultural water demands, together with the regulation and interception of streamflow by reservoirs and other water-control infrastructure, may have contributed to the decline in surface runoff despite the overall increase in precipitation. The decline in evaporation may also reflect changes in climatic and environmental conditions during the study period.

Analysis of cyclical variations provided another dimension of long-term hydrological variability. Precipitation, surface runoff, and evaporation all exhibited multi-scale cycle fluctuations, although their dominant periods and temporal distributions differed among the hydrological cycle elements and hydrological stations.

The intra-annual analysis further revealed seasonal differences and temporal relationships among precipitation, surface runoff, and evaporation. The maximum precipitation, surface runoff, and evaporation occurred in July, August, and June, respectively. Peak surface runoff occurred approximately one month later than peak precipitation, reflecting a delayed response

to rainfall as soil moisture, groundwater conditions, and catchment storage influence runoff generation. In contrast, evaporation peaked earlier than precipitation, which may be associated with longer sunshine duration and vegetation activity during the early summer period.

The analysis of heavy rainfall events provided an additional event-based perspective. Heavy rainfall showed an overall increasing trend, whereas peak flood discharge decreased. The contrasting trends between heavy rainfall and peak flood discharge suggest that changes in flood response cannot be attributed to rainfall changes alone. The regulation of runoff by reservoirs and other water-control infrastructure, particularly those constructed since the 1970s, may have contributed to the reduction in peak flood discharge. These results indicate that the assessment of heavy rainfall should consider not only changes in rainfall characteristics but also the associated runoff response.

Overall, long-term trend analysis identifies the overall direction of hydrological change; analysis of cyclical variations reveals multi-year fluctuations; intra-annual analysis characterizes seasonal variability and the temporal relationships among hydrological cycle elements; and event-based analysis captures the hydrological response to heavy rainfall. Integrated multi-dimensional and multi-scale assessments can provide a more comprehensive characterization of the complexity of watershed hydrological processes under urbanization and provide a basis for developing watershed-scale rainwater management strategies.

In the next section, section 4.4 answered question 4, and section 5.3 was the result of following the methodology described above.

4) Which indicators can be used to characterize hydroecological functions at the watershed scale? When models are used to assess ecosystem services, how should their parameters be selected and adjusted to ensure the accuracy and applicability of the model outputs?

Water yield, carbon storage, and habitat quality were selected to characterize selected hydroecological functions in the NRB. Water yield represents the water-related ecosystem function, carbon storage reflects the capacity of ecosystems to store carbon, and habitat quality characterizes the capacity of the landscape to support biodiversity.

The applicability of ecosystem service modeling depends not only on model selection but also on appropriate parameterization. In this research, the parameters required for the selected InVEST models were obtained from published studies. Parameter selection was therefore based on their relevance to the environmental conditions and LULC types of the NRB.

The ecosystem service assessment revealed an overall decline in water yield, carbon storage, and habitat quality between 2000 and 2022, indicating a weakening of the assessed hydroecological functions of the NRB. These changes were closely associated with LULC transformation during the urbanization process, particularly the conversion of natural and semi-natural land into built-up or otherwise intensively used land. Impervious areas generally exhibited higher water yield but lower carbon storage density and habitat quality, whereas forest areas showed the opposite pattern. The simultaneous decline in the three indicators indicates that urban expansion can affect multiple ecosystem functions.

The results of ecosystem service assessment can support the identification of ecological priority areas and provide a spatial basis for differentiating rainwater management strategies according

to LULC characteristics. Natural areas provide multiple ecological and hydrological functions and should therefore be prioritized for conservation and restoration. In contrast, highly urbanized areas characterized by extensive impervious surfaces require measures that compensate for the loss of natural infiltration and retention.

The fifth research question addressed water security in terms of water-source protection, flood-inundation risk, and water quality.

5) How should water security be assessed, and which indicators should be considered?

This research analyzed three dimensions of water security: water source protection, flood inundation risk, and water quality. These dimensions represent, respectively, the protection and availability of water resources, the potential threat of flooding to human settlements and infrastructure, and pressures on the aquatic environment caused by pollution. Integrating these dimensions helps identify the major water security issues across the watershed and areas that require different management strategies.

