Ecohydrology
Series Editors: Chunmiao Zheng
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Xiangzheng Deng
John Gibson *Editors*

River Basin Management

Springer

Ecohydrology

Ecohydrology is an interdisciplinary field studying the interactions between water and ecosystems and utilizing that for enhancing environmental sustainability. With the growing concerns about nature conservation with increasing human activity/urban growth, there is a dramatic increase in research activities studying the changes in our ecosystems and related impacts. Apart from the geosciences point of view, these studies also come from fundamental scientific fields like physics, biology, and chemistry, as well as from engineering and social perspectives. The planned handbook consists of five individual volumes aiming to provide a comprehensive overview of the state of the art of current ecohydrological studies: fundamental concepts, practical monitoring methods, modeling studies, as well as special topics in water-limited environments. Each volume is edited by well-known expert(s) in the field, bringing in international authors for each chapter. The book is structured in a way that is appropriate for advanced graduate students and professionals in diverse scientific and engineering communities devoted to relevant fields, including geoscience, chemistry biochemistry, and biology, as well as various engineering disciplines. Although the handbook is planned to be published in series, each volume provides a self-contained description of its topic, with a standard and consistent format across each volume: Vol. 1, Water and Ecosystems; Vol. 2, Observation and Measurement of Ecohydrological Processes; Vol. 3, Water-Limited Environments; Vol. 4, Integrated Ecohydrological Modeling; and Vol. 5, River Basin Management.

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River Basin Management

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Series Preface

In the broadest sense, ecohydrology is an interdisciplinary field studying the interactions between water and life. With the growing concerns about nature conservation and environmental sustainability under intensifying global change and human activities, there has been a dramatic increase in research activities studying the ecohydrological processes and how they shape and impact the ecosystems we live in. Apart from the geosciences point of view, these studies also involve fundamental scientific fields like physics, biology, and chemistry, as well as engineering and social perspectives.

The handbook has been planned to consist of five individual volumes aiming to provide a comprehensive overview about the state of the art of contemporary ecohydrological studies: fundamental concepts and theories, field observation and monitoring methods, integrated ecohydrological modeling, river basin management, and special topics in water-limited environments. Each volume is edited by well-known experts in the field, bringing in international authors for each chapter.

Individual volumes are intended to include specific topics, such as interactions and feedbacks between ecological and hydrologic processes under different vegetation types and landscape patterns, soil seasonal freezing/thawing processes and their ecohydrological effects, groundwater-surface water interactions and their controlling factors, mechanisms of water utilization and transpiration by vegetation canopies across multiple scales, system complexity and scaling of coupled ecological-hydrologic processes, integrating ecohydrological models with economic models for decision support, field observatories to support integrated ecohydrological studies, assessment of ecosystem services and development of decision-making frameworks, and basin-scale biogeochemical processes and water quality issues.

The book is structured in a way that is appropriate for advanced graduate students and professionals in diverse scientific and engineering communities devoted to relevant fields, including geoscience, hydrology and water resources management, biogeochemistry, and biology, as well as various engineering disciplines. Although the handbook is planned to be published in series, each volume provides a self-contained description of its topic, with a standard and consistent format across each volume.

It is noteworthy that the motivation for this handbook stems from a large ecohydrological research program sponsored by the National Natural Science

Foundation of China (NSFC) from 2010 to 2018. The research program, titled "An Integrative Study of Ecological and Hydrologic Processes in the Heihe River Basin," utilizes a well-instrumented inland river basin in Northwest China to explore fundamental ecohydrological processes across multiple spatiotemporal scales and to develop sustainable water management and ecosystem preservation strategies. Many of the chapters in the handbook draw from the data, findings, and perspectives of the Heihe Program. We gratefully acknowledge the financial support by the NSFC.

Chunmiao Zheng
Guodong Cheng
Bojie Fu
Series Editors

Volume Preface

There is a crucial need to achieve a more sustainable management of the world's water resources. Major areas of the world already face problems of water scarcity, and far too many rivers and lakes are polluted. This global priority is reflected in the United Nations' *Sustainable Development Goals*:

> By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity (SDG 6.4)

These issues are especially pertinent in China, whose per capita water resources are only one-quarter of the world average. The stress on freshwater resources in China will only intensify due to the competing demands of agriculture, urbanization, and industrialization.

There is an especially large need for improved water management within inland basins, which cover about one-tenth of the world's land area. The trans-basin movement of water faces major environmental and engineering challenges and remains controversial, and so improved management of water within basins offers more feasible options to enhance the efficiency of water use. Many of these basins are in arid environments, and so the pressing economic and ecological concern for these areas is: How do we make sure that water is allocated properly across competing uses?

In light of the importance of the water management issue for river basins, we considered it important to edit a book that presents new research drawing on agricultural, economic, environmental, geographic, and governance perspectives. Much of the evidence in this book is from the Heihe River Basin, which is the second largest inland river basin in China. It is located in the arid and semi-arid regions of northwest China, extending over the provinces of Qinghai, Gansu, and Inner Mongolia.

While this evidence comes from a specific area, the application of integrated economic and environmental modeling that is presented in various chapters can usefully be applied to river basin management elsewhere. Indeed, the international collaboration of researchers evident in these chapters is a testament to the worldwide interest in freshwater management issues.

The editors are extremely grateful to the contributors of all chapters for their unflagging efforts to bring this project to completion. We are indebted to the Springer editorial office and publishing team for keeping the project on track. We hope that readers will find the book informative and that insights they can gain from the book can help to improve the sustainable management of water.

February 2019

Xiangzheng Deng
John Gibson
Editors

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Finally, we are grateful to the Springer staff for their lasting enthusiasm to help us produce this work. We are grateful to all the authors of the numerous books and research publications mentioned in the list of references at the end of this work. This valuable literature formed the foundation of this work. We express our gratitude to those researchers and organizations for their contributions that reinforced our knowledge.

Contents

Management Innovation for Integrated River Basin Management 1
Qing Zhou, Xiangzheng Deng, Omaid Najmuddin, Qian Zhang, and Chunhong Zhao

Forecasting Industrial Water Demand Using Case-Based Reasoning: A Case Study in Zhangye City, China 33
Bohan Yang, Weiwei Zheng, and Xinli Ke

Urbanization and Industrial Transformation for Improved Water Management 61
Feng Wu, Qingling Shi, Shaikh Shamim Hasan, Chenchen Shi, and John Gibson

Impacts of Land Use and Cover Changes on Water Balance in River Basin 91
Siqi Jia, Xiangzheng Deng, John Gibson, Qingling Shi, and Chunhong Zhao

Adapting Water Scarcity for River Basin: Optimization of Land Uses 119
Zhihui Li, Xiangzheng Deng, Aisha Arowolo, Qunou Jiang, and Haiming Yan

Water and Land Effects on Agricultural Development for River Basin: Resource Restriction and Sustainable Development 151
Guofeng Wang, Jiancheng Chen, Fuchun Zhang, Xiaoxue Zhou, and Xiangzheng Deng

Spatiotemporal Surface of Agricultural Water Requirement for Integrated Water Resources Management 183
Wei Song, Yaqun Liu, Xiangzheng Deng, Ying Zhang, and Ze Han

Oasis Agriculture: Improving Water Usage Efficiency Within River Basin 211
Guofeng Wang, Jiancheng Chen, Abdus Samie, Wei Song, and Zhan Wang

Mitigating Climate Change Impacts for Optimizing Water Productivity 245
Zhongxiao Sun, Feng Wu, Aisha Arowolo, Chunhong Zhao, and Xiangzheng Deng

Impacts of Water Scarcity on Socioeconomic Development in Inland River Basins 281
Qing Zhou, Xiangzheng Deng, Feng Wu, Zhihui Li, and Wei Song

Virtual Water Flow at County-Level of the Heihe River Basin in China 307
Yali Zhang, Qing Zhou, and Feng Wu

Optimal Water Allocation Scheme in Integrated Water-Ecosystem-Economy System 333
Wei Song, Yaqun Liu, Aisha Arowolo, Ying Zhang, and Qian Xu

Hydrological Ecosystem Services for Integrated Water Resources Management 361
Gui Jin, Xiangzheng Deng, Shaikh Shamim Hasan, Chunhong Zhao, and John Gibson

Decision Support System for Integrated and Adaptive Water Governance 387
Zhongyuan Li, Qian Zhang, Feng Wu, and Pei Wang

Index 419

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Management Innovation for Integrated River Basin Management

Qing Zhou, Xiangzheng Deng, Omaid Najmuddin, Qian Zhang, and Chunhong Zhao

Contents

Introduction . . . 2
Assessment of Water Scarcity . . . 4
    Water Stress and Its Drivers . . . 4
    Water Stress Indicator . . . 5
    Water Stress Assessment for Heihe River Basin . . . 6
Water Supply Management . . . 11
    Water Conservancy Projects: Reservoirs and Dams . . . 11
    Water Transfer . . . 12
    Impact Analysis of Investments on Water Projects . . . 13
Water Markets . . . 16
    Water Right . . . 16
    Water Price . . . 17
    Irrigation Water Price Reform in HRB . . . 18
River Basin Management Comparisons . . . 21
    Hydrology Context of the Three Basins . . . 22
    Drought and Irrigation . . . 23
    Rapid Industrialization and Urbanization . . . 24
    Management Strategies . . . 25
Conclusion . . . 29
References . . . 30

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Abstract

Water scarcity and stress have attracted increasing attention, as water has become increasingly regarded as one of the most critical resources in the world's sustainable development. In order to achieve a more sustainable water resource management at river basin level, this chapter takes Heihe River Basin (HRB) in Northwest China as a representative example to address the water scarcity situation and gives an outlook of strategies and innovations for river basin management. Since a good understanding of the water stress situation is a prerequisite to make proper water strategies, by applying the Water Poverty Index (WPI), the water stress situation in HRB and the driving factors are evaluated first. Results indicate that water stress has become more severe over time in the HRB. Then water resource management strategies and innovations from supply and demand side are discussed, especially for the effects of water conservancy project and water price reform in HRB. Furthermore, with comparable characters and similarities in the hydrological contexts, a comparative study between HRB and two other river basins Murray–Darling Basin (MDB) in Australia and the Colorado River Basin (CRB) in the USA was conducted. Comparisons in water allocation, water organizations, water acts, and scientific projects are analyzed. Finally, recommendations for integrated river basin management for the HRB have been proposed.

Keywords

Water scarcity · Integrated river basin management · Water markets · Water price · Water projects · Heihe River Basin

Introduction

Water is essential for life and critical to food security, ecosystem service, and socioeconomic development. The overwhelming scarcity is challenging the earth's sustainable development. Contemporarily, human needs for fresh water are still increasing in the process of industrialization, urbanization, and ecological conservation (Cosgrove and Rijsberman 2014; Deng and Zhao 2015). An estimated 80% of the world's population faces a high level of water insecurity, particularly those in Asia and Africa (Bakker 2012). China faces a serious water crisis, as it has 20% of the world's population with only 5–7% of global freshwater resources (Piao et al. 2010). A falling supply of water caused by climate change and a rising water demand from different users have posed great threats to the society, especially in arid and semiarid inland river basins.

Rivers and river basins are important components for acquiring and protecting water resources, and they provide good habitats for humans to live (Bakker 2012; Sivapalan et al. 2012). However, many inland river basins are facing challenges to coordinate environmental protection and economic development in the context of increasing water demand. The scarcity essentially represents the conflicts between thirsty farms and cities since the irrigated agriculture is predominant in most inland river basins. Agriculture is the main consumer of fresh water resources. At the same time, the rapidly developing industrial sector and an increasingly wealthy urban population have started to compete with agriculture for water (Deng et al. 2014b; Jiang et al. 2014). The overexploitation of groundwater is pervasive in most arid inland river basins since the diminishing surface water resources can no longer meet the agricultural water demand. The overexploitation of deep groundwater thus causes a number of environmental problems, such as land desertification and a reduction in the amount of natural vegetation cover (Qiu 2010; Deng and Zhao 2015). Furthermore, water use inefficiency and water waste are prevalent and have added to the water crisis.

Many have claimed that the global water crisis is one of governance much more than of resource availability (Grafton et al. 2013). Poor management of water resources is the main contributor to the irrational water allocation, overdrawing of renewable water resources, low water-use efficiency and agricultural water productivity. Water resource management is one of the key panaceas for coordinating social–economic development and eco-environmental construction in arid river basins. The appropriate management of water resources is essential for achieving sustainable development including social and economic development, poverty reduction and equity, and sustainable environmental services. Integrated river basin management strategies are urgently needed since traditional river basin management strategies cannot meet the needs of the dramatic socioeconomic development in the developing countries and regions.

Water supply management has long been considered as an important way to cope with increasing water scarcity. For instance, increase of water storage capacity and decrease of rainfall drainage for agricultural irrigation, together with prohibiting exploitation and occupancy of river beds, and devising innovative water policies at both administrative level and jurisdictional level (Gleick et al. 2011) are examples which draw researchers' attention. However, water use for environmental adaptation is increasing sharply in arid and semiarid areas, which mainly comes from water engineering excluding natural water supply from precipitation and runoffs. For instance, in urban areas, water demands are for building public green, supplementing rivers and artificial lakes, while in rural areas, for supplementing swamps and low-lying lakes (Wang et al. 2015).

Modern civilization has made a remarkable progress in water management in the past few centuries, shifting from an engineering-based water management system to one that increasingly incorporates economic approaches. Public attention has been drawn on how to value water and how to economically use water (Tiwari and Dinar 2002; Schoengold et al. 2006; Venot and Molle 2008). Markets have been considered to be the most efficient way of allocating scarce resources by economic theory even though complete valuation of natural resource is impossible. It has been deemed that natural water resources, as externalities of the economic system, should be marketized with proper economic value. The physical water allocation on social welfare has spatial heterogeneity due to partial economic valuation issues. Partial valuation of water resource leads to Pareto inefficiency by market failure caused by asymmetric information. Thereafter, administrative policies always play uncertain roles to the practical results of welfare allocation mechanism.

In this chapter, we give a brief review of the water scarcity problem faced by the world and resource management strategies and innovations from a supply and demand management perspective. At last, by giving a comparison of the river basin management strategies of three typical river basins in the world, we present our findings and insights from research focused on the evolution of different approaches to an integrated and holistic water resource management and their implications for arid and semiarid areas.

Assessment of Water Scarcity

Water Stress and Its Drivers

Water availability has never been satisfied from a quantitative and quality perspective. Clean, safe, and adequate freshwater is vital to the survival of all living organisms. Though the earth is abundant with water resources, less than 2% of the total amount can be used or exploited by humankind. From the limited 2%, almost all of this (more than 98%) occurs as groundwater, while only less than 2% is available in the more visible form of streams and lakes (Bouwer 2000). When the annual renewable freshwater supplies are below 1700 m^3/capita/year, water is definitely physically scarce. It is not surprising that some arid regions are already experiencing high “water stress,” especially densely populated arid areas like Central and West Asia, and North Africa, with projected availability of less than 1000 m^3/capita/year (Rijsberman 2006).

Situation has become more worrisome in regard to water quality. The problem of water pollution is prevalent; many rivers, lakes, aquifers, and oceans are contaminated by point or nonpoint pollutions (Biswas and Tortajada 2001). According to the UN reports, about 16% of the world’s rural population do not use improved drinking water sources; 50% of people living in rural areas lack improved sanitation facilities (WWAP 2015). Eutrophication of surface water and coastal zones is expected to increase almost everywhere until 2030 (UNDESA 2012). More people are projected to die from water-related diseases during the period of 2002–2020, assuming the proportion of deaths to the total global population (Gleick and Heberger 2014). Poor water quality threatens human health and ecosystems, reduces the availability of safe water for drinking and other uses, and limits economic productivity and development opportunities.

Agriculture continues to be the biggest consumer of water resources and also one of the main reasons of pollution. Globally, 60–80% of water is used for irrigation, while the figure rises to nearly 90% in some low-rainfall areas (Gleick and Heberger 2014). It is projected that future population will increase, suggesting an increase in food demand and subsequently an increase in agricultural water demand if the current efficiency is not improved. Excessive use of fertilizers and pesticides has led to water pollution, particularly in the developing world. Similarly, water quality impairments can also have negative impacts on agricultural sector by causing salinity, the largest water quality problem facing the agricultural sector (Haddeland et al. 2014). And thus the dynamics leads to an increased competition among water users for the shrinking supplies of unpolluted water.

Climate change is expected to alter the hydrologic cycle and will subsequently impact water availability and demand. IPCC has projected that average global temperature will rise by between 1.1 °C and 6.4 °C over the next 100 years. There is a strong evidence that climate change is altering global and regional hydrologic cycles, with impacts predicted to be manifested as changing precipitation patterns, increased intensity of extreme weather events and consequent natural disasters, retreating glaciers resulting in altered river discharge regimes, and more intensified droughts in semiarid regions (Bates et al. 2008). Furthermore, the increase in global warming generally is expected to result in an increased evaporative demand. Many semiarid and arid areas (e.g., Mediterranean Basin, Western USA, southern Africa, northeast Brazil, southern and eastern Australia) are particularly exposed to the impacts of climate change on water resources through change in runoff, alterations in recharge of groundwater aquifers, shift in water table levels, and water quality problems and diminishing water resources.

Water Stress Indicator

Water stress indicators are important for policy-makers to devise appropriate management strategies. Condensed indices of water stress are very useful for focusing and simplifying the problem, more influential in affecting policy-makers' decisions and are more effective at drawing public attention than the long lists of multiple factors or measures. As a result, the indices, rather than precise measures, have been considered as an important water management tool that holds considerable political appeal. Substantial efforts have been made by researchers to generate suitable expressions to represent water scarcity and stress, such as the Water Poverty Index (WPI) (Zhang et al. 2015). The interdisciplinary approach, Water Poverty Index (WPI), allows spatiotemporal patterns and trajectories of water scarcity and stress to be measured. The WPI was originally developed as a holistic tool to measure water stress at the household and community levels in the early 2000s which considers water availability from both the biogeophysical perspective and the socioeconomic perspective of people's ability to access water (Sullivan 2001; Sullivan and Meigh 2007). It provides a basis for ranking administrative units in terms of water availability and the effectiveness of water management through combining a cluster of data that are both directly and indirectly relevant to water scarcity and stress into a single number. It assists both national and local decision-makers to better determine policy priorities for making interventions in the water sector.

Water Stress Assessment for Heihe River Basin

An Overview of the Study Area

Zhangye City, a prefecture-level city of Gansu province in Northwestern China, is located in the middle reach of the Heihe River and the hinterland of the Hexi Corridor, includes six counties or districts, namely, Ganzhou District, Linze County, Shandan County, Minyue County, Gaotai County, and Sunan Minority Autonomous County (Fig. 1). The annual precipitation in Zhangye City is only 198 mm as it is located within the arid continental climate zone. The average annual temperature is around 6°C, and the hottest and coldest months are July and January, respectively. Flat topography, fertile soil, and sufficient sunshine hours (up to 3000 h per year), together with primary irrigation by the Heihe River, have transformed Zhangye City into one of China's 12 key national commercial grain bases. However, expanding agriculture and rapid economic development have resulted in the excessive use of water resources. In 2007, both the annual available water resources and the actual annual water utilizations for Zhangye City were 2.36 billion m^3, of which 1.96 billion m^3 were from surface water and the reminder was from groundwater. The majority (99%) of water usage is for socioeconomic purposes, and of this amount, 95% is used for agriculture. Ecological and environmental water demands have not been able to be accommodated in this socioeconomic-dominant system. As a result, the city faces an environmental–economic dilemma through increasing dependency on the scarce water resources and increasing environmental degradation (Cheng

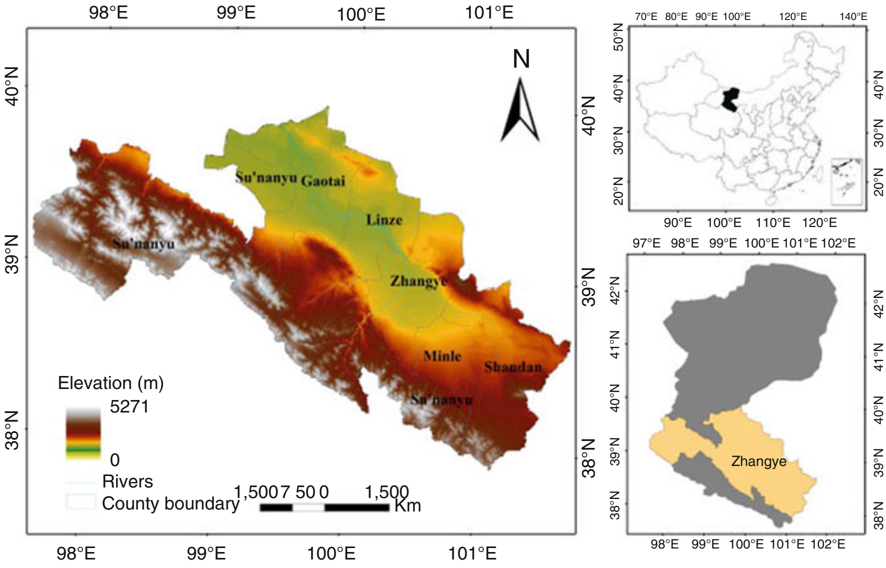

Fig. 1 Location of the study area: Zhangye City in the middle reaches of the HRB (Reprinted from (Zhang et al. 2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

et al. 2014). Consequently, there is an imperative to alleviate water stress and promote water-use efficiency in this case study area.

General Workflow of WPI and Its Calculation

The WPI has been successfully applied to make both international comparisons and numerous case studies at the local level (Sullivan and Meigh 2007). Following the conceptual framework of the WPI, measures of water availability, access to water, the capacity for sustaining access, water use, the environmental factors that impact water quality, and the ecology that water sustains all need to be considered to provide a multidimensional picture of the water stress situation (Sullivan 2001). Here, we use the conventional composite index approach and matrix (quadrant) approach to generate the spatiotemporal pattern, typologies, and trajectories of water stress in the study area (Fig. 2). The primary step is to select suitable variables to represent each component (water stress indicators), following which we calculate the WPI and use different graphical devices to illustrate the spatiotemporal patterns, typologies, and trajectories of water stress for the study area.

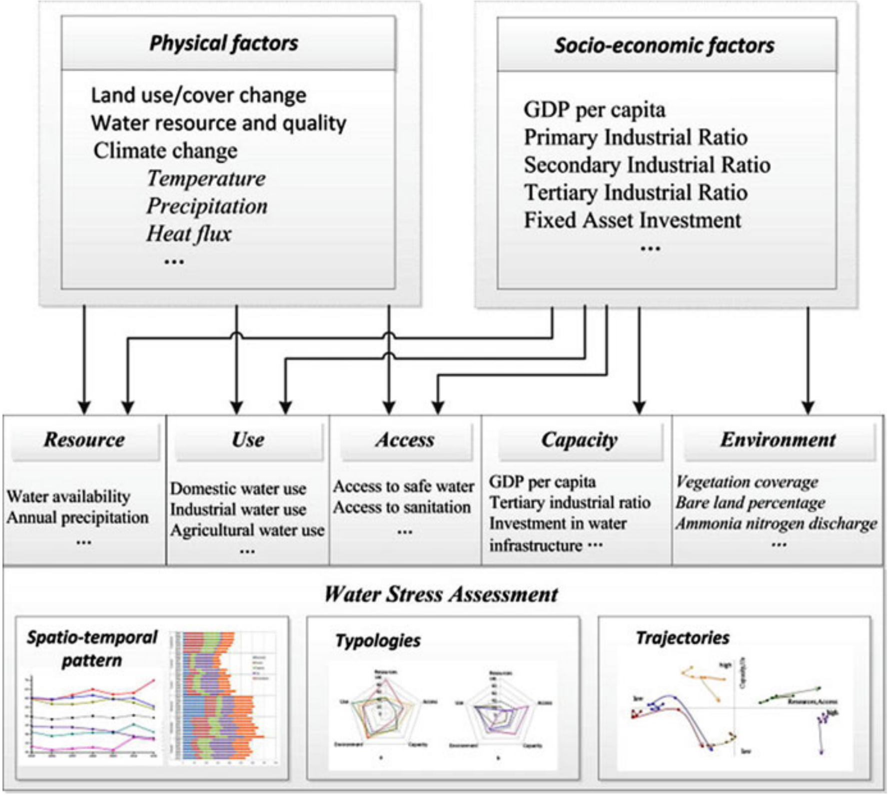

Fig. 2 General workflow of this study (Reprinted from Zhang et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

Water Stress Indicators

The indicators we used to represent the components of Resources, Access, Capacity, Use, and Environment in this case study are listed in Table 1 and the statistics of these variables for Zhangye City for 2005–2011 are presented in Table 2 "Resources" refers to the total available water and here we use the total amount of domestic, agricultural, and industrial water usage plus precipitation as a proxy. "Access" means not only acquiring safe water for daily needs, but also water for irrigating crops and for industrial use. In Zhangye City, most water consumption is for agricultural usage; therefore, we choose the agricultural gross ratio and the percentage of the population with access to safe water as the indicators for characterizing access. "Capacity" represents the power to purchase water and the ability to manage water supply. GDP per capita and tertiary industrial ratio are used to represent the level of economic development and are selected as the indicators of capacity. "Use" comprises domestic, agricultural, and nonagricultural water usage, and therefore indicates the total amount of domestic, agricultural, and industrial water usage in a county. "Environment" is represented by a summary of the annual average normalized differential vegetation index (NDVI), bare land area percentage,

Table 1 List of indicators used in the calculation of the WPI

Component/*Indicator*	Description
Resources	
Total water usage per capita	Total annual amount of domestic, agricultural, and industrial water usage (m^3/person year)
Precipitation	Annual precipitation in a county (mm)
Access	
Percentage of the population with access to safe water	$\frac{\text{number of households with access to safe water (in a county)}}{\text{total number of households (in a county)}}$ (%)
Agricultural gross ratio	Agricultural gross population as a percentage of total population in a county (%)
Capacity	
GDP per capita	Per capita GDP of a county (Chinese Yuan)
Tertiary industrial ratio	Tertiary industrial output value as a percentage of total GDP in a county (%)
Use	
Domestic water usage	Total amount of domestic water usage in a county (m^3)
Industrial water usage	Total amount of industrial water usage in a county (m^3)
Agricultural water usage	Total amount of agricultural water usage in a county (m^3)
Environment	
NDVI	Summary of the annual average normalized differential vegetation index in a county
Bare land area percentage	Bare land area as a percentage of the total land area in a county (%)
Ammonia nitrogen discharge	Annual discharge amount of ammonia nitrogen in a county (ton)

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Table 2 Statistics of indicators used in calculating the water stress index

Indicators	Mean	Min	Max	SD
Resources	**37.67**	**2.14**	**93.65**	**29.15**
Total water usage per capita (m^3/person year)	1981.17	819.52	3225.64	607.78
Precipitation (mm)	253.46	79.30	702.00	133.87
Access	**46.91**	**9.86**	**81.44**	**23.57**
Percentage of the population with access to safe water (%)	77.24	38.15	99.45	20.11
Agricultural gross ratio (%)	38.18	24.40	48.07	7.74
Capacity	**35.52**	**13.52**	**80.28**	**20.62**
GDP per capita (10^3 Chinese Yuan)	15.78	5.21	57.38	9.62
Tertiary industrial ratio (%)	30.08	17.60	41.50	6.94
Use	**64.26**	**4.96**	**99.79**	**31.48**
Domestic water use (10^6 m^3)	9.76	0.83	27.44	7.28
Industrial water use (10^6 m^3)	10.45	0.81	38.23	7.48
Agricultural water use (10^6 m^3)	3.42	0.47	10.09	2.53
Environment	**51.25**	**29.32**	**63.51**	**10.40**
NDVI	15.79	8.89	22.89	4.31
Bare land area percentage (%)	30.07	5.20	72.39	22.20
Ammonia nitrogen discharge (ton)	179.18	19.87	645.76	123.20

Data sources: Statistical Bureau of Zhangye City in China (2005–2011). Reprinted from Zhang et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C

and annual ammonia nitrogen discharge, which are indicators that measure water quality and the ecology that water sustains.

Each indicator is standardized to a range of 0–100, and each component is the average of its indicators with equal weights. The WPI for a particular location is calculated as the average of five components, namely Resources (R), Access (A), Capacity (C), Use (U), and Environment (E), with equal weights. The values of the components and of the resulting WPI thus lie between 0 and 100. The lowest value (WPI = 0) represents a situation of the most severe water stress, and the highest value (WPI = 100) represents the best situation where there is the lowest risk of facing water scarcity and stress. The subcomponents are categorized into positive and negative indicators. For positive indicators, the higher the original value of a factor, the less severe the water stress and there is a better water management situation. For negative indicators, the lower the original value of a factor, the higher the level of water poverty.

Results

The longer the bars in Fig. 3, the higher the values of the WPI, and the less severe the water stress situation for a particular county. The highest value of the WPI is double the lowest value. The patterns shown in Fig. 3 demonstrate the distinct spatial variation in water scarcity and stress, even for small regions (such as parts of the water basin) at the local level, here with respect to counties.

In the graphical device used for presenting the trajectories of water stress (Fig. 4), the origin and terminations of the *x*- and *y*-axes represent the minimum and maximum

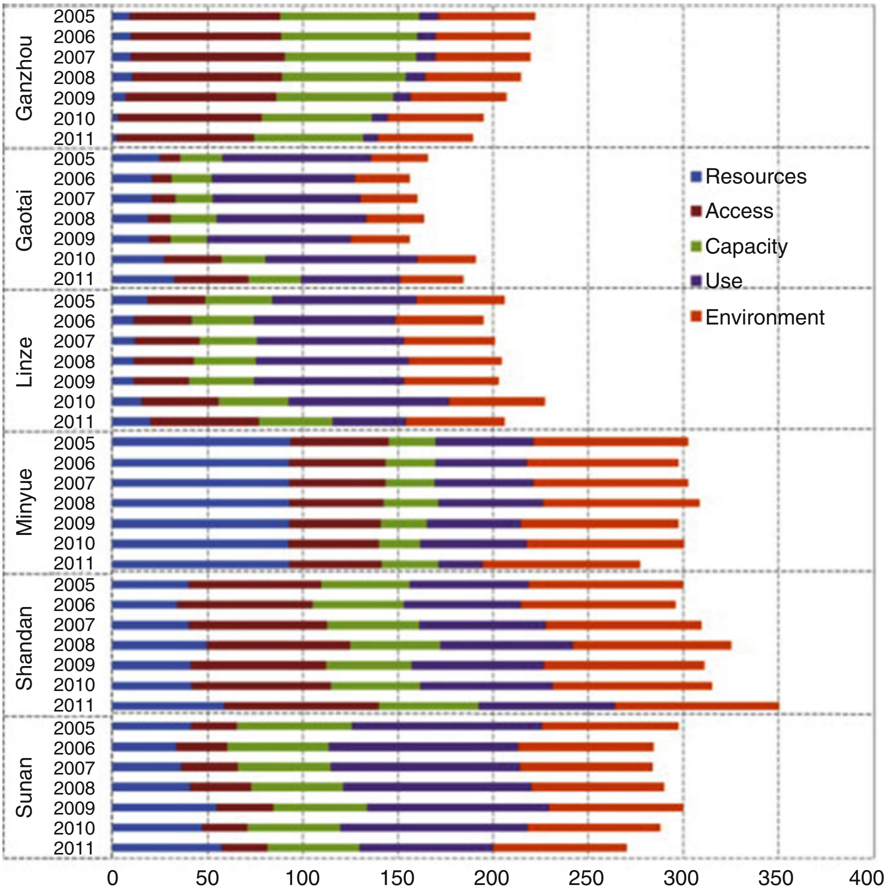

Fig. 3 Water stress index and its components for the six studied counties of Zhangye City (Reprinted from (Zhang et al. 2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

values of the mean values of Resources and Access and of Capacity and Use, respectively. The arrows show the temporal trajectory of each county through the dimensions from 2005 to 2011 (Fig. 4). A trajectory of points from the lower-left (low–low or LL) quadrant to the upper-right (high–high or HH) quadrant would indicate a substantial improvement in both water Availability–Access and Capacity–Use, and can be defined as progression. In this case study, only the curve for Shandan County is located in the HH quadrant, and the trend heads slightly upwards and to the right, indicating an improving water situation. The curves for Gaotai, Linze, and Sunan counties all trend downwards and to the right, which means an increase in Availability and Access but a decrease in Capacity and Use. Minyue's curve trends downwards and slightly left in the HL quadrant, even though the original value of Availability and Access for this county is high. Ganzhou's curve trends downwards and left in the LL quadrant, showing regression over time in both dimensions.

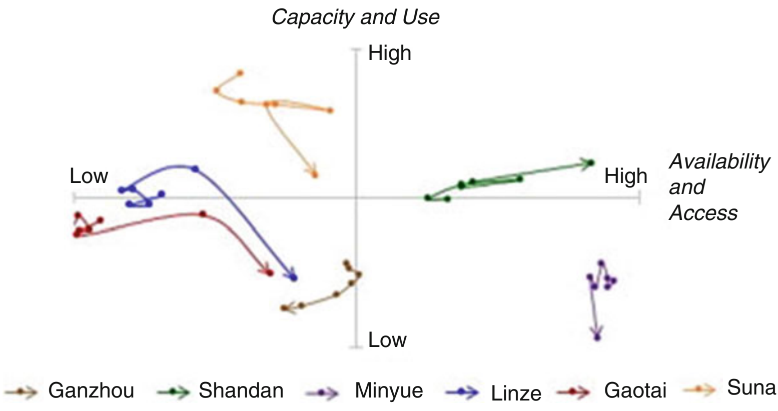

Fig. 4 Trajectories of water stress for the six studied counties of Zhangye City (Reprinted from Zhang et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

The results indicate that water scarcity and stress have become more severe for most of the counties in Zhangye City over the period 2005–2011. There is clear spatial variation in water scarcity and stress between the different counties. Specifically, Shandan County scored relatively highly in the WPI and across multiple components, reflecting its progressive policies on access and management and its good water governance. In contrast, Ganzhou district, which contains the largest single percentage of the total population of Zhangye City, has faced increasing water scarcity and stress, and is regarded as having poor water governance. An analysis of water stress typologies using radar maps shows that each county had a distinct radar map pentagram shape, which indicates that each county faced its own particular challenges and opportunities in the context of water scarcity and stress. In addition, the trajectories map reveals that none of the counties has substantially improved both water access and management, a finding that should attract the attention of decision-makers. In short, the WPI, serving as a simple, transparent, and holistic tool, provides a better understanding of the complexities of water scarcity and stress by integrating physical, socioeconomic, and environmental factors. This is particularly the case when changes in the index can be assessed over a reasonable period of time and when the trajectories of the index and its components can be tracked and its typologies identified. The WPI appeals to decision-makers and should also serve to empower the public to participate in practicing effective and efficient water management through determining and justifying policy priorities.

Water Supply Management

Water Conservancy Projects: Reservoirs and Dams

Water demand for urban consumption, industry, and irrigated agriculture continues to increase under climate change. Water supply is limited and frequently faces hydrological uncertainties like erratic rainfall, natural hazards: floods and droughts.

To protect water supplies against these extremes and changes, more storage of water is needed, especially in arid and semiarid areas. Water reserves and control projects are constructed during times of water surplus to use its water in times of water shortage.

Traditionally, such storage has been achieved with dams and surface reservoirs. From the 1930s to the 1980s, numerous dams were built all over the world for hydropower generation, flood control, or multipurpose water development (Haddeland et al. 2014). These projects have played important roles in providing assured water supply for domestic, agricultural, and industrial purposes and reducing flood and drought damages. Studies have shown that water investments reduce damages from extreme weather events from 25% to 30% of GDP to around 5%, making these investments a crucial element in achieving social stability (Biswas and Tortajada 2001).

Though people really have gained lot of benefits through construction of dams and reservoirs, disputes also arouse for the disadvantages and the adverse effects they may cause. Dams have a number of disadvantages like interfering with the stream ecology, adverse environmental effects, and evaporative losses (especially undesirable for long-term storage). Construction of dams is costly, and leads to displacement of people and loss of scenic aspects and recreational uses of the river. Dams prevent nutrient and water flowing to the downstream that is needed to maintain and nourish the rivers and deltas, a crucial source for agriculture production and fish. Other public health problems are also concerned such as increased water-borne diseases. Furthermore, though hydropower dams can boost development, they block most of the sediment, eventually losing their capacity as they fill up with sediments. In the USA, several dams have already been breached, and more are scheduled for destruction, mostly for ecological and environmental reasons.

Water Transfer

When demand for water outstrips the amounts that are generated within the river basin, supply-oriented approaches will remain important and new water sources will have to be found either by desalinizing sea water in coastal regions or by taking water from neighboring river basins, that is, through interbasin water transfers (IBTs), which usually helpful in arid areas. IBTs are designed to secure access by artificially conveying water to locations where people need which is increasingly becoming the dominant solution to water insufficient areas. Inter basin water transfers currently divert about $540 * 10^9$ m^3 of water, which represent approximately 14% of all global water withdrawals (Howe and Easter 2013). And at the same time many small interbasin water transfers are gradually increasing in order to solve water shortage.

The South–North water transfer in China is a famous water transfer project that has been conducted to alleviate the water scarcity in Northern part of the country. The project not only provides water resource guarantee for Western China's social economic development, but also increase the runoff of the rivers and improve the water environment in that region at the same time. The transfer project benefited the eco-environment in water-received area by helping to stop and control soil and water loss and land desertification, decrease natural disasters, improve the agricultural eco-environment and local survival for the inhabitant, restore the ecosystem, and enhance environmental capacity and load-bearing capabilities.

Though the concept of transferring water from one river basin to another has evolved over centuries as a useful means of meeting water demands, it generates some of the largest controversies and deepest conflicts over water resource development (Howe and Easter 2013). Supporters claimed that water transfer plays a crucial role for rational allocation and avoiding overexploitation of natural resources. Furthermore, water transfer projects not only brought opportunities for ecological and economical use of water resources, but also contributed towards regional industrial and societal development (Gupta and van der Zaag 2008). However, opponents argue that despite their high cost and “high profile” in terms of the complex engineering and technical inputs that they require, the ecological and social implications of such schemes have been, and continue to be, questioned. They claims that such projects have the potential for serious ecological impacts, including introduction of non-indigenous organisms, changes in water quality and hydrologic regimes, and alteration of habitat which results in severe ecosystem perturbation (Tang et al. 2014).

Whereas, empirical knowledge of ecological consequences of interbasin water transfers is still limited and research for assessment of water transfer impacts to date are inadequate. It is imperative to develop coordinated research methodologies to be incorporated into the planning and evaluation of interbasin water transfer projects.

Impact Analysis of Investments on Water Projects

Government investment on large water conservancy project has huge impacts on local economic development and ecosystem. For instance, large water transfer projects like the Three Gorges Hydraulic Power Station in China cost 5.19 billion in USD and led to migration of 1.13 million people, and the Hoover Dam in the USA made great economic contribution of power generation for 8 million people in Arizona, Nevada, and California. Furthermore, partial valuation of natural land use results in heterogeneously proportional changes between land price and the prices of other normal commodities that are caused by hysteretic price on continual utilization without market transfer. Therefore, modeling water allocation needs to consider more complex structure of the factor inputs from the demand side. It will provide economic insights for policy analysis of the efficiency of government investment on large water projects. It also provides a macro-view economic valuation of natural water resource through entire engineered economic system that can be also assessed by social welfare implication of relative changes through micro economic approach.

Methodologies and Conceptual Model

Computable General Equilibrium (CGE) modeling from both water supply side and demand side provides insights of policy-oriented impact of water resource allocation. It is a systematic equilibrium-based research on water allocation from both water supply side and water demand side, which indicates sustainable adaptation of a regional integrated water system for both ecological and economic development under water scarcity condition (Rosegrant et al. 2000).

Improved CGE Model was designed by introducing natural capital, water, and land into the modeling framework. Water and land have been partially valued and plugged into Social Accounting Matrix (SAM) to indicate relative demands. Water use for urbanization and environmental adaptation as a part of water demand is mainly provided by water engineering and financed by Central Government and Provincial Government. It is outside of systematic balancing but have a huge impact on economic structure and sustainable development in dry rural area. Study on total regional water demand has to consider a general equilibrium as an analysis tool to systematically explore interrelationships and interactions at a regional extent. Thereby, based on unit price assumption in CGE Model, economic valuation of water use provides leverage through marketized mechanism to analyze interaction and interrelationships between water consumption and economic activities with governmental financing. Systematic analysis in laboratorial experiments is provided by GAMS (The General Algebraic Modeling System) to test relatively proportional changes in the modeling system under different scenarios.

The conceptual model designed three-nested Constant Elasticity of Substitution (CES) production function in the regional CGE model. It means that the nonlinear relationship among factors is designed instead of traditional linear relationships of CES production function. Intuitively, evolutionary civilization is nonlinear process. It covers endogenous nonlinear technology improvement, nonlinear resource utilization, and nonlinear human activities. Thereafter, researchers have to recognize economic scales that are based on different levels of productivity.

Land and capital are designed in the first level of economic scale in the modeling framework. Theoretically, land is an irreplaceable resource on the earth. Since humans hunted for food in “pristine” environment during ancient times, we have started to learn from the natural environment. After humans learned how to use stone to make fire, our agricultural activities started to rely on how to use land. According to different land utilizations, capital has been accumulated through the “learning-by-doing” process to support human sustainable living. With advanced technology, humans have constantly created and improved adaptive environment, and built numerous skyscrapers for efficient land use, but the total available land is still limited.

Labor as a production factor is designed in the second level of economic scale in this modeling framework. From ancient times to modern times, labor-intensive jobs are gradually substituted by advanced machines. Although endogenous capital growth is attributed to technology improvement, labor contributes to both aspects of capital accumulation and research development. Thus, the substitution of additional labor input is designed at the second level productivity. Human activities brought industrialization and civilization. Our living standard and environment have been improved, however polluting the natural environment.

Particularly, in recent two hundred years, human-dominated ecosystem (HDE) has been pressured by rapid growth of urbanization expansion. In the past several decades, “urban fringe” has been paid much attention because ecosystem along urban area is bearing much pressure of increasing human activities (Muller and Lenz 2006). Moreover, with increasing individuals and public utility level, government policies can now easily distorting ecosystem and economic system. Globally water demand for environmental adaptation and conservation are sharply increasing with downhill climate changes.

Case Study and Implications

Gansu Province, where Heihe river flows through, including 14 prefectures, is located at northwest of China. It has a population of 26 million in 2008, with a total area of 425,800 km^2. It is mostly covered by semiarid to arid land, alternatively influenced by subtropical monsoon climate and temperate continental climate. Water scarcity still remains severe due to the constraints of regional characteristics of the unique geographical location. The annual available water was less than 1100 m^3 per capita, which is only a half of the national average or one-eighth of the world’s average. Furthermore, Gansu has been undergoing a rapid transformation of industrialization with flourishing in Tertiary Industry from the 1980s. The urbanization rate was about 38.75% in Gansu Province until the end of 2012, which was lower than the national average at 52.57%, ranking the fourth lowest in the country. Increasing water demand for both environmental adaptation and urbanization gradually draw public attention (Wang et al. 2015). Provincial government had invested and subsidized over 0.51 billion USD on large water projects from 2002 to 2008 for supplementing water supply and enhancing water facilities.

Therefore, under the background of urbanization and drought area expansion in Gansu Province, many questions have not been answered yet. For instance: What percentage of changes in the economic production is driven by the changes in water scarcity? How the economic impact of water scarcity and urbanization changes the economic structure? How much rural and urban welfare will be reallocated? While government investment influenced this process, by how much did the economic outputs were changed as result of large water projects? This case study focused on both sides of water supply and water demand through the CGE modeling framework introduced above. Systematic analysis in laboratorial experiments is provided by GAMS to test relatively proportional changes in the modeling system under different scenarios. This chapter gives some insightful conclusions and implications. For further information please refer to Wang et al. 2015.

Water use for urbanization and environmental adaptation as a part of water demand is mainly provided by water engineering and financed by Central Government and Provincial Government. It is outside of systematic balancing but has a huge impact on economic structure and sustainable development in dry rural area. Government investment on large water projects will enhance economic efficiency but depreciate present value of social welfare in order to benefit future generation in the study area. Huge governmental financing on water projects brings present value of social welfare depreciated. Water use for municipal environmental adaptation will continuously pressurize water supply side. Water unit price can be sharply increased by water scarcity and increasing cost of factor inputs. Furthermore, increasing governmental financing on water production projects depreciates present value of social welfare but benefits future generation by enhancing economic efficiency of water use.

Study on total regional water demand has to consider a general equilibrium as an analysis tool to systematically explore interrelationships and interactions at a regional extent. Thereby, based on unit price assumption in CGE Model, economic valuation of water use provides the leverage through market mechanism to analyze interaction and interrelationships between water consumption and economic activities with governmental financing. Meanwhile, one of the key issues is to release some limitation of land properties in China. However, since the nonzero transaction cost of land mobility breaks through the assumption of perfectly competitive market mechanism with zero transaction cost, increasing governmental financing on water production projects have expanded water-saving area from 2002 to 2008 in drought regions of Gansu Province. That can be considered as a compromised policy-oriented implementation of land use with water use.

Water Markets

Undoubtedly, with rapid development of industrialization and urbanization, water demand will increase in the future, and the gap between water supply and demand will be fiercer in arid and semiarid regions such as Northwest China (Cheng et al. 2014). There is an imperative need to investigate the management of water demand and the market mechanism for water allocation so that the current mode of extensive agricultural water use can be transformed. Price control and quota control are the two main water demand management strategies. The extensive quota management usually fails to reduce the water demand for the poor administrative management and less-stringent quota regulations. On the other hand, price control which is based on market mechanism has been given a high priority hoping that the reasonable price signals can regulate the extravagant water consumption and promote water conservation and the rational allocation of water resources (Huang et al. 2010).

Water Right

Water right, a prerequisite for water markets, is considered as a key water management instrument to improve water use efficiency. The way water property rights are defined may influences the decisions regarding water ownership, use and transfer, and the well-defined water rights can lead to effective allocation of scarce water among irrigators, industries and households (Hanjra and Qureshi 2010). Countries define water rights in various ways from their historical backgrounds. The systems of riparian rights and prior appropriative rights were developed in England and the Western USA. Public allocation systems, in which water is defined as public property with the state as the owner of water, and where the water rights are administratively allocated to users through water permits from governments, has been applied as an alternative.

Since water markets do not determine the initial allocation of rights, and it can come into play only when the water rights or use rights have been established. The main concerns about water rights includes: how to define and establish an efficient water rights system and the mechanism to evaluate the performance of current water rights system; the way how water rights are traded and the efficiency valuation (Grafton et al. 2013), all are needed to be considered in a water rights system. Furthermore, how to use the water rights system to improve water use efficiency, especially irrigation efficiency from interactions between different water rights and other attributes is also a hot debate.

Water Price

Water pricing has been considered as the most effective way to advance water reallocation and water conservation (Tiwari and Dinar 2002). As an important socioeconomic tool, it could reveal economic and scarcity values of water resource and encourages water users to utilize the resource more wisely. For agriculture, appropriate irrigation water pricing could guide farmers to adopt irrigation technologies with high irrigation efficiency or to change to a more productive cropping pattern (Schoengold et al. 2006).

Underpricing of irrigation water is frequently identified as the primary cause of excessive use of water for irrigation. Researchers and policy-makers reckon that undervalue of water in agriculture may lead to a chronic overuse of it. Although agricultural water demand is high, the irrigation water price is relatively low, much less than its production cost. Price leverage cannot play a significant role in the context of the current pricing regime and farmers' response to price increase is intrinsically weak.

The price elasticity of the derived demand for irrigation water is an economic measure that is often used to evaluate the effectiveness of price incentives in facilitating water conservation. Previous studies on water price elasticity and its influence on water utility revealed that the demand for irrigation water is inelastic because the price is too low (Schoengold et al. 2006). But simulation analysis has shown that when the price of water is raised to a relatively high level, the pricing can promote water savings (Huang et al. 2010). On the other hand, some scholars still doubt about water pricing effects on water saving that could lead to some socioeconomic and other external effects such as agricultural production reduction, rural poverty and overutilization of groundwater resources brought by increasing water price (Venot and Molle 2008).

To date, most of the existing studies on agricultural water use and irrigation water prices have considered the qualitative aspect only, while quantitative relationship between water demand and price has been neglected or underexamined. In order to assess the effectiveness of the pricing mechanism as a policy tool in dealing with water stress in irrigated agriculture, two key research questions need to be discussed: Is water pricing really an effective instrument in controlling water demand under current circumstance? Does increasing water price significantly promote water conservation? And if so, how will this influence farmers' decisions and crop production? To answer the above questions, studies of price responsiveness in irrigation water demand based on the water demand function have been used to figure out the relationship and influencing mechanisms between irrigation water price and water demand (Zhou et al. 2015). Also, impact of increasing water price on farmers' income, crop structure and groundwater extraction have been discussed in the following section. In the next section, we discuss about water price reforms in the Middle Reaches of Heihe River basin. This area was chosen for its severe water stress situation and substantial role of grain production in China. Consequently, based on our research findings, the appropriate policy recommendations, aiming for adaptive water management, were developed.

Irrigation Water Price Reform in HRB

Zhangye City, which is located in the middle reaches of the Heihe River, is a prefecture-level city of Gansu Province in Northwest China, and the hinterland of the Hexi Corridor. Expanding agriculture and rapid economic development result in the excessive use of water resources. The majority (99%) of water usage is for socioeconomic purposes, and of this amount, 95% is used for agriculture. Ecological and environmental water demands have not been able to be accommodated in this socioeconomic dominant system.

Low water prices have been widely disparaged for the low efficiency in irrigation systems. Farmers have little incentive to conserve water or to adopt new water-saving irrigation technologies. Agricultural water price is very low in Zhangye. Because of the low prices, farmers have no incentive to change their inefficient irrigation modes and to adopt new irrigation skills or to purchase more expensive but efficient equipment. Since price elasticity of irrigation water demand changes at different levels of water prices, the price increase will lead to the increase of the elasticity, and thus a more responsive feedback occurs between farmers and the irrigation water markets. From the year of 2015, in order to control irrigation water demand, irrigation water price reform has been launched in Gaotai and Minle as pilots. The surface water price was increased from 0.1 to 0.2 Yuan/m^3, and groundwater tariff was increased by 10 times from 0.01 to 0.1 Yuan/m^3 (Zhou et al. 2015). The sharp increase in water price may have some impacts on cutting the extravagant water demand and leading farmers to choose less water intensive crops and/or higher water productivity plants, namely, the plants with higher economic return per cubic meter water. Also, the price reform will have some impacts on water saving, cropping pattern and groundwater extraction.

Influence on Water Saving

The current irrigation water price is very low in Zhangye, which can hardly cover its cost. The average surface water price for agriculture was only 0.071 Yuan/m^3 before 2011, which was increased to 0.1 Yuan/m^3 in 2015. However, surface water is still not able to cover its cost at a price of 0.15 Yuan/m^3. The current groundwater price is very low, that is, only 0.05 Yuan/m^3. Furthermore, the irrigation cost is only a small portion of total crop farming cost, that is, less than 10% of the total input of crop production. The local government has issued a standard for levying agriculture irrigation water tariff. The water tariff consists of two parts, the basic tariff and the metering tariff. Charges for canal, pipeline, and drip irrigation use a unified price. For groundwater, the cost of irrigation is primarily the expense of power and pumping equipment. Water resource itself is almost free. No restriction is imposed on the volume of water extraction in each well, though digging new wells in principle requires the approval of water authorities. Farmers measure their irrigation cost by electricity and fuel bills and the concept of water cost is generally absent. In this context, the number of wells has been thus continually increasing in recent years. Based on the average amount of irrigation water per hectare, the water demand shows a slight decrease trend when facing an increasing water price. It indicates that increasing water price helps to promote water saving and induce a transform of the traditional irrigation mode.

Generally, different water rates may develop significantly varying water utilization behaviors considering the cost for implementing water conservation technologies. When the price is far below the cost adoption of new technology, the traditional irrigation mode will not be altered and water saving will merely come from reduction of irrigation water. But when price is increased to the level where its cost is higher than the cost of new technology adoption, new irrigation technology will be promoted and the extravagant irrigation mode will be given up.

Considering the current low water price elasticity of irrigation water demand in Zhangye, implementation of the price instrument may not be too effective in the present situation. Another problem needs to be considered is that when water price is higher than groundwater extraction cost, farmers will have the motivation to dig more wells and use more groundwater for irrigation. Currently, well management is not strict and overextraction of groundwater is a common practice in Zhangye and in many other China’s cities. Though the sole increases of water price may not be very effective at current stage, price leverage together with other measures, such as quota system, can still be a potential instrument for alleviating the increasing water demand.

Influence on Cropping Pattern

Since the 1950s, Zhangye City has been a commercial grain production base established by the Central Government of China. It has a double cropping system with wheat growing in winter and maize in summer. Before year 2000, more than 70% of sown area in Zhangye was wheat and maize. In recent years, changes in agricultural policy in China have allowed farmers to choose their crops and thus more cash crops (such as alfalfa and vegetables) were planted in order to increase farmers' income. In 2008, the sown area of vegetables increased by nearly 20%. However, grain farming still remained dominant in Zhangye City. Water-intensive crops such as maize and wheat are still grown as main crops. Among these crops, maize is the most water intensive one. The average water requirements during the growing period for wheat and maize are 602 mm and 500 mm, respectively. Although water resource is limited, farmers still cultivate maize over large areas, and thus consume more water as compared to other crops. Recently, with the intensification of water scarcity, shifting to higher added value crops has been strongly encouraged.

The rationale behind this is that the shift could generate higher output value with a given amount of water, indicating higher crop water productivity as a result of shift. Increase of water price will also affect planting structure preference of farmers' crops in the long run. Additionally, cropping structure is more likely to be influenced by government policies and market situation. Therefore, in order to save water and increase water productivity, high water consumption for low value added crops needs to be substituted by the production of high value added crops; however, minimum grain production demand needs to be satisfied at first.

Influence on Groundwater Extraction

With limited surface water resources, increasing water price and water demand, groundwater extraction is a feasible substitution. Groundwater for irrigation has been increased by more than 70% since year 2000, and the number of wells has been increased by 25% in Zhangye.

In Zhangye, each pump is operated independently and serves only a small group of farmers. The irrigation management is taken primarily by village collectives or by individual farmers who acquired well leases from collectives. The licensing system for new wells is not effective. Digging new wells is subjected only to the financial constraint and resource availability. Furthermore, as water is a free resource, the only costs are electric power and the expenses for digging wells.

Increasing surface irrigation water price may lead to a further overexploitation of groundwater considering the low price of groundwater, the unrestricted extraction of groundwater on existing wells, and no effective control on digging new wells. For this, it is imperative and urgent to implement strict groundwater management and levy groundwater resources.

Imposing a groundwater resource levy may not completely alleviate water scarcity. For this reason, introducing the groundwater resource levy must be taken in parallel with a restriction on the total volume of water-withdrawal, an improvement in water saving irrigation technologies, and promotion of industrial transformation.

Farmers' Response to Increased Water Price

The perverse impacts of water price increases on agricultural output and farm income are partly because the current water price is far below the shadow price of water resources, which is estimated as the marginal product value based on the production function theory. When price is far below the shadow price, farmers have little incentive to invest in the application of water-saving irrigation technologies or to reduce their sown area. When price is in the efficient price range where the price elasticity of water demand is high, pricing leverage would be an effective instrument. It would provide the necessary incentives for farmers to adapt to the rising prices by using irrigation water more efficiently, and giving up extravagant irrigation methods, such as flood and furrow irrigation, and adopting more efficient water-saving irrigation modes, such as spray irrigation and drip irrigation.

Although an increase in water price could lead to a decrease in agricultural water use, it does not necessarily mean that a water price increase would be a good measure. From experiences of other countries, farmers' water use decisions are significantly unresponsive to changes in the price of water when the elasticity is low. Large price increases would cause relatively small reductions in irrigation water use, but high negative effects on agricultural income and wealth. Moreover, if the water cost accounts for more than 20% of farmers' income, a price hike would hurt farmers' enthusiasm for production, particularly grain crops will most likely to decline when facing increasing irrigation water cost. This could have a series of implications on regional economy and trade. Food imports, especially import of cereal grains would increase. Thus, there is a trade-off between water consumption reduction and the regional agriculture and economic development based on the price responsiveness.

Furthermore, apart from the increasing production cost, the responsiveness of farmers' water use to different prices is influenced by many other factors. For instance, water management systems, market conditions, availability of substitute crops, farmers' freedom of decision-making for agricultural production, and the overall status of rural and urban economic development. All these factors need to be considered when implementing the price mechanism.

To create incentives for conserving water and improving irrigation efficiency, price mechanism should be accompanied with clearly defined and legally enforceable water rights, restricted water quota measures, and reform of water authorities and water–user associations. Furthermore, increases of surface irrigation water price may lead to the overwithdrawal of groundwater, and therefore, effective groundwater licensing and levying must take place to limit the total volume of groundwater withdrawal. In nutshell, improving irrigation efficiency through better management and the adoption of water-saving technologies is the ultimate way to deal with the challenges faced by irrigated agriculture in the middle reaches of the HRB.

River Basin Management Comparisons

Rivers and river basins are important components for acquiring and protecting water resources, which play an important role in ensuring the sustainable water supply for ecosystem services and human well-beings. The inland rivers in Northwest China are good cases with the context of extensive economic development and contemporary transformation and policy reforms. The North and Northwest China account for half of the total area of the nation, but only have less than 20% of the total available water resources (Bakker 2012). Meantime, considerable progress in integrated river basin management strategies has been made in both theory and practice in some developed countries. Studying the river basin management in the developed countries and making comparisons between their river basin management strategies can provide useful guideline for the river basin management in developing regions such as the Northwest China. However, until now, very few studies have paid attention to the river basin similarities and made comparison analysis between specific river basins in different countries. Some of the previous research works by Chinese scholars summarized the lessons learned from the Murray–Darling Basin (MDB) by introducing the river basin management approaches and the Integrated Catchment Management Strategy. However, one gap is that they did not provide specific guidelines about how these approaches can be used in China's river basins. Also, these research works did not incorporate the most recent initiatives of the river basin management. In the recent research works, the management modes of the MDB in Australia have been analyzed in terms of the basin scale management, three-layer organizational coordination system, marketization as well as the agreement between states. However, they did not provide specific cases in China.

What are the similarities and differences of the typical river basins in terms of the physical conditions, water problems, as well as the river basin management strategies? To what extent can these water management strategies be used as guidelines for integrated river basin management in rapid developing countries with arid or semiarid climate conditions? This chapter answers these questions by comparing the river basin management strategies of three important river basins: the Heihe River Basin (HRB) in Northwest China, the MDB in Australia and the Colorado River Basin (CRB) in the USA which show comparable characters and similarities in the hydrological contexts and river basin activities.

Hydrology Context of the Three Basins

The HRB is one of the typical inland river basins in Northwest China. Geographically, it has three reaches with hydrological variation. The upper reaches in Qilian Mountain belong to the northern margin of the Tibet Plateau. It is the headwater of Heihe River as well as the runoff area, with abundant rainfall and less evaporation. Being the oasis of the Hexi Corridor and the desert plain, the middle reaches are the key areas for agriculture and it is the grain base for Gansu Province (Wang et al. 2015). The lower reaches in north of the Langxinshan Gorge form the oasis in Inner Mongolia, making it an essential ecosystem barrier of North China (Deng and Zhao 2015).

The MDB is one of the largest and one of the driest river systems in the world. It contains Australia's three longest rivers: the Darling River (2740 km), the Murray River (2530 km), and the Murrumbidgee River (1690 km) (Banks and Docker 2014). Geographically, the MDB is divided into the northern basin and the southern basin. The southern MDB, which includes the Murray and Murrumbidgee Rivers, is where the majority of water resources are found, and it is also where the around 90% of the water extraction come from. The region is fed by winter rains and snowmelt from the high country along the Western slopes of the Great Dividing Range. The northern MDB receives most inflows from tropical summer rains in Queensland and northern New South Wales. The rivers flow from inland to the west, crossing expansive semiarid plains. The Darling River enters the Murray at Wentworth, which flows into South Australia before turning south towards the Southern Ocean. The basin diverse environments and nationally significant and iconic tourist destinations are ideal for a wide range of recreational activities.

The Colorado River is one of the critical rivers of the Southwestern USA. Rising in the central snowcapped mountains in the north central Colorado, the river flows generally from southwest across the Colorado Plateau and through the Grand Canyon before reaching Lake Mead on the Arizona–Nevada border, where it turns south towards the international border. After entering Mexico, the Colorado approaches the large Colorado River Delta at the tip of the Gulf of California, between Baja California and Sonora. The river and its tributaries (the Green, the Gunnison, the San Juan, the Virgin, the Little Colorado, and the Gila Rivers) are called the CRB, which constitutes one-twelfth of the USA's continental land area. Ninety-seven percent of the CRB watershed is in the USA. Seven Western states in the USA and part of the Mexico get beneficial interests from the CRB.

Drought and Irrigation

The water availability varies across the MDB, CRB, and HRB; the annual precipitation of the HRB is much less than the MDB and the CRB. For the MDB, the dry conditions from the mid-1990s to early 2010 were dubbed as the "Millennium Drought" (van Dijk et al. 2013). This drought was mainly confined to the southern MDB and was dominated by autumn and early winter rainfall deficits in terms of the numbers of rain days and the intensity of daily rainfall events. Just as the Northwest China, Australia is one of the world's most arid countries, and around 70% of the land receives less than 500 mm rainfall per year. Similar with the MDB and the HRB, since the late 1990s the CRB has been affected by severe drought. The water storage in the basin's reservoirs dropped sharply during this period. Colorado, New Mexico, Utah, and Wyoming in the upper basin have been on the dry record, with the driest years in 2002 and 2004. Additionally, the drought from 2000 to 2007 has reduced total water storage in the CRB reservoirs from nearly full to 55% of capacity. Since precipitation and temperature patterns are important controlling factors for the droughts, this evidence strongly suggests that the extended droughts are likely to occur and the long-term water availability should be of concern. The issues on increasing aridity, more intense and frequent droughts of CRB also have been mentioned in other research works.

Irrigation practice has been the closest and probably the most widespread association of human activity with the hydrological process of the river basin system. It can be clearly noticed that the irrigated agriculture is predominant in our cases of the HRB and the MDB. Actually, dating back to the sixth millennium BC along the Nile River in Egypt, people manipulated water to sustain settled agriculture in Mesopotamia and then Egypt. Contemporarily and globally, the situation is even clearer with the fact that irrigation accounts for 70% of global water withdrawals, although these figures vary considerably across countries. Furthermore, from 1960 to 2000 the world's population more than doubled, but the cultivated land only increased by 13%. It is easy to move from this fact to assume that irrigation plays an important role in world agriculture (Haddeland et al. 2014).

For the HRB, large-scale development of irrigated farming induces dramatic increase of water demand for the last decades. The irrigation encompasses 205, 230 hectares, accounting for 91% of the area of cultivated land in the whole basin (Deng and Zhao 2015). Similarly, although Australia has a relatively small population (approximately 19 million), irrigated agriculture with water from rivers is predominant. More than 2 million people live in the MDB and more than 1.3 million people living outside the basin also depend on its water resources. During 2001–2006, the basin's population grew by 3%, lower than the national population growth of 6%, which was affected by the impact of the ongoing millennium drought (1995–2009). For the water activities, the Murrumbidgee River was the first one developed for irrigation, and is also one of the most developed rivers in Australia. The irrigated area has been increased by 26% from around 1983 to around 1996, and the amount of water increased by 76% during this period. In terms of the CRB, the Colorado River is a vital source of water for agricultural and urban areas in the Southwestern USA. It not only provides water to irrigate 15% of US crops, but also supports billions of dollars of economic activity. About 90% of the pastureland and harvested cropland in the CRB is irrigated. More than 1600 species of plants grow in the CRB.

Rapid Industrialization and Urbanization

From a global perspective, aside from the agricultural sector, the industrial and domestic sectors account for the remaining 20% and 10% of the water consumption. Nevertheless, a growing body of evidence suggests that the impact of urbanization on river systems is more severe than other land uses such as agriculture and forestry land. Urbanization can result in major changes in stream hydrology, geomorphology, water quality, and stream communities. Degradation of stream ecosystems also occurs at low levels of urban land cover. In arid and semiarid areas, the existing water resources are already at a carrying capacity level, and correspondingly there is a considerable water demand in the process of rapid urbanization and economic growth (Deng et al. 2014a). A large-scale, long-term, repeated cross-sectional study of domestic water use problems has been done in East Africa by concentrating on changes in domestic water use over three decades in nine towns and cities in Kenya, Tanzania, and Uganda, which reflect the diversity of urban environments, and living conditions.

Specifically, the Hexi Corridor, an arid area in Northwest China where the HRB is located, is a good example in this case. The water for urbanization comes at the expense of agriculture and grain production interests, which in turn renders their economic losses of water from ecosystems (Fang et al. 2007). Significant water previously utilized for agriculture has been transferred to urban systems to keep the industrial output, thus greatly affecting agriculture and grain production. Subsequently, agricultural systems and rural areas have to transfer water from ecosystems in order to lessen their economic loss. As a result, the eco-environment gradually deteriorates due to water scarcity. With the implementation of national policy on "Integrated Development of Western China," plenty of water previously used for natural ecosystems and irrigation agriculture have been saved and used in industrial and urban systems to maintain the economic development.

Similarly, some of the fastest growing urban and industrial areas in the USA are located in this Basin. In the 1990s, the states in the CRB had the highest rates of population growth in the country. Roughly 30 million people depend on the CRB for drinking water, and its waters are essential to farmers, tribes, industries, anglers, power distributors, and rafters. In 1990–2000, Arizona's population increased by approximately 40%, while Colorado's population increased by about 30%. During 1960–2009, population in the seven states of CRB region grew by more than 166.4% compared with 77.2% for the whole USA. Even though many innovative urban water conservation programs have reduced per capita uses, population growth is driving increases in urban water demands.

Management Strategies

Water Allocation

Historically, the MDB in Australia and the CRB in the USA were also once faced with the urgent problems in terms of drought and water shortage issues (Dawadi and Ahmad 2012). Accordingly, the river basin management strategies have been gradually developed after consumptive extraction and confliction in water utility in the past decades.

Water contracts, water laws and agreements are types of water allocation strategy in terms of law and institutions. The MDB is perhaps the most exotic river system, in which a world scale water reform and planning have been used to reduce consumptive extraction to better sustain river ecosystems under climate variability. The MDB began to develop the River Murray Agreement as early as the year 1914 after several years of debate, droughts, and community actions. Since then, there have been various intergovernmental agreements related to the MDB water management. In 1987, the MDB Agreement superseded River Murray Agreement followed by negotiations beginning in 1985. In addition, in response to the "Millennium Drought" (1997 to early 2010), the Water Act 2007 from the Commonwealth Government is an ambitious piece of legislation that seeks to return water allocations in the MDB to sustainable levels. It marked a distinct shift away from the principles of consensus, negotiation and balance that were central to the decision-making process in the MDB during previous decades. The first and foremost aim is to enable the Commonwealth, in conjunction with the

Basin States, to manage the basin water resources for the national interest. Also, it established the Commonwealth Environmental Water Holder (CEWH) with the objective of protecting and restoring the environmental assets of the Basin. A central aim of the Act was to centralize decision-making responsibility at the Federal Government level to both expedite adaptation and to manage the MDB as a whole, for the national interest.

In accordance with the Water Act 2007, the Murray–Darling Basin Authority (MDBA) took over the role from the MDB Commissions in 2008 as an independent, and expertise based statutory agency body responsible for overseeing water resource planning in the MDB. Aiming to provide leadership and collaborate with agencies and communities across the basin as a whole, the MDBA in its current and preceding forms has been managing aspects of the basin's water resources for many years. One responsibility of the MDBA was to prepare, implement and enforce the Basin Plan and undertaking activities relevant to jurisdictional water resources. After a policy discussion paper released in October 2010, and the Proposed Basin Plan in November 2011, the MDBA released the revised Proposed Basin Plan in May 2012, and then Basin Plan being was signed into law in December 2012. It is based on managing basin water resources in the national interest rather than on jurisdictional or sectional based views.

Similarly, the CRB has the most complete allocation of its water resources, which is known as "Law of the River." Firstly, the Colorado River Compact was negotiated between seven CRB states and the federal government in 1922. It suggested the basin be divided into an upper and lower half, with each basin having the right to develop and use a certain amount of water. Furthermore, the Compact gave to the Lower Basin the right to increase its annual beneficial consumptive use of water. In this way, it defined the relationship between the upper basin states where water supply originates, and the lower basin states where the water demands were developing. As time moves on, this compact has evolved over subsequent decades through additional federal acts, contracts, court decisions, and agreements for water from the Colorado apportioned to users (Dawadi and Ahmad 2012). The Boulder Canyon Project Act of 1928 ratified the 1922 Compact. It authorized the construction of Hoover Dam and other related irrigation facilities in the lower basin. Also, it authorized the secretary of the Interior as the sole contracting authority for water use in lower basin of the CBR.

In terms of the water agreement and lows, the California Seven Party Agreement of 1931 aimed to settle the long-standing conflict between California agricultural and municipal interests over the CRB water priorities, while the Mexican Water Treaty of 1944 committed the amount of water flow to Mexico. For the Upper river basin, the Upper Colorado River Basin Compact of 1948 created the Upper Colorado River Commission and apportioned the water for the upper states, followed by Colorado River Storage Project of 1956 provided a comprehensive wide water resource development plan and authorized the construction of projects for river regulation and power production, irrigation, and other uses. In addition to the above laws and contracts, there are several documents. All of these were collectively known as the "Law of the River."

In contrast, lacking of effective coordinated water allocation scheme, the amount of water flowing into the lower reaches has continually been decreasing in the HRB. Some of the water allocation schemes have been implemented in the HRB in small scale. For instance, there are currently two main kinds of management strategies for community irrigation in the HRB: the collective management strategy and Water User Associations (WUAs) management strategy (Deng and Zhao 2015). WUAs are independent water management organizations, which take over the village leaders to be responsible for water allocation, channel maintenance, water charges and other relevant issues in a specific village. However, these are all implemented in the regional scale and the sustainable development of inland river basins needs an appropriate coordination among all the reaches. Also, a series of the water compact, water agreement and lows can also be adopted in the HRB.

Aside from water compacts, water laws and agreements, the principles on water markets, water price, water rights, and water policy have continued to play their role on river basin management. For the MDB, water management in Australia has changed profoundly around the year 1994. In response to the poor performance of inefficient government-owned utility-based industries, the Commonwealth Government transferred water delivery responsibility to the economic portfolio, and water was included in market-based competitive reforms under the National Competition Policy. The reforms also aimed to unbundle the property rights of water extraction from the ownership of land, thereby allowing the implementation of a water markets with tradable water entitlements to optimize productive output (Skinner and Langford 2013). Some of the principles remain relatively unchanged in the continued water resource management in Australia, including water planning, water price, water policy, as well as consultation, transparency and accountability.

Also, a series of water actions including water price, water right and water bank are also implemented in the CRB. One of marked water activities in the CRB is the agriculture–urban water transfer. Historically, the majority of water diversions have been for the irrigation purpose in the Western USA. Today, agriculture–urban water transfers are taking place throughout the CRB to increase water supplies. This water transfer from agriculture rights to municipalities is particularly dominant in Denver, Las Vegas, and Phoenix. With about 80% of Western US water supplies devoted to irrigated crop production, agricultural water appears to constitute the most important, and perhaps final, large source of available water for urban use in the arid Western USA. Under the water markets, these transactions often represent “win–win” situations for buyers and sellers, as water typically shifts from lower value agricultural uses to higher value urban uses.

According, there are three modes that have been implemented in the HRB for the irrigation: water price, water tickets, and water rights (Zhou et al. 2015). For the water price mode, the government would charge some fees for water services. For the water tickets mode, the farmers need to purchase water tickets from village leaders or WUAs before the farmland irrigation activities. The water rights mode refers to the water right card issued to farmers to guarantee their water consumption rights. However, these water allocation strategies are implemented in small scale and are limited to irrigation.

Water Organizations and Water Acts

Water organizations have a long history in Australia and the USA, and play an important role in the river basin management. For the MDB, the water organizations were developed together with water agreement to effectively implement the water compacts, water lows, and agreements. At the beginning, river Murray commission was established to administer the provisions of the River Murray Agreement. Thereafter, in response to the MDB Agreement, Murray–Darling Basin Commission was established in January 1988 as a replacement of River Murray Commission to efficiently manage and equitably distribute water resources. Furthermore, in order to optimize the economic, social, and environmental outcomes, the National Water Initiative (NWI) was approved by the COAG in 2004, and it is the Australian blueprint for water reform. The NWI reconfirmed the importance of water planning in achieving ecological and environment security. Key elements of the NWI included promotion of water trading and a commitment to restore a large amount of environmental flows to the MDB. The NWI sets out a number of specific objectives including effective water planning, clear, nationally compatible and secure water access entitlements, conjunctive management of surface water and ground water resources, resolution of overallocation and overuse, clear assignment of the risks associated with changes in future water availability, effective water accounting, open water markets, and effective structural adjustment. At the same time, Living Murray Initiative was set up to return water recovered through infrastructure upgrades and water buybacks. The Murray–Darling Basin Authority (MDBA) in its current and its preceding forms has been managing the basin's water resources for many years.

For the CRB, the water banking and related authorities were established to ensure long-term offstream water supplies. The Arizona Water Banking Authority (AWBA), established in 1996 is a representative case. It aims to increase utilization of the state's Colorado River entitlement and develop long-term storage credits for the state. Some of the water institutes in state level also contribute to the water storage and supply. Aimed to recover the water stored by the AWBA, for nearly two decades, the AWBA, the Arizona Department of Water Resources and the Central Arizona Water Conservation District have been engaged in an innovative program to store Colorado River water in the aquifers of Central and Southern Arizona.

In the HRB, as mentioned above, the collective management can be referred to as a simple form of water organization, where village leaders are in charge of the village water allocation, channel maintenance, water charges, and other relevant issues to fulfill their water management duties. In contrast, WUAs is independent water management organizations, which take over the village leaders to be responsible for water allocation, channel maintenance, water charges and other relevant issues in a specific village. In terms of the water organization of the whole river basin, the year 1997 witnessed the establishment of the Heihe River Basin Bureau for integrated management of water resource in the HRB. It is a significant milestone because it has allocated the water resource for five times among the HRB with the support of scientific research from Chinese scholars to alleviate the conflicts between natural water shortage and the high water consumption. Still, the big challenge is that different counties have its own management focuses and time schedules, leading to another kind of water waste.

Water Projects

The Sustainability of Semi-Arid Hydrology and Riparian Areas (then simplified as SAHRA), which begun in 2000, was a good test to integrate scientific research to the sustainable management practices. In response to the rapidly growing water challenges due to the rapidly growing population and economy as well as climate change in semiarid or arid lands in the USA as well as in other parts of the world, the Center for Sustainability of SAHRA was founded in 2000. The main aim was to promote sustainable management of water resources by conducting water resources-related science, education, and knowledge transfer in the context of critical water management issues of semiarid and arid regions. Funded by NSF Science and Technology Center, the Center is in the University of Arizona, and numerous partner organizations also contributed to the Center.

At the end of the twentieth century, an Ecological Water Diversion Project (EWDP) was successfully implemented in the HRB by the Chinese central government. Numerous studies on water, atmosphere, ecology, and anthropogenic activities in the HRB have also been conducted. Recently, the National Natural Science Foundation of China launched a major research plan titled “Integrated Study of the Eco-hydrological Processes of the Heihe River Basin” (referred to as the “Heihe Plan”) in 2010. The “Heihe Plan” is a program that will help China advance the study of watershed science to international frontiers based on existing integrated studies of the Heihe River Basin. The scientific aim of the “Heihe Plan” is to improve the understanding of the formation and transformation mechanisms of water resources in inland river basins and the potential for sustainable management (Cheng et al. 2014).

Conclusion

Water scarcity and stress have attracted increasing attention, as water is regarded as one of the most critical resources for the sustainable development of the world. In the context of climate change and population growth, management of water resources faces pressures from different aspects, such as food security, ecological conservation, and human welfare. New thinking about water supply and demand is needed to simultaneously meet human and environmental demands for water in arid and semiarid areas. The supply-oriented approach can alleviate regional water scarcity through physical water storage and transfer, but is not the ultimate solution. A demand-oriented management by implementing market tools including price and water right can help to regulate water consumption and improve water use efficiency, but may face market failure. Holistic and integrated management approaches and innovations on how supply management, demand management and their integration can best be implemented will be necessary to develop sustainable systems so as to achieve outcomes of better economic, social, and environmental balance in arid and semiarid regions.

Integrated river management involves balancing sets of economic, environmental, and other interests. Positive trends include the incorporation of all the components of watershed, and taking the basin as a whole unit is fundamentally critical for integrated river management. Rivers in the arid or semiarid regions provide abundant topics of integrated river basin management. The arid and semiarid region in Northwest China, characterized by naturally limited water resources combined with unreasonable water utilization, is a representative case in which integrated river basin management has become a critical issue for socioeconomic development. In this study, the MDB, the CRB, and the HRB are selected as comparative cases due to the similar water issues and the experience in river basin management.

River basin management is a continuous process that involves decision-making and scientific study with the aim of achieving particular goals in the future. In order to achieve sustainable water utilization, water agreements, laws, institutions, organizations, and scientific projects all need to be improved and modified to meet different needs. Furthermore, it is necessary to develop strong communication channels between organizations, local communities, and NGO to provide social initiative and guarantee to help implementation of IWRM. Also, river basin management institutions and scientific river basin study should closely work together for integrated river basin management and development.

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Forecasting Industrial Water Demand Using Case-Based Reasoning: A Case Study in Zhangye City, China

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Contents

Introduction 34
Study Area and Data Sources 36
  Study Area 36
  Data Sources 39
Methodology 39
  CBR Forecasting Framework 39
  Case Representation 42
  Case retrieve 42
  Case Reuse and Revise 47
  Case Study and Retaining 48
  Case Attributes Weighting Based on the Back Propagation Neural Network 49
Results 51
  Validation of the CBR Model 51
  Forecasting of the Target Case 53
Discussion 53
Summary 56
Appendix 56
References 59

Abstract

Forecasting the industrial water demand accurately is crucial for sustainable water resource management. This study investigates industrial water demand forecasting by case-based reasoning (CBR) in an arid area, with a case study of Zhangye City, China. CBR uses past experience to solve new problems. Since CBR is a methodology rather than a technique, this definition makes case-based reasoning

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system be an open system, which can constantly absorb new technologies and methods, and be more conducive to the development of itself. This research constructed a case base with 420 original cases of 28 cities in China, extracted six attributes of the industrial water demand, and employed a back propagation neural network (BPN) to weight each attribute, as well as the grey incidence analysis (GIA) to calculate the similarities between target case and original cases. The forecasting values were calculated by weighted similarities. The results show that the industrial water demand of Zhangye in 2030, which is the target case, will reach 11.9 million tons. There are ten original cases which have relatively high similarities to the target case. Furthermore, the case of Yinchuan, 2010, has the largest similarity, followed by Yinchuan, 2009, and Urumqi, 2009. This research also made a comparison experiment in which CBR is more accurate than the grey forecast model and back propagation neural network in water demand forecasting. It is expected that the results of this study will provide references to water resources management and planning.

Keywords
Industrial water demand · Forecast · Case-based reasoning · Water resources management · Zhangye city · BP neural network · Artificial intelligence · Grey incidence analysis · Case similarity · Grey model

Introduction

Water scarcity is becoming increasingly severe in arid and semiarid regions of the world (Rijsberman 2006; Deng and Zhao 2015; Mekonnen and Hoekstra 2016; Katz 2015), whereby access is not only limited by water resources availability, but also by resource conservation, environmental friendliness, appropriateness of technologies, economic viability, and social acceptance of development issues (Johannsen et al. 2016). The gross amount of water resources on the earth is about 1.38 billion km^3, of which 97.5% is seawater. Only 2.5% is freshwater, most of which are polar ice snow, glaciers and groundwater. Water resources have become a bottleneck to economies all over the world (Nian et al. 2014). If there is no further action, more than 40% of countries will face a water resources crisis in 2030; arid regions will bear the brunt (Connor 2015). In order to solve the problem of water shortage, research on two aspects of open source and throttling must be carried out; water supply, water use, and water saving should be planned to guide the short-term and long-term water supply of the cities.

Industry plays a fundamental role in the national economy of China. Over the past decades, it has been proved that the forecasting results by some departments of China are obviously greater than actual water uses (Bai et al. 2017). Since the 1950s, with the rapid development of socio-economy, the world population grew sharply, the processing of urbanization moved fast, people's lives improved continuously, and the world's gross water consumption also grew rapidly. To cope with the growing demand for water resources, many countries began to put water resources management into the government functions. At the same time, planning and management departments have also begun to make the water demand forecast as the means to planning work, to achieve the macro-control of contradiction of the water resources supply and demand.

Industrial water demand forecasting is complicated due to various departments and enormous differences in industries, which were unfavorable for analysis and calculation (Deng et al. 2014). To forecast the industrial water demand accurately and scientifically is always the key point to water resources planning and management in the current socioeconomic development period. City industrial water demand forecast is based on the history of the change regulations of city's industrial water consumption data, and considering the influence of subjective factors such as society, economy, and objective factors such as weather, using scientific mathematical, to forecast city future industrial water demand for a period of time under the requirement of accuracy. According to the forecasting time of water demand and the demand of water supply system, the forecast of industrial water demand can be divided into long-term, medium-term, and short-term forecasting. Medium- and long-term forecast is based on the development of city economy, population growth, the improvement of industrial production capacity and so on, to forecast the future water demand of the whole city industry. In general, long-term forecasts can be as long as 6–10 years, or even longer, for long-term planning of industrial water supply systems; The medium-term forecast is usually 1–5 years, and refers to the annual water demand forecast in the next few years, and is used for the short-term planning of the industrial water supply system; City short-term industrial water demand forecast refers to the monthly, weekly or daily industrial water demand forecast, or in a day by the hour forecast, is usually forecast the water demand of next month, next week, next day or next 24 hours. This research introduces the medium- and long-term forecast of industrial water demand.

Scholars have applied many methods to water use forecasting. Time series methods, such as regression analysis (Adamowski and Karapataki 2010), quota method (Zhai et al. 2012), constant rate model (Mohamed and Almualla 2010), and principal component analysis (Haque et al. 2016), calculate and forecast water demand through constructing statistic models of data series. However, the industrial water demand has many affection factors, such as zone, infrastructure, industrial category, production, population, and climate, which interact with each other. Past forecasting models cannot completely simulate this nonlinear relationship, that is, there are always large uncertainties in industrial water demand forecasting. To reduce these uncertainties, nonlinear theories, such as neural network (Liu et al. 2003; Bai et al. 2014; Adamowski 2008), marginal analysis (Zhang et al. 2013), scenario simulation (Wetherhead and Knox 2000; Gato et al. 2007), and multi-model (Mo et al. 2005; Pulido-Calvo et al. 2007) have been introduced into water demand forecasting. To a certain extent, these methods have improved the forecasting accuracy; nevertheless, they still have not considered the internal mechanism of industrial water demand variations adequately. Furthermore, regardless of time series methods or nonlinear theories, they were driven by historic regulation of water demands. However, the trend of the industrial water demand is not fixed in time. With the variation of natural resources and the environment, and the adjustment of industrial policies, the simulation results of past methods did not always agree with the facts. For different periods of economic development, the evolving regulars of industrial water consumption are different. It is hard to define particular models or restrained regulations to reflect the relationship between the industrial water demand and other socioeconomic factors.

To process the bottleneck, this study proposed an approach to forecast the industrial water demand by case-based reasoning (CBR). CBR is an object-oriented method (Bello-Tomás et al. 2004; Bergmann and Stahl 1998; Reyes et al. 2015) of comprehensive analysis, and is affiliated with artificial intelligence (Shin and Han 1999). The most obvious feature of CBR is that it does not need to define unambiguous rules, but uses the underlying expression of cases, which would reduce the model construction time, and effectively solve the problems of fuzziness and uncertainty when acquiring knowledge. CBR can use historic data and choose appropriate cases to analyze and forecast accurately, without a clear internal mechanism of objects development (Kolodner 1993). CBR is advantageous in simplifying knowledge acquisition, improving efficiency and quality of problem-solving, and accumulating knowledge (Kolodner 1993; Leake 2015; Zhao and Yu 2011), and is widely applied in fields that have abundant experiences but weak theory models, such as fault diagnosis (Olsson et al. 2004; Yang et al. 2004), business administration (Madhusudan et al. 2004; Li et al. 2009; Shin and Han 2001), medical application (Fan et al. 2011; Holt et al. 2005; Huang et al. 2007), emergency management (Amailef and Lu 2013; Liu et al. 2012), land use development (Du et al. 2010; Li and Liu 2006) etc. In the long-term forecasting of the industrial water demand, the training samples and target object are at different development stages; they may present uncertainties of internal resources use level, technical transformation process, and institutional evolution. Therefore, methods constructed by paradigms may have difficulties to meet the demand of uncertain planning. Instead, CBR can avoid uncertainties and regulations of complex forecasts without a linear hypothesis (Kolodner 1993).

To forecast the industrial water demand of Zhangye City in 2030, the approach was divided into three parts: First, this research constructed an industrial water demand case base, which contains 420 original cases of 28 cities in China from 2000 to 2014. Secondly, six attributes were extracted as case attributes and weighted by back propagation neural network (BPN). Finally, this study applied grey incidence analysis to calculate the similarities between the target case and original cases, and used the similarity weighted method to forecast the industrial water demand of the target case.

Study Area and Data Sources

Study Area

Zhangye City is located in middle of Hexi Corridor, the northwest Gansu Province, between 97°20′ and 102°12′ east longitude, and 37°28′ and 39°57′ north latitude, East–West span 4°52′, 210~465 km long, South–North span 2°29′, 30~148 km wide. It covers a total area of 41.1 thousand km^2, which occupies 9.2% of the province's total

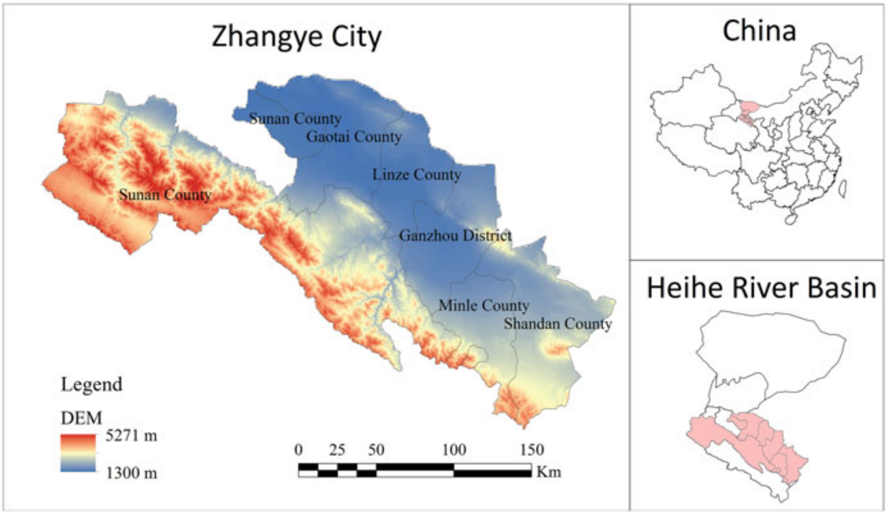

Fig. 1 Location of Zhangye City in Heihe River Basin, China (Reprinted from Yang et al. (2017) with permission of Water)

area, also accounting for 14.82% of that of Hexi Corridor (Fig. 1). Zhangye City faces the Yanzhi Mountain on the east, adjacent to Wuwei and Jinchang.

Physiographically, Zhangye City lies at the second step, the transitional zone of Tibetan Plateau and Inner Mongolian Plateau. The city is located at the wasp waist belt of Hexi Corridor, from south to north, with the three areas Qilian Mountains, central corridor plain, and Heli Mountains. Qilian Mountain in the south is 3500~5547 m above sea level, which constitutes 50% of the whole area; it is a chain of mountains which are high and magnificent. It has ice and snow glaciers, 4800 m above the sea, where the snow stays all year long. Below 4000 m above sea level, there are luxuriant forests and rich grasslands, vast tracts of primordial forest, and natural pasture. Central corridor plain is 1260~2500 m above sea level, the area covers 38.4% of the whole city. The land is flat, and the views are awesomely extensive. The landscape sloped gently from southeast to northwest, this area is noted for its rich soil, and it is an important oasis agriculture region, which consist of Zhangye Basin, Maying Basin and the piedmont alluvial plain of both south and north sides of the mountain. The oasis is flat and rich in water resources, also has adequate solar and hot resources, it provides superior natural conditions for the development of agriculture, forestry, animal husbandry, and fishery industries in the whole region. Oasis area is 0.402×10^4 km^2, accounting for 9.6% of the total area of Zhangye, which is surrounded by deserts and Gobi. It is a relatively closed eco economic system. Qilian Mountain in the south is an important water source for oases, and Heihe is the main water system for the survival and development of the oases in Zhangye. The northern mountains of Heli are at an altitude of 1600~3000 m, accounted for 11.6% of the whole area. Most of the mountains are not high with sparse vegetation; the south sides of the mountains are very steep, while the north sides are gentle. The northern mountains include Longshou Mountains and Heli Mountains, which are collectively called the North Corridor Mountains. They are the natural barrier of Zhangye from the sand storms in the north.

Zhangye is located in mid-latitude areas, in the hinterland of China, far from the sea, affected by the Qinghai-Tibet Plateau, a warm temperate continental climate. Qilian Mountains belong to the alpine semiarid climate; they have the characteristics of rich light energy, large temperature difference, short summer and light heat, long winter and cold, dry and little rain, and uneven distribution. The mean temperature of this area is 6~8 °C, 104~328 mm annual precipitation. The major catastrophically climate events include drought, dust storms, dry hot wind and frost, which caused a certain influence on the development of Agriculture. There are 26 rivers in Zhangye, water resources throughout the city a total of 2.65 million m^3, which include 2.48 million m^3 surface water amount and 18 million m^3 net groundwater resources. There are Black River, Shuyoukou River, Dayekou River, and Shandan River, which belong to inland river, and 26 seasonal small rivers and ditches. Black River is the largest river in the area, with 1.58 million m^3 annual runoff, accounting for 56.3% of the surface runoff. Glaciers are distributed in the south of Qilian Mountains, the height is usually over 4000~8000 m. The glaciers cover a total area of 110.27 km^2, 2.7549 m^3 in total reserves; they are the main supply source of groundwater in the city. The wetland resources are abundant in Zhangye, and wetland area reached 210,400 square hectares; there are mainly natural wetlands and constructed wetlands, and the value of wetland ecosystems is relatively high. Due to the irrational exploitation and utilization of water and soil resources by mankind in recent years, the ecological environment is deteriorating gradually. Land desertification, soil salinization, and vegetation degeneration are serious, river shrinking, groundwater recession, water shortage and wetland ecological degradation have seriously restricted the development prospects of the city.

Zhangye city is the largest economic zone and the largest water consumption area of the Heihe River Basin and is also a critical hub of “the Silk Road Economic Belt and the 21st-Century Maritime Silk Road” (B&R). Zhangye is a typical arid area with a continental climate. From the perspective of added value in 2016, the dominant industries of Zhangye are mining, manufacturing and electricity, gas, water production and supply. In the future, industry will continue to play an important role in Zhangye’s economy. Figure 2 shows the trend of industrial water consumption and industrial added value in Zhangye from 2000 to 2014. In general, the trend of industrial water consumption can be considered as fluctuating growth. In the current period of industrial transportation, the industrial water consumption may be greatly affected by the breaking of the water balance in Zhangye City. Therefore, it is necessary to forecast the industrial water demand scientifically and accurately in the context of excessive use of the region’s water resources due to rapid economic growth and increasing population pressure, and the result will provide a reference for water management in Zhangye, even in Heihe River basin.

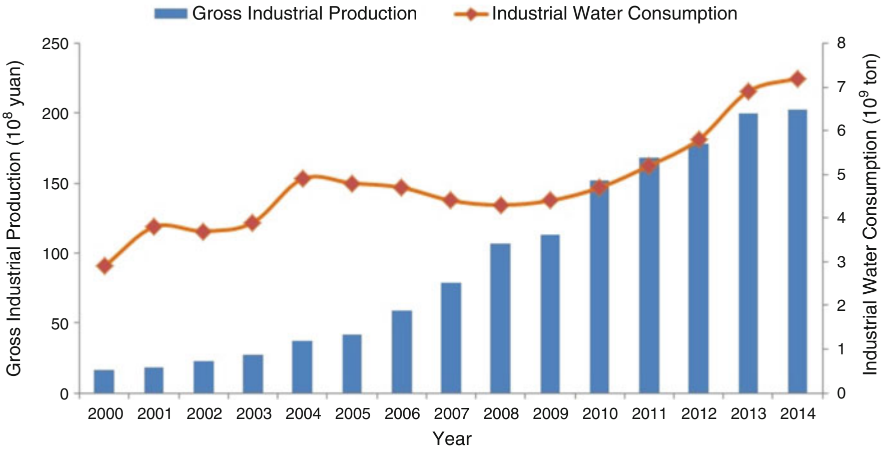

Fig. 2 Gross industrial production and industrial water consumption in Zhangye during 2000–2014 (Reprinted from Yang et al. (2017) with permission of Water)

Data Sources

The data of industrial population, per capita GDP, gross industrial production, industrial fixed assets investment and industrial electricity consumption from 2000 to 2014 were obtained from the Statistical Yearbook of each city (2001–2015). The data of industrial water consumption and gross amount of water resources from 2000 to 2014 were obtained from the Water Resources Bulletin of each city (2001–2015). Data processing and computing is based on Matlab (Matrit Laboratory), which is an advanced development environment. The weighting calculation by BP neural network, similarity calculation by grey incidence analysis, and target case forecasting by weighted similarity method are all handled on the platform of Matlab.

Methodology

CBR Forecasting Framework

Roger Schank is the first man who discovered CBR when he was studying dynamic storage technology, and he also proposed Dynamic Memory Theory in his book – "Dynamic Memory: A Theory of Reminding and Learning in Computers and People," which is known as the earliest thought of CBR. In 1985, Konlodner et al. firstly used the term of CBR in the literature, which made the foundation of CBR establishment. In recent years, CBR has been used in diagnosis, planning, economy, agriculture, design, and many other fields, and achieved significant goals. As a model of artificial intelligence developed from machine simulation of surface to deep thinking development, CBR has been widely used by cognitive science and artificial intelligence. CBR is a methodology that uses previous cases to solve new problems (Jonassen and Hernandez 2002). The core concept of CBR is based on cases or experiences, then is adjusted according to the differences between the new and the past situations to modify the original project for the new conditions, namely to get the solution of new problem as well as a new case. The four assumptions proposed by Kolodner in 1996 is the basic theory of CBR: (1) Regularity: similar problems share the similar solutions; (2) Typicality: similar problems have recurrence; (3) Consistency or relative stability: If the conditions change a little, the explanations or solutions need to be changed a little accordingly; (4) Adjustability: It is common that there is few difference between two cases, so that it is relative easily adjustable in a small error range (Jonassen and Hernandez 2002).

The basic assumptions of CBR are that similar problems have similar solutions (Zhao and Yu 2011). The paradigm of CBR processing problems is inspired by the human decision-making process (Shen et al. 2015). It collects a set of cases, which are original cases, to form a case base. Each original case has a problem and a solution. When a new problem appears, CBR can retrieve the most similar original case from the case base according to the conditions, and apply its solution to the new problem through analysis and modification. As a new original case, the solved target case and its solution will be kept to renew the case base. Therefore, the CBR problem-solving architecture, as shown in Fig. 3, typically consists of four components: *Retrieve, Reuse, Revise,* and *Retain* – commonly referred to as "*4Rs*" (De Mantaras et al. 2005). CBR has the merits that it is easy to obtain knowledge, simple to express it and fast to reason it, especially in the fields of fault diagnosis and decision support which have abundant experiential knowledge but lack strong theoretical models and a complete domain knowledge system (Kolodner 1993; Zhao and Yu 2011).

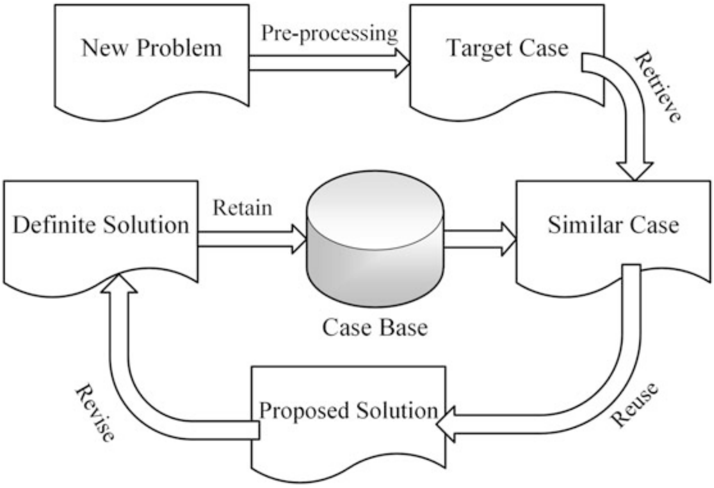

Fig. 3 Case-based reasoning (CBR) circle (Reprinted from Yang et al. (2017) with permission of Water)

Although the rapid development of statistical models has made the forecasting accuracy greatly improved, due to the multi-influence of nature, socio-economy, management, and policies, a lot of information contains uncertainties such as randomness and fuzziness, which makes the causal relationship extremely difficult to grasp. The estimation accuracy of the statistical model is still limited. Nevertheless, the case-based reasoning method does not have to rely on the inherent causal relationship, and is suitable for operation control of the strong nontheoretical models. On the other hand, a large amount of historical industrial water data and other related data, which has been accumulated in the process of industrial production, can be made full use to estimate the target case, and further improve the practical significance and maneuverability. Therefore, this paper used the core theory of CBR to forecast the industrial water demand of Zhangye City. Specifically, the technique flow (Fig. 4) of this paper contains four steps: Step 1 constructed the case base by integrating the data of industrial water consumptions and its attributes of 28 cities evenly distributed over China. Step 2 computed the weights of each influential factor by the back propagation neural network. Step 3 calculated the similarities between the target case and original cases by Grey Incidence Analysis. Step 4 screened out the cases with low similarities and kept the higher ones, then forecasted the industrial water demand by weighted similarity.

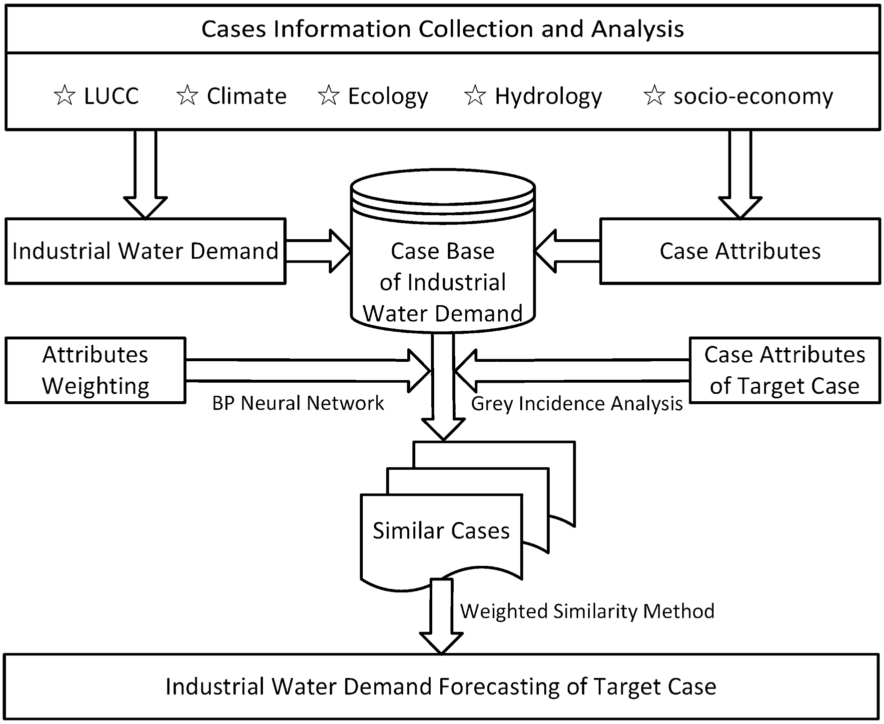

Fig. 4 CBR-based framework of industrial water demand forecasting (Reprinted from Yang et al. (2017) with permission of Water)

Case Representation

Case representation is the base and primary question for case-based reasoning processing. It describes the past problems and their solutions, and is the first step of case-based reasoning. The input case firstly can be represented through the patterns, which can be identified by the system. Therefore, the system can conduct case retrieve, case reuse, etc. According to the convenience, effectiveness, extendibility, and applied fields, case representation can use various knowledge representation of artificial intelligent for reference, such as frame description, semantic network, natural language representation, object oriented description, or 2-tuple and 3-tuple. No matter which representative method can be used, an effective case representation generally contains three comments: (1) Problem description: a description of characteristics of the problem and its surrounding environment; (2) Solution description: a description of the problem solution; (3) Effect description: a description of the result after solving the problem, in which problem description and solution description are essential for any case-based reasoning. Problem descriptions actually encode knowledge into a set of data structures that can be accepted by the computer with some signed notation. In the case content, the problem description generally divides into the case external performance and the characteristic attribute, namely the problem basic manifestation. Attribute refers to the basic characteristics, which are the main content of the case, also are the basic of the case retrieval and similarity calculation of the CBR system. However, not all attributes can have influence on the results of the CBR, and different characteristic attributes can bring different influences for the results. In order to make it more reasonable, this study introduces the concept of attribute weight, which is to reflect the important level of each attribute in computing the case similarity. Whether the weight estimation is appropriate or not will directly affect the quality of the measurement results. Then, a case's aggregate of all attributes can be represented as $F = \{(f_1, \omega_1), (f_2, \omega_2), \ldots, (f_n, \omega_n)\}$, where f and ω represent each attribute and their weight, respectively. Significantly, $\omega_i \in (0, 1)$ is the weight of the ith attribute, and $\sum_{i=1}^{n} \omega = 1$, n is the total attributes.

Case retrieve

With the increase of case's scale in case base, it must take an appropriate case index strategy to improve the efficiency of case retrieve. It usually can use clustering algorithm to classify the cases, then establish the index according to the classification results. Case retrieve is the key and core content of case-based reasoning. And it is a method of reasoning to obtain solutions to current problems by accessing the solutions of past similar problems in the case base. The result of case retrieve can be a best case, or a group of similar cases. Then synthesize the similar cases, to produce the best solution. The efficiency of case retrieve is closely related to the index structure of the case. The main difficulties of case retrieve are the following: (1) extraction of attributes from a case. The attribute information needs to be extracted whenever establishing the case base or conducting the case retrieve. In this information of attributes which needs to be extracted, if it is related to the external information of the case, such as author, title, it is always easy to handle by computer. However, when it is related to the internal attribute information of the case, such as the subject and other information, if using a manual process, there will be a very high request for processing staff of case retrieve and service. In addition, at times of numerous information resources, if the case processing is only completed by manual work, it can result in unreponsive update and nonunified processing standard. Therefore, one of the difficulties of case retrieve is extracting the attribute information timely and accurately. (2) Improving the efficiency of case retrieve system. The characteristics of case retrieve results in that only complete a large number of ordinary retrieve can achieve a successfully case retrieve. With the increase of case base, the speed of case retrieve will be slowed down, that is to say there is a linear relationship between the speed of retrieve and the case base size. The limitation of these models is difficult to accept in the fields with large base content and high real-time requirement. At the same time, in order to improve the efficiency of retrieve system, The question must be considered when designing the case retrieval algorithm is how to solve the storage and sorting of the large amount of intermediate results when in the process of case retrieve, and how to determine the retrieval correlations to the target. To obtain the solution of the case accurately and quickly is an important aspect of the evaluation of CBR system. The techniques relevant to case retrieve includes: case index establishing, case base organization, case retrieval strategy, and similarity calculation.

Case Index Establishing

The case index is like a book catalog, and is a group of important and abstract symbols, which can identify a case from the case base. In simple terms, case index is a marked feature that can distinguish a case from other cases. Therefore, case retrieve uses certain effective retrieval strategy to extract the cases which can meet the conditions of reasoning. And each case must be distributed an index to ensure it can be retrieved. Similarly, it should establish the index when inputting a new case. The index is a key point of CBR to ensure the cases, which are similar to the target case, can be retrieved constantly. The case index can be fixed, or is dynamic, which is closely related to the other case retrieval techniques. For example, only by the nearest neighbor method as the search strategy, case index can be fixed; using knowledge-directed method for retrieve, case index is constantly changing.

Case Base Organization

Case base should be organized according to the characteristics of case representation. Accurate retrieve can ensure retrieving the most similar cases, and effective retrieve can ensure retrieving the cases quickly in an acceptable period of system response. These two factors are closely related, it will not guarantee the accuracy with sacrificing the efficiency, or simply pursuit the retrieval speed to sacrifice the possible similar space. Hence, a good case base organization is closely related to a good retrieval algorithm, and strives to achieve the best balance between accuracy and efficiency. Some types of case base organization are as follows:

(1) Flat organization: It is the simplest case base organization. It is similar to a two-dimensional table of the relational database, and is consist of a group of similar records. It has the advantage of simplicity and easy to add or delete the cases. The shortcoming is that it needs to be reconstructed for complex case base configuration.
(2) Cluster organization: It stores similar cases in clusters. Its advantage is easily to choose corresponding cluster to retrieve according to the features of target case, and only needs to calculate the matching degree can obtain similar cases. The disadvantage is that if selecting the improper cluster index, narrow space case retrieve may lead to omissions of similar cases.
(3) Layered organization: It is a case base organized by hierarchy. Layered organization provides a way to find appropriate cases and speed up the retrieve. The disadvantage is the high complexity, and the cost of adding and deletion cases is great.
(4) Network organization: It is a more complex organizational structure. It is built by category, and the relationship between the index pointer and cases. This organization is good for case retrieve and reasoning. The drawback is difficult to establish an effective network organization, and the complexity of adding and deleting cases is higher.

Case Retrieval Strategy

Currently, the most frequently used methods for case retrieve are K-nearest Neighbor (KNN), Inductive Retrieval, Knowledge Guidance, Template Retrieve, etc. (1) K-nearest Neighbor: At present, most CBR retrieve models adapt the KNN, which emphasizes the one-to-one matching of case attributes. The KNN is a method of finding the closest similarity from the case base to the target case. (2) Inductive Retrieval: It is proposed by machine learning researchers when they were extracting rules from historical data and constructing decision trees. CBR systems use it to classify or index cases, and in practice, the ID3 algorithm is often used to build decision trees; (3) Knowledge Guidance: it uses current knowledge of the cases to determine which attributes are important when retrieving cases, and organize and retrieve according to these attributes. Obviously, if the corresponding knowledge is very complete, then the knowledge-based indexing method can guarantee the relative stability of the results of the case base, so that it will not change dramatically with the increase of new cases. However, it is difficult to obtain this knowledge and use the knowledge appropriately in the CBR system. In this case, many systems often combine this approach with other technologies. (4) Template Retrieval: As is similar to SQL query, template retrieval can return all cases in a range of certain parameters. The template retrieval is usually used before other technologies, for example, it can use template retrieval to reduce the search space of nearest neighbor method before using the KNN.

For a given target case, how to retrieve and choose the most similar case in the case base determines the learning and reasoning performance of the case-based reasoning system. The similarity between the cases is the key of retrieve. For assessing case similarity, it usually compares the target case with the old cases by establishing a similarity function. The common similarity measure functions are Tversky contrast matching function, modified Tversky matching method.

Similarities Calculation Based on Grey Incidence Analysis

No matter socioeconomic systems or many technical systems of forecasting science are grey system with incomplete information. Since it is a grey system, then it should be studied by the grey system theory and method. Broadly, any system is grey system due to its incomplete information and cognition. “Grey” is the basic attribute of things. If the system is very small, and has a physical prototype, then it is an intrinsic grey system; if the system is large, and lacks physical prototype, then it is an extrinsic grey system. The grey system focuses on the problem of explicit denotation but with no clear connotation, and it can also deal with the problem of both unclear connotation and extension. For industrial water demand forecasting system, its denotation and connotation are both not clear, therefore, the gray system theory can use its advantages.

Grey incidence is a basic concept of the grey system. The grey incidence refers to the uncertain relationship between things, the factors of the system, or the factors and the main behaviors. Grey system theory takes disadvantages and shortcomings of the traditional factor analysis method and fuzzy theory processing method into account, and adopts the grey incidence analysis as the system analysis. Grey incidence analysis is the basic content and one of the essences of the grey system theory. The basic task of grey incidence analysis is based on the micro or macro geometry approaches of behavior, to analyze and determine the influence degree of factors, or contribution measure of factors on the main behavior. As a development system, incidence analysis is actually a quantitative analysis of the dynamic development trend, more precisely, is a comparative analysis of the development trend. The comparison of these factors is essentially the analysis and comparison of geometric shapes between geometric curves, namely, the closer the geometry is, the closer the development trend is, and the greater the correlation degree is. The calculation of correlation coefficients is a quantitative analysis of correlation degree between the factors. Therefore, factor analysis according to this method, at least there will be no exception which makes a positive correlation as a negative correlation. Moreover, the grey incidence analysis has no requirement about the sample size, as well as the typical distribution. Thus, it has been widely used in factor analysis, decision making and the comprehensive.

Whether it can retrieve reasonable cases, thus obtaining the optimized solution, is key to the success of a CBR model. The case retrieve of the CBR system mainly depends on the similarity calculation between the target case and original case. Accordingly, the grey incidence analysis (GIA) brings a new thought to similarity calculation of cases. GIA is one of the most important parts of grey system theory. It is also the cornerstone of grey system analysis, modeling, forecasting and decision making. GIA is an important technical analysis method. It can serialize and model the grey relationship, which has no clear operating mechanism and physical prototype. GIA is a new method of factor analysis. It can quantitatively analyze the dynamic process of the system to examine the relevance of system factors. And it is a comprehensive method combined with quantitative and qualitative analysis. The basic idea of GIA is to judge the degree of correlation according to the similarity degree of the sequence curves of the factors. If the shapes of the two curves are similar to each other, the correlation degree is high. On the contrary, the degree of association is low. GIA is carried out in the factor space composed of system factor set and grey incidence operator set. The grey incidence refers to the uncertain association between the system factors and between factors to the system principal behavior. The basic task of GIA is based on the micro or macro geometric proximity of behavior factor sequences to analyze and determine the degree of influences between factors or the contributions of factors to principal behavior. The essence of incidence analysis is a whole comparison, which is a reference system and a quantitative comparison.

In mathematical statistics, regression analysis, variance analysis, and principal component analysis are methods for system analysis. These methods have the following shortcomings: (1) A large amount of data is required, because the small is difficult to find the statistical rules; (2) The relationship between each factor and the system characteristic data is required to be linear, and the factors are independent of each other; (3) The sample data is required to obey a typical probability distribution, but in practice, this requirement is often difficult to be satisfied. Especially in our country, the statistical data is relatively limited, and the existing data has large gray scale, so it is difficult to find typical distribution rules for many data; (4) With the large amount of calculation, the process is complex and tedious; (5) The phenomenon of quantitative results inconsistent with qualitative analysis may lead to distortions and reverses of system relations and regulations. To some extent, GIA covers the shortages well. It is applicable for the sample amount and sample rules. And the calculation is quiet small, the application is very convenient, and the results of the analysis generally coincide with the qualitative analysis. Therefore, grey incidence analysis is a more practical and reliable method of analysis in systems. In comparison with other methods, GIA had a better applicability in this research, and could also compute the degrees of correlation accurately.

Assuming the case set has n cases, namely the original case set $C = \{C_1, C_2, \ldots, C_n\}$; each case has m attributes, namely the factor set of the original case $F = \{f_{i1}, f_{i2}, \ldots, f_{im}\}$, $i = 1, 2, \ldots, n$; the target case set $T = \{T_1, T_2, \ldots, T_q\}$ and the factor set of target case $A = \{a_{p1}, a_{p2}, \ldots, a_{pm}\}$, $p = 1, 2, \ldots, q$. Thus, the n dimensional weighted grey similarity ($G(T_p, C_i)$) between target case (T_p) and each original case (C_i) can be expressed as:

$$G\left(T_p, C_i\right) = \sum_{j=1}^{m} \omega_j \times \rho\left(a_p(j), f_i(j)\right) \tag{1}$$

$$\rho\left(a_p(j), f_i(j)\right) = \frac{\min\limits_i \min\limits_j \left|a_p(j) - f_i(j)\right| + \lambda \max\limits_i \max\limits_j \left|a_p(j) - f_i(j)\right|}{\left|a_p(j) - f_i(j)\right| + \lambda \max\limits_i \max\limits_j \left|a_p(j) - f_i(j)\right|}, \quad \lambda \in [0, 1] \tag{2}$$

where ω_j is the weight of the jth influential factor; $\rho(a_p(j), f_i)$ represents the similarity of the jth factor between the target case and the original case; λ is discrimination coefficient values 0.5 by experience.

Case Reuse and Revise

After case retrieval, one or more original cases with the relative high similarity to the target case will be obtained, and then provide the CBR system using the retrieved case based on the solution to the problem or results to solve new problems. This process is called case reuse. Case reuse process through some reuse patterns, using attributes of similarity cases for the target problem for constructing reuse solution. The reuse solution can be modified, or be used as the final solution of the case. Case reuse patterns have essential influences on the accuracy of the reuse solutions. This study used weighted similarity method to conduct case reuse. Besides, the process of deciding how to deal with a target case based on the results of case reuse is called case evaluation. There are two kinds of case evaluation results: (1) After the case reuse, if a good result is achieved, the case solution obtained by case retrieval can help the user to solve the problems encountered, and then can enter the case preservation phase; (2) The effect of case reuse is not good, that is, the solution of similar case obtained by case retrieval cannot help the user to solve the problem well, then it can enter the case correction stage. There are five attributes for the case evaluation: (1) correctness; (2) independence; (3) compatibility; (4) continuity; and (5) redundancy.

Case revise is acknowledged to be the most challenging problem in case-based reasoning systems. Because the case reuse is essentially using the old problem solving experience to deal with new problems, thus obviously, no matter how rich actual experience may not be able to solve the current problems, that means it needs to revise the reused cases. In the specific application of the technology, the case is mostly revised in a rule-based manner to suit the new situation. Due to one of the main reasons to use CBR for problem solving is the lack of domain knowledge, through CBR can circumvent the problem of knowledge acquisition. However, using a rule-based manner will face the problem of knowledge acquisition (or rules extraction), which means it go back to the perennial problem of expert system. With the diversity of the real world, it lead to the concrete analysis of concrete problems in the case revise, without relatively consistent method.

In many ways, case revise is the only weakness of case-based reasoning systems. Although on many occasions the revise is useful, but not essential. In the foreseeable future, revise can only be used for specific problems and specific analysis. In fact, many successful case-based reasoning system are not modified, but directly applied the retrieved original cases to new problems. They are only the case retrieval system, and the users decide to whether they can be revised according to the actual situations. Considering the success rate of retrieving matching case, which can ease the dependence on case revise. Thus, the improvement of CBR technology is mainly reflected in case retrieve. In other words, the rationality of case retrieval strategy has a direct impact on the implementation of the whole reasoning system. In case-based reasoning system, make a good retrieval strategy and optimizing the weights of the attributes of the case is the key to improve the accuracy of case retrieve. Therefore, the research of case retrieval mechanism has become a main research direction of case-based reasoning.

In most cases, the similar cases retrieved from case base need to be modified, before used as a new solution to the problem. There are many methods of case revise, such as manual-based revision, weighted-average-based revision, difference-driving-based revision strategy, automatic revision strategy based on fuzzy logic and revision model based on generalized operator. Therefore, the retrieval process was not to choose one case which has the largest similarity, but a case set inside which the similarities of every case were all above the threshold. In this research, the industrial water demand of the target case could be obtained by analyzing the features and industrial water consumptions of similar original cases. After the comparison of multiple methods, this study used the weighted-average-similarity method to forecast the industrial water demand:

$$R_p = \frac{\sum_{j=1}^{n} \left(G\left(T_p, C_i\right) \times S_j\right)}{\sum_{j=1}^{n} G\left(T_p, C_i\right)} \tag{3}$$

where R_p is the forecasting result of the pth target case; S_j is the industrial water consumption of the jth original case.

Case Study and Retaining

Case-based reasoning system is a self-learning system. When the new input problem is solved by case-based reasoning, it will form a complete new case in the process of problem solving. Since new cases may be used for similar problems in the future, it is necessary to add it to the case base and complete the self-learning function of the system. As new, typical, effective cases continue to be added, the system will become more useful, as well as learning and knowledge acquisition. However, as new cases continue to join, without proper measures, the last case base will become very large and the reasoning efficiency will be reduced. Therefore, not every new case for solving a new problem has the value of retaining. Can the new case from the processing of CBR satisfy the new client's requirement? Is it necessary to save to the case base? Is the new case compatible with the original cases from the case base? And how to reduce the redundancy of the case base? These questions are the key problems to be solved in case study and retaining. For the same or similar cases in a case base, the new cases should be abandoned and not retained in the case base. Only when the new case differs significantly from the original cases, they can be added to the case base, which is the case study and retaining. For the case study, it should not only learn from the similarity, but also learn from the usage of the cases, which can reflect the evolution of knowledge. The common method is to find out the old cases which are similar to the new problem in the case base. If the similarity is greater than a certain threshold, which means the new case may not provide new information, so it do not need to be saved. Otherwise, it can be retained.

Usually the work of case study and retaining can be divided into two categories: (1) think the biggest knowledge container is case knowledge reuse, namely abstract experience and knowledge from the knowledge container of case reuse as possible; (2) is a system based on abstract case representation, especially, such as the method of Thomas Reinartz. The primary task of the two methods is to analyze the relationship between them and the knowledge in the case base, and to evaluate the accuracy of the new method. Reinartz et al. have made important contributions in these aspects. They defined a series of indicators to evaluate the important attributes of the case and the case base. These indicators are settled in the case base, some composite index is also extended in dynamic monitoring and case base state. Case study and case base retaining is divided by Thomas Reinartz method into two steps: the first step is calculating the evaluative indexes; the second step is determining which processes of case study and retaining have to be conducted. To use fuzzy logic to represent model features is the main characteristics based on case reuse knowledge as the biggest knowledge container. By generating the fuzzy granularity on feature space, the dependence of rules on granulation feature space is mined by rough set theory, and the fuzzy relation is used to represent the multi granularity classification of generating cases.

Case Attributes Weighting Based on the Back Propagation Neural Network

The attributes of industrial water can be categorized into environmental factors, economic factors and social factors. Although environmental factors are critical to the industrial development of a city, they are also relatively stable and will not have a noticeable impact on urban industry in the short term. However, socioeconomic factors, such as rapid economic development, population growth, industrialization level and technological change, play a decisive role in urban industry. Accordingly, combining with previous studies and availability of data, this research chose per capita GDP to characterize the regional economic development; industrial population and industrial electricity to characterize the industrial scale; industrial production and industrial fixed assets investment to characterize the regional industrial level; and gross amount of water resources to characterize the constraint of regional natural environment. Hence, the above six indexes were selected as the attributes of the industrial water demand in this chapter. Due to the different impacts of each factor on the industrial water demand, it is important to scientifically and reasonably estimate the weights of each factor which may affect the forecasting accuracy. Therefore, it may lead to a large error if the weights are inadequate.

The weight of case attribute, namely the impact degree of each attribute on case matching. Only by giving different attribute to different weights, can the results of case matching be more objective to reflect the similarity between case and case. The reasonable determination of attributes weighting is particularly important for improving the accuracy of case retrieve in multiattribute CBR. Subjective weighting methods, such as the analytic hierarchy process (AHP) and the Delphi Method, may bring weights instability and one-sidedness. However, the method of the back propagation neural network (BPN) can self-adapt the weights according to the impacts of each influential factor on the industrial water demand (Ding et al. 2011). The BPN is one of the most widely used artificial neural networks (ANN) in learning methods of the feed-forward neural network (Guan et al. 2005). ANN is a mathematical model based on the principle of biological. The actual information processing is done mainly by simulating the structure of the brain's nervous system and its processing of reflection. ANN is also a mathematical structure model consisting of the system nodes (neuron) and the connection between the nodes (nerve fiber). The process of each node simulating the neuron represents the processing function of input information and output results, which is called activation function. The connection between two neurons simulated nerve fiber, represents the weighting of the input information. All the process of the information simulated the process of human brain's memory. The network itself is to simulate the biological laws of nature as a function or algorithm, so as to realize the logicality of biological expression. ANN is a comprehensive research field between artificial intelligence and computer science; its structure and composition have the common characteristics of these two disciplines. Among them, the way and method of information processing of neuron can represent mathematical models, logic rules and so on, the weights between neurons reflect whether the neurons are connected or not. The structure of artificial neural network consists of three parts: input layer, output layer and hidden layer. The input layer is the input of information and the implantation of data, and the output layer is the process of exporting the processing results. The hidden layer, which is invisible and between the input layer and the output layer, is the process and calculation of the input information. ANN is a process that can simulate the brain system processing information reflection. It exports the results, which are in accord with the expert experience, and return the diverging data and information to continue to deal with. This is a parallel loop, as well as a self-adapting and self-learning system.

BPN has the abilities of self-learning and self-adapting. The BPN has been widely applied in many fields, such as pattern recognition, expert system, prediction and signal processing, etc. In the classical structure of the BPN, the outputs of each layer are sent directly to each neuron of the next layer. A three-layered BPN contains an input layer that receives and distributes inputs, a middle (or hidden) layer that captures the nonlinear relationships of inputs and outputs, and an output layer that produces calculated data. When the weights are trained, if the outputs of the network are not equal to the expected outputs, the network will send the errors back to the input layer and the middle layer and retrain to control the errors at a very low level.

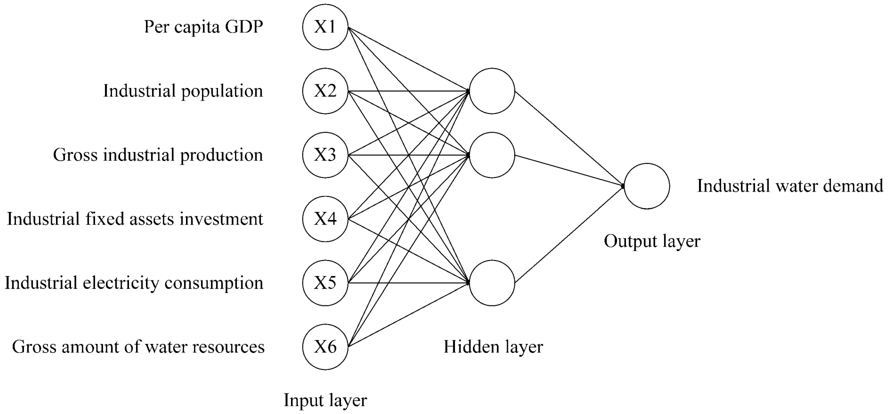

Fig. 5 Structure of the BPN to train the weights of case attributes

After the training, the weights can be obtained according to the weight matrix throughout the network. In this study, this research used 364 cases of 28 cities during 2000–2012 in which case attributes were used as input data, and observed industrial water consumptions were used as target data (Fig. 5). The training algorithm for the BPN was Traingdm. The coefficients of the hidden layer, which were the weights of each attribute, were calculated after self-learning.

After calculating the similarities between the target case and each original case, combining with the threshold (σ), whether the target case is similar to each original case could be judged. The threshold was determined by expert experience, and was constantly adjusted in the process of selection. Specifically, when $G(a_p,C_i) \geq \sigma$, namely the target case is similar to the original case, and both of them have a similar socioeconomic development level and almost the same industrial water demand. Therefore, it can forecast the industrial water demand of the target case by analyzing the industrial water consumption of similar original case/cases. Conversely, when $G(a_p,C_i) < \sigma$, there are few similarities of socioeconomic situations and the industrial water demand between the target case and original case.

Results

Validation of the CBR Model

The validation process used the data between 2000 and 2012 to forecast the industrial water demand of the years 2013 and 2014 in Zhangye City. The case set contained 364 cases by using the statistics of 28 cities in China from 2000 to 2012. Table 1 shows the weighting result of each influential factor which were calculated by the BP neural network.

Table 1 Weights of case attributes (Reprinted from Yang et al. (2017) with permission of Water)

Case attributes	Weight	Predicted value of Zhangye in 2030
Industrial Population	0.2200	39.10×10^3
per Capita GDP	0.1874	41.91×10^3 yuan
Gross Industrial Production	0.1176	37.53×10^9 yuan
Industrial Fixed Assets Investment	0.1951	19.06×10^9 yuan
Industrial Electricity Consumption	0.1247	2.37×10^9 kw·h
Gross Amount of Water Resources	0.1553	3.63×10^9 ton

Table 2 Comparison between forecasting based on CBR and observed values in 2013 and 2014 ($\times 10^6$ tons) (Reprinted from Yang et al. (2017) with permission of Water)

Year	Forecast	Observed	Relative error
2013	65	69	−5.80%
2014	73	72	1.39%

Table 3 Comparison of industrial water demand forecasts in Zhangye, 2013 ($\times 10^6$ tons) (Reprinted from Yang et al. (2017) with permission of Water)

Methods	Forecast	Observed	Relative error
CBR	65	69	−5.80%
GM(1, 1)	81	69	17.39%
BPN	55	69	−20.29%

From the above table, industrial population had the highest weight among the six features. In contrast, gross industrial production was the lowest. Then, grey incidence analysis was used to calculate the similarities between the target case and each original case. With the modified threshold σ (= 0.95), the number of similar cases according to the target cases of Zhangye City in the years 2013 and 2014 were screened by 16 and 14, respectively.

Further, these screened cases were applied to forecast the target cases by grey incidence analysis. This paper used the relative error to test the accuracy of the CBR model. The smaller the error was, the higher the accuracy would be. Table 2 gives the forecasting results in comparison with the observed value in 2013 and 2014.

The forecasting results of the industrial water demand in Zhangye City were 65 million tons in 2013 and 73 million tons in 2014. Comparably, the observed values were 69 and 72 million tons, respectively. Thus, the relative errors were −5.80% in 2013 and 1.39% in 2014. Apart from the comparison of different years, this paper also compared different methods of forecasting to make sure CBR was more suitable for industrial water demand forecasting. Table 3 illustrates the different forecast results of the Grey Model (GM(1, 1)), BP neural network (BPN) and CBR in Zhangye City for the year 2013.

From the above table, the forecast results of the industrial water demand were 81 million tons of GM(1, 1) and 55 million tons of BPN, respectively. Accordingly,

Table 4 Similar cases and similarities to the target case (Reprinted from Yang et al. (2017) with permission of Water)

City_Year	Similarity	City_Year	Similarity
Yinchuan_2008	0.9560	Urumqi_2010	0.9566
Urumqi_2008	0.9523	Xining_2011	0.9512
Yinchuan_2009	0.9600	Xining_2012	0.9530
Urumqi_2009	0.9585	Xining_2013	0.9520
Yinchuan_2010	0.9677	Zhangye_2014	0.9525

the relative errors were 17.39% and −20.29%, respectively. By contrast, the forecast result of CBR had relatively high accuracy, which suggested that the forecasting result of CBR was fully justified by real conditions of industrial water consumptions in Zhangye City.

Forecasting of the Target Case

After the above analysis, CBR can be applied to forecast the industrial water demand of Zhangye City in 2030. In light of the validation process, the case base extended to 420 cases of 28 cities from 2000 to 2014. Firstly, this study used the autoregressive integrated moving average model (ARIMA (q, d, p)) to predict the attributes' values of Zhangye City in 2030 (Table 1). Secondly, this study calculated the similarities between the target case in 2030 and each original case (Appendix A). When the threshold $\sigma = 0.95$, the number of original cases similar to the target case was 10 (Table 4). Finally, this work applied the weighted similarity method to forecast the industrial water demand of Zhangye City in 2030, which was 11.9 million tons.

Discussion

CBR uses past experience to solve new problems. The basic assumption is that the higher the similarity is, the more similar the solution is. This assumption is based on the reproducibility and regularity of objective things. Due to the repeatability of things, the similar problems with similar environmental conditions are repeatable, and the repetition of past problems can be used as reference and experience for future guidance. The regularity of the things makes the problems can be comparable and referenced, so the method of solving similar problems can be used as a useful reference for current problems. In the areas where regulations are not easily understood or structured, case-based reasoning, which provides a powerful aid to problem solving. In case-based reasoning system, knowledge is in the form of case representation. When solving problems, through the similarity of the target case and the original cases, and the use of past experience to guide the solution of the problem, thus, not every problem start all over again from the beginning. In some applications, due to the constraints of subjective, objective conditions and the environment, it is difficult to obtain the required information of solution, or is difficult to be described with accurate mathematical models or rules of structured knowledge. But it also has a large number of cases to record the environment and solving experience when problems occur. In these areas, cases are easier to access than rules and mathematical models.

A case-based reasoning system can continuously learn through problem solving, and this learning does not require training at all. When the problem is successfully solved, the problem solving experience will be retained. This learning and inductive mechanism based on CBR is easy and effective. In addition, since CBR is an incremental learning approach, as the number and types of cases increase continuously, the coverage range of problem solving is also increasing. The merits and characteristics of machine learning based on CBR make it particularly suitable for building expert systems. Since CBR is a methodology rather than a technique, this definition makes case-based reasoning system be an open system, which can constantly absorb new technologies and methods, and be more conducive to the development of itself. Functionally, CBR can be used more often as a component of an intelligent component with other methods in a system, to play its own advantages. However, from a theoretical point of view, CBR also has some demerits: (1) The judgment process of case-based reasoning relies on experience and cases. The quality of the cases in the case base has a great impact on the system; (2) Guidance on the conclusion is not strong. Because of the inherent mechanism of the grasp is not strong, so it just can provide users a scheme under the initial feeling, and the conclusion is often with loose rules; (3) Lack strict theory. Although the case-based reasoning has the support of cognitive science and artificial intelligence, it still lacks the strict theory, which also results in that case-based reasoning system is difficult to have a general and effective method in some fields, such as case revision. (4) Not achieving real intelligence. The current system and technology make it necessary for people to participate in the actual operation of the CBR system, except case retrieve. All other aspects need to be vigorously developed. The problems to be solved in these aspects are not only the problems of CBR, but also some of the bottlenecks in artificial intelligence.

In this study, industrial water demand forecasting by CBR is more accurate in comparison with GM (1, 1) and the BP neural network. However, the case base construction in this paper just considered the socioeconomic factors, but lacked environmental factors. The incompleteness of case attributes may restrain accuracy improvement. In order to construct a case base that is as comprehensive as possible, this research collected original cases with a wide coverage. Not only the industrially developed cities such as Beijing, Shanghai, and Guangzhou, but also the relatively backward ones were collected as original cases.

The BP neural network was applied to weight case attributes, which has been proved to be feasible. Although the research works of BPN has been relatively mature, using this method for our research is still faced with great challenges. On one aspect, for the applied fields, BPN is mainly used for information processing, automation, engineering, and economy, rarely for water demand forecasting. On the other hand, for the applied angle, BPN is mainly used for control, monitoring, and assessment, and its core theory is to obtain the output layer results according to input layer data and training network, without involving the weight data of the internal model. However, the difficulty of this research acted in a diametrically opposite way. In the condition of existing input and output layer data, it got the best network model through model simulation and network training, then computed the internal weighting relationship of the model. From the empirical results, the index system of the BPN model has high reliability and validity. However, the BPN also has some disadvantages, such as a poor rate of convergence, and easily getting stuck in the local minimum. Furthermore, as the BPN is based on the gradient information of the error function, when the problems are complex or the gradient information is hard to obtain, BP may be helpless. To overcome the disadvantages, many optimization algorithms have been introduced in the study and design of neural networks such as constructing a neural network based on the particle swarm optimization algorithm (Chen and Yu 2005), and using evolutionary algorithms to optimize the neural networks (Venkatesan and Kumar 2002; Harpham et al. 2004; Salajegheh and Gholizadeh 2005), which have been proved feasible and effective.

Besides, grey incidence analysis was used for similarity calculation. Compared with other data analysis algorithms, GIA method is not strict with the data. Only a small amount of sample data can be used to analyze and measure, and there are no limitations. In general, compared with the traditional algorithm, using GIA to forecast the industrial water demand based on case reasoning has advantages as follows: (1) Classically, the traditional retrieval algorithms require enough sample data. If the data is not enough, the significance of the results is not strong, and it is difficult to achieve a convincing result. However, GIA is a good solution to this problem. (2) Some of the traditional retrieval algorithms have high level requirements about probability distribution of the data. Only the data fits the probability distribution can be used, and it requires no multicollinearity among factors. But these constraints do not exist in GIA. (3) GIA has no specific requirements on data characteristics, So it can also use grey relational analysis for the sample data which do not meet the specific probability distribution. (4) The amount of calculation of traditional retrieval algorithms are particularly huge, it is difficult to achieve by relying on manual calculations, unless with the help of computer aided. GIA is simple to solve the problem that manual calculation cannot achieve.

To validate that the CBR has a relatively high accuracy in industrial water demand forecasting, a control experiment was implemented by GM (1, 1) and the BPN. The accuracy of GM (1, 1) is lower than that of the CBR, and is suitable for short-term period forecasting. The forecasting of the BPN needs more consistent internal regulations of training samples. However, each city has a distinctive driving mechanism of development mode and industrial water consumption, which makes it difficult to train the network simulation. Therefore, CBR is more appropriate for industrial water demand forecasting.

Summary

This study used case-based reasoning to forecast the industrial water demand in Zhangye City, extracted six attributes of the industrial water demand as features of the case and constructed a case base containing 420 cases. The BP neural network was employed to calculate the weights of features. This work also selected grey incidence analysis to compute the similarities between the target case and original cases. After constantly adjusting the threshold, the cases with relatively high similarities were screened to forecast the industrial water demand. Our main conclusions are as follows.

(1) The effectiveness, workability, and accuracy of CBR in the process of forecasting the industrial water demand have been validated by both longitudinal and crosswise comparisons. The forecasting accuracies reached −5.80% and 1.39% respectively in 2013 and 2014 by using CBR. Moreover, when forecasting the industrial water demand of Zhangye in 2013, accuracies of only −17.39% and 20.29% were obtained for the Grey Model and BP neural network, respectively. Therefore, CBR showed better adaptation in forecasting the industrial water demand of Zhangye in 2030.
(2) In the validation process, 13 and 11 similar original cases were screened for the target case in 2013 and 2014 respectively. Accordingly, the forecasted industrial water demands of Zhangye were 65 and 73 million tons in 2013 and 2014, respectively. In light of the validation results, the forecasting value of the industrial water demand in Zhangye in 2030 was 11.9 million tons, with 10 similar original cases.

The development of the industrial water demand has characteristics of uncertainty and fluctuation. This study proposed a CBR method to forecast the industrial water demand, which proved to provide relatively high accuracy. With the implementation of strict water resource management policies in China, the government departments are responsible for water management by scientifically planning the industrial water demand and use, which is crucial for guiding water consumption control in Zhangye as well as in other cities in China and other developing countries. Therefore, the results of this paper provide a reference for water resources management and planning, for the consideration of decision-makers.

Appendix

See Table A1.

Table A1 Similarities between Original Cases and the Target Case (Industrial Water Demand of Zhangye in 2030) (Reprinted from Yang et al. (2017) with permission of Water)

Cities	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Hefei	0.9057	0.9109	0.9070	0.9072	0.9052	0.9090	0.9209	0.9066	0.9093	0.9100	0.8582	0.8371	0.8042	0.7794	0.7104
Guangzhou	0.7721	0.7963	0.7949	0.7248	0.7150	0.7122	0.7547	0.7502	0.7167	0.6338	0.6845	0.6931	0.6740	0.6559	0.6122
Fuzhou	0.8711	0.8686	0.8691	0.8820	0.8508	0.8371	0.8404	0.8117	0.7913	0.8182	0.8044	0.7972	0.7769	0.7473	0.7062
Guiyang	0.8908	0.8854	0.8834	0.8910	0.8991	0.8825	0.8933	0.8898	0.8743	0.8940	0.8894	0.8877	0.9123	0.8821	0.8821
Xining	0.9023	0.9019	0.9020	0.9057	0.9067	0.8956	0.8898	0.8975	0.8954	0.9312	0.9418	0.9512	0.9530	0.9520	0.9376
Yinchuan	0.9047	0.9061	0.9073	0.9116	0.9179	0.9227	0.9312	0.9453	0.9560	0.9600	0.9677	0.9401	0.9215	0.8841	0.8748
Qingdao	0.8367	0.8397	0.8275	0.8247	0.8081	0.7875	0.7927	0.7838	0.7461	0.7221	0.6951	0.6694	0.6378	0.6105	0.6053
Suzhou	0.8239	0.8235	0.8103	0.7577	0.7258	0.6989	0.6631	0.6332	0.6132	0.5992	0.5531	0.5405	0.5212	0.5030	0.5058
Kunming	0.8654	0.8675	0.8672	0.8730	0.8762	0.8589	0.8660	0.8587	0.8630	0.8709	0.8697	0.8746	0.8669	0.8506	0.8471
Shenyang	0.8752	0.8844	0.8923	0.8989	0.8970	0.8842	0.8769	0.8804	0.8526	0.8249	0.7979	0.7802	0.7558	0.7454	0.7380
Changchun	0.8943	0.8979	0.9077	0.9154	0.9186	0.9141	0.9047	0.8942	0.8927	0.8842	0.8700	0.8594	0.8346	0.8123	0.7866
Urumqi	0.9106	0.9119	0.9153	0.9193	0.9234	0.9279	0.9330	0.9384	0.9523	0.9585	0.9566	0.9268	0.8957	0.8923	0.8802
Chongqing	0.7586	0.7605	0.7406	0.7352	0.7229	0.7130	0.7086	0.6593	0.6400	0.6316	0.6110	0.6114	0.6183	0.6053	0.5642
Tianjin	0.8076	0.8063	0.8035	0.8021	0.8016	0.8057	0.8005	0.7612	0.7126	0.6760	0.6274	0.5952	0.5849	0.5554	0.5399
Zhengzhou	0.8300	0.8241	0.8165	0.8216	0.8252	0.8296	0.8223	0.8034	0.8022	0.7851	0.7600	0.7297	0.7395	0.7256	0.7125
Chengdu	0.8349	0.8283	0.8224	0.8158	0.8073	0.7968	0.7981	0.7740	0.7570	0.7742	0.7424	0.7022	0.6598	0.6475	0.6617

(*continued*)

Table A1 (continued)

Cities	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Dalian	0.8859	0.8779	0.8917	0.9040	0.9200	0.9081	0.9050	0.8817	0.8386	0.8042	0.7790	0.7715	0.7331	0.7254	0.7127
Shanghai	0.7132	0.7093	0.7135	0.7128	0.7025	0.6817	0.6606	0.6315	0.6087	0.6054	0.5858	0.5721	0.5665	0.5550	0.5521
Wuhan	0.8295	0.8314	0.8371	0.8259	0.8386	0.8406	0.8350	0.8345	0.8134	0.7899	0.7408	0.7123	0.6725	0.6430	0.6239
Beijing	0.8001	0.8008	0.8025	0.8049	0.8078	0.7887	0.7715	0.7408	0.7489	0.7372	0.7108	0.6855	0.6833	0.6698	0.6639
Changsha	0.8558	0.8552	0.8557	0.8576	0.8568	0.8624	0.8693	0.8728	0.8700	0.8343	0.7890	0.7686	0.7187	0.6982	0.6872
Nanchang	0.8558	0.8643	0.8593	0.8647	0.8779	0.8747	0.8850	0.8934	0.8922	0.8848	0.8597	0.8391	0.7886	0.7707	0.7528
Nanjing	0.8688	0.8637	0.8640	0.8665	0.8700	0.8643	0.8604	0.7396	0.8040	0.7861	0.7461	0.7134	0.6813	0.6642	0.6656
Jinan	0.8462	0.8490	0.8519	0.8606	0.8629	0.8607	0.8642	0.8654	0.8455	0.8277	0.8023	0.7949	0.7831	0.7598	0.7495
Wuxi	0.8582	0.8564	0.8551	0.8329	0.7904	0.7708	0.7421	0.7212	0.6861	0.6729	0.6403	0.6264	0.6091	0.5997	0.5959
Shijiazhuang	0.8810	0.8847	0.8851	0.8827	0.8835	0.8659	0.8605	0.8517	0.8495	0.8434	0.8353	0.8341	0.8204	0.8002	0.7826
Xi’an	0.8899	0.8928	0.8907	0.8911	0.8922	0.8962	0.8990	0.8950	0.8930	0.8975	0.9022	0.9091	0.8821	0.8605	0.8553
Zhangye	0.9061	0.9082	0.9100	0.9087	0.9090	0.9136	0.9157	0.9179	0.9192	0.9236	0.9293	0.9347	0.9447	0.9465	0.9525

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Urbanization and Industrial Transformation for Improved Water Management

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Contents

Introduction 62
Study Area 66
Methodology and Materials 71
    Modeling Urbanization 74
    Modeling Water Allocation 75
    Modeling Watershed Hydrology and Water Supply 78

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Results and Discussion ... 80
  The Prediction of Urbanization and Industrial Transformation ... 80
  The Effect of Urbanization on Water Supply and Water Demand ... 81
  Industrial Transformation ... 82
Conclusions ... 85
Summary ... 87
References ... 87

Abstract

Urban ecosystems coupling social and biophysical processes require interdisciplinary effort. An integrated framework is explored by linking a hydrological model (SWAT- Soil and Water Assessment Tool) and an economic model (CGE-Computable General Equilibrium) for allocating the water resource to maximize the water use efficiency in a river basin in China. A case study of the Heihe River Basin is presented to illustrate how the framework can be used to analyze the water supply and demand in the process of urbanization. The industrial transformation will happen along with the urbanization, both of which will lead to rapid increase of water consumption. In addition, the rate of urbanization mainly characterized by the economic development, population growth, and water resource limitations. Therefore, the study analyzed the water demand of each county using the CGE model, with the population growth, capital accumulation, and technical progress used as exogenous variables. Simultaneously, the land use/cover change with urbanization will back to influence water supply through the hydrological process. The results indicate that the total water consumption in the middle reach of the Heihe River Basin will increase from 21.74×10^8 m^3 in 2010 to 24.35×10^8 m^3 in 2050. In addition, the results indicate that the runoff in the lower reach of urban will increase by 9.14%. The groundwater infiltration will decrease in 2050, indicating that more water can be withdrawn from Heihe River to meet the increasing water demand due to urbanization in the middle reach on condition that the ecological water demand in the lower reach remains unchanged.

Keywords

Water · Urban · Hydrology · Economy · Modeling · Industrial transformation · Water management

Introduction

Water is an essential resource for guaranteeing socio-economic development and maintaining healthy ecosystems. Less than 1% of the world's fresh water is accessible for direct human uses (Berrittella et al. 2007). Attention is increasingly being paid to water resources because of extreme pressure from economic growth and corresponding changes of the patterns of life, as well as the serious water scarcity induced by climate change and anthropogenic activities (Cai 2008). The growing scarcity of fresh water has been caused by a rapid increase in water demand to develop economies, improve the environment, support people's daily life, and sustain development in many regions of the world (Watkins 2006). However, when urban development takes place in catchments where river hydrology is strongly influenced by surface water and groundwater interactions, the evaluation of land cover change on river discharge requires investigation of a greater range of hydrological processes and not just the changes in surface runoff characteristics. Urbanization, accelerated industrialization, and increased domestic water use have aggravated the problem. World projection has shown that water consumption for most uses will increase by at least 50% by 2025 compared to the 1995 level. Water resource constraint is a critical issue facing many countries, especially those in the developing world, where rapid demographic transformation and economic development continue to cause growing water demand.

Traditionally, the agricultural sector is the largest consumer of water resources in China – more than 60% of all freshwater withdrawals are used for agriculture, most of which in the form of irrigation. As 80% of the food is produced on irrigated cropland, irrigation water plays an important role in feeding the large population. However, China is transforming from an agriculture-based towards an industrialized and urbanized economy at a fast pace. The proportion of urban population increased from 22% in 1983 to 47% in 2010. In terms of the structure of the economy, the primary sector now constitutes only 10% of the total GDP of China, compared with 33% in 1983. During the coming decades, water scarcity is expected to rise due to a rapid increase in the demand for water as a result of urbanization, industrial transformation, and economic development. Water shortage turn can become one of the bottlenecks that would hamper the further development of the regional economy. Despite the magnitude and scale of socioeconomic changes across the country, to date, there is not an integrated hydro-economic system that can simultaneously examine the national and regional impacts of primary socioeconomic forces, including urban population growth and economic structural change, on water use and allocation, rural livelihoods, and the overall economy in China.

Urbanization alters water availability by changing land use and land cover, which affect watershed hydrological processes and resulting increasing water demand. Urbanization is one of the most important anthropogenic modifications of the global environment. Urbanization presents humans with a dilemma (Foley et al. 2005). On one hand, urban development is essential because it provides convenience of infrastructure, goods and services needed by people, government, economic development, industry, and trade; on the other hand, land surface modifications occur during the process of urbanization including vegetation reduction, soil compaction, and change from impervious surfaces to impervious surfaces such as roofs, roads, and parking lots. Cities impact on the hydrological cycle in several ways by: extracting significant amounts of water from surface and groundwater sources; extending impervious surfaces thus preventing recharge of groundwater and exacerbating flood risks; and polluting water bodies through the discharge of untreated waste water. Since much of the water consumed by cities generally comes from outside the city limits, and the pollution they generate also tends to flow downstream; thus, the impact of cities on water resources goes beyond their boundaries (Hoekstra and van den Bergh 2006). Furthermore, increased area of impervious surface causes a decrease in the volume of water that infiltrates into the ground, resulting in an increase in volume of surface water and a decrease in its quality (Liu et al. 2013). In turn, the changes in hydrologic regime can have significant implications for allocating water for use in different parts of a river basin (e.g., upstream vs. downstream) to keep a balance between water supply and demand. Urban ecosystems are appropriate model systems for examining coupled social-biophysical processes (Collins et al. 2000). Ensuring sustainable water supply for urban ecosystems has been a grand challenge globally (Chen et al. 2014).

Water scarcity, which emerges when demand exceeds supply, poses unprecedented challenges to human and ecological security (Cheng and Zhao 2006). Water scarcity cannot only result from natural processes, but it can also be induced by human activities (Cai 2008; Fang et al. 2007); and it can potentially become a serious problem in the future in response to changes in climate, population, and environment. The impact of climate and environmental change on water resources availability has caused sustainability concerns around the world (Kundzewicz et al. 2007; Piao et al. 2010). Water scarcity resulting from climatic and environmental changes leads to a decrease in both agricultural production and food security (Yang et al. 2003). It can also impede socioeconomic development and endanger urban ecosystem health (Piao et al. 2010). Either physical or economic, water scarcity experienced in some regions is an artificially created scarcity such that access and availability is restricted in spite of an apparent abundance of water (IWMI 2006).

Despite agriculture is still the largest consumer of water – accounting for an estimated 72 % of the water withdrawals worldwide and over 90% in low-income, developing countries (Hoekstra and Mekonnen 2012). Water demand by municipal and industrial sectors is growing at a much faster rate (Rosegrant and Ringler 2000). Urbanization and industrialization are the engines of economic growth (Bertinelli and Black 2004) and they present some big challenges to water sustainability in both developed and developing world (Grimm et al. 2008; McDonald 2008).

China has been experiencing rapid urbanization and economic development, which have led to the fast growth of urban water demands as well as river runoff (Fang et al. 2007). Urban water demand arises from increasing population growth and economic activity in cities. Furthermore, urbanization causes an increase in impervious surface cover, which alters the hydrologic, or flow, regime of rivers and thus impacts urban metabolic system (Liu et al. 2013). Increased area of impervious surface causes a decrease in the volume of water that infiltrates into the ground, resulting in an increase in volume of surface water and a decrease in its quality.

The Heihe River Basin of Northwest China is located within arid and semi-arid climatic regions, where potential evaporation and transpiration exceed precipitation. Water supply in the region is provided by the runoff of the Heihe River. Nevertheless, in the Heihe River Basin, the utilization of water resources has already approached or exceeded its threshold (Wang et al. 2009). Water transfer from agriculture to urban sectors seems to be a good choice despite some negative effects (Celio et al. 2010; Levine 2007). Thus, facing water scarcity issues, an appropriate allocation of water resources in the Heihe River Basin is necessary in order to meet the water demand within the entire river basin. At any rate, improving water use efficiency and enhancing water security have become the key issues to local, regional, and global economies. Previous research has widely examined the trends in temperature, precipitation (Li et al. 2010), and potential evapotranspiration (Wang et al. 2009) and the spatial and temporal patterns of both green and blue water flows (Zang et al. 2012) in the Heihe River Basin or its subbasins. However, to the knowledge of the authors based on the reviews, there have been no studies to date on the effect of urbanization and industrial transformation on water balance between supply and demand in this basin.

Hydrological models allow for simulating the hydrological effects of land use-land cover change. Thus, they can help understanding the dynamics of water supply and develop more informed and adaptive strategies of water resource management. The hydrological model, namely, Soil and Water Assessment Tool (SWAT), has been widely utilized in water quantity and quality assessments at wide range of scales and environmental conditions (Castillo et al. 2014; Faramarzi et al. 2009). Applications of SWAT have been reported in rural (Kirsch et al. 2002; Saleh et al. 2000), in urbanized (Franczyk and Chang 2009) areas, and also in coastal watersheds (Castillo et al. 2014; Lee et al. 2011). In addition, the SWAT has been successfully used to simulate the hydrological processes in the small upstream watershed of the Heihe River Basin (Huang and Zhang 2004; Li et al. 2009).

In addition, to optimize and assess the allocation of water, Computable General Equilibrium (CGE) models, which are based on equilibrium prices determined with water accessibility and demand among sectors, can be utilized. CGE model has widely been used in water allocation-related studies. Some of these studies include the temporal effects of reallocating water from agriculture to recreational use (Seung et al. 2000), the allocation of surface irrigation water to improve economy-wide gains (Diao et al. 2005), and water allocation as an alternative to more storages or desalination plants (Gómez et al. 2004). Some other studies include the effects of groundwater resources regulation on agriculture and nonagriculture sectors (Diao et al. 2008), the allowable water withdrawals under different water management scenarios (Calzadilla et al. 2010), and the improvements on irrigation management to alleviate water scarcity (Calzadilla et al. 2011). In addition, a “bottom-up” CGE model has been used to evaluate the short-run effects of the Australian drought of 2002–2003 (Horridge et al. 2005).

As for the economic models that allocate water resources across sectors, there are two general approaches to estimate water use value, i.e., market-based valuation techniques and nonmarket-based valuation techniques. Nonmarket approaches include the inferential valuation method and the stated preference method. The inferential valuation method refers to the shadow price estimation when individual consumption occurs, while the stated preference method estimates users’ willingness to use water resources under various predesigned conditions. Some scholars have conducted fruitful research studies with these nonmarket methods, but generally with high uncertainty. When it comes to the market-based valuation methods, the CGE model is a typical one that is widely used to evaluate the impact of external shocks on water utilization efficiency at different scales, especially the impacts of socio-economic policies on water flow across sectors. Most studies of the CGE model mainly focused on the effects of shifting water rights and water allocation across sectors, regulation of surface and ground water resources, and water resource management.

Burgeoning economic development, in combination with urbanization, is exerting more and more pressure on national water resources in China. Improving water use efficiency is widely considered as an effective way to achieve significant water savings (Li et al. 2010). The hypothesis that industrial transformation is an important source of economic growth was initially developed in Lewis's classical model of a dual economy, which will reallocate production factors (Lewis 1954); the efficiency of factor allocation plays a substantial role in influencing economic growth through pushing productivity upward (Chen et al. 2011). Consequently, industrial transformation is recognized as a key factor in the sustainable use of natural resources in economic development.

Global water demand is projected to increase by 55% in 2050, mainly due to growing demand from manufacturing, thermal electricity generation, and domestic use, all of which mainly results from growing urbanization in developing countries (Rosegrant and Ringler 2004). As easily available surface water and groundwater sources have been depleted in many urbanized areas, cities will have to go further or dig deeper to access water or will have to depend on innovative solutions or more advanced technologies such as reverse osmosis for desalination, or reclaimed water to meet their water demand (WWAP 2015).

The contradiction between the decrease in water supply and the increase in water demand has posed a new challenge to sustainable development, although a number of international institutions have issued some water-related policies to keep a tradeoff between maintaining water supply for economic development and meeting ecological water demand. The hypothesis that industrial transformation is an important source of economic growth was initially developed in Lewis's classical model of a dual economy, which will reallocate production factors; the efficiency of factor allocation plays a substantial role in influencing economic growth through pushing productivity upward. Consequently, industrial transformation is recognized as a key factor in the sustainable use of natural resources in economic development.

Study Area

The Heihe River Basin is located in arid/semi-arid region and has been suffering from serious water scarcity (Li et al. 2009). The total basin area is 0.24 million km^2 and the average altitude of the basin is over 1200 m. The major river of the basin is the Heihe River, with a total length of 821 km, and is composed of three major reaches: upstream, middle, and downstream. Our study area includes the upstream and middle reaches of the Heihe River (Fig. 1). The upstream reach, which is the water source area, is located at southern Qilian Mountains. This region is characterized by remarkable vertical zonality; the elevation ranges from 5290 m

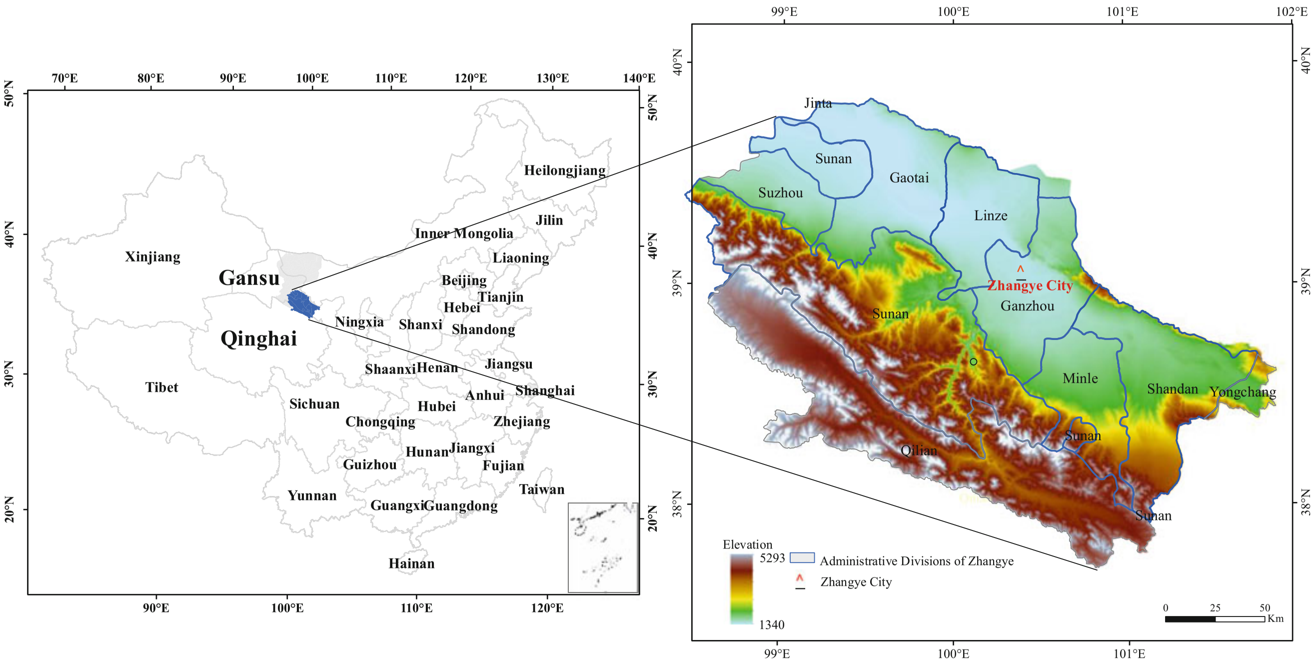

Fig. 1 Study area: Zhangye City (Reprinted from Wu et al. (2015) with permission of Ecological Modelling)

in the high-mountain zone to 2000 m in the low-mountain or hill zone. This results in a steep gradient in mean annual precipitation, which decreases from about 500 mm to 250 mm as elevation