Water source protection zones were delineated based on river width and the size of linear and areal water bodies, forming a graded protection system. Flood-inundation risk varied across the NRB, with particularly high risk around the low-lying northern Nansihu Lake area. Water quality in the NRB remains a major challenge, with only 20% of monitoring stations classified as having good water quality and over 30% classified as poor, while pollution pressure is higher in the eastern part than in the western part. TN was the dominant pollutant, likely associated with intensive agricultural activities.

Based on the water security assessment, areas with important water-source functions should receive priority protection and stricter control of potentially damaging land uses; areas with high inundation risk require greater emphasis on rainfall retention, storage, drainage, and flood regulation; and areas experiencing poor water quality require stronger control of pollutant inputs and improved wastewater management and reuse. Integrating these spatially differentiated requirements with hydrological and ecosystem service assessments enables rainwater management measures to respond to the specific water security conditions of different parts of the NRB.

In conclusion, rapid urbanization in the NRB was accompanied by substantial LULC transformation and changes in watershed hydrological processes, including increasing precipitation and heavy rainfall and decreasing surface runoff and evapotranspiration. Meanwhile, declines in ecosystem services, while the water security assessment identified spatially differentiated challenges in water source protection, flood inundation risk, and water quality. The effects associated with rapid urbanization are not confined to individual urban areas or to a single water-related problem. Instead, urbanization alters land surface characteristics, hydrological processes, ecosystem functions, and water security conditions across the watershed. These findings provide the direct basis for watershed-scale rainwater management.

Drawing on the integrated assessment of hydrological processes, ecosystem services, and water security, the study developed a watershed-scale stormwater management strategy for the NRB. It included the following five aspects: Climate-adaptive rainwater management, decentralized

rainwater management, establishment of protected areas, rainwater segregation and sewage reuse, and integrated watershed management.

6.2 Limitations and outlook

Despite providing an integrated assessment of urbanization, hydrological processes, hydroecology, water security, and watershed-scale rainwater management, this research has several limitations.

First, the effectiveness of the proposed stormwater management strategy was not quantitatively evaluated through simulation. Consequently, its potential to reduce surface runoff and flood risk, increase stormwater retention, and improve ecological functions remains uncertain. Further research could address this limitation by applying hydrological models to evaluate the performance of different rainwater management scenarios. Combining modeling results with field observations would also help refine the management plan over time.

Second, the analyses relied primarily on historical hydrological and LULC data and did not account for future climatic and urban development. Shifts in precipitation patterns and extreme rainfall, together with population growth and continued urban expansion, may significantly alter watershed hydrology and the performance of rainwater management measures. Incorporating climate projections and alternative LULC scenarios would be an important extension of this research. It would provide a clearer indication of how well the proposed strategies may perform under a range of future conditions and help identify measures that remain effective.

Third, the analysis of the hydrological cycle focused on precipitation, surface runoff, and evaporation, without quantifying infiltration. However, infiltration plays an important role in linking precipitation with soil water, groundwater recharge, and surface runoff and is particularly sensitive to LULC changes associated with urbanization. Future work could incorporate infiltration and, where sufficient data are available, soil moisture and groundwater processes using field observations and hydrological models. A more complete representation of watershed hydrology would provide a stronger basis for rainwater management.

Overall, future research should extend the current retrospective assessment by incorporating scenario-based projections, quantitative evaluations of management measures, and long-term monitoring. These extensions would help assess and improve the robustness of the proposed stormwater management strategy under a wider range of future conditions.”

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Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertationsschrift zum Thema

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selbstständig verfasst und keine anderen als die angegebenen Quellen benutzt habe. Alle Stellen, die wörtlich oder sinngemäß aus Quellen entnommen wurden, habe ich als solche gekennzeichnet.

Des Weiteren erkläre ich an Eides statt, dass diese Arbeit weder in gleicher noch in ähnlicher Fassung einer akademischen Prüfung vorgelegt wurde.

Dortmund, 10.08.2026

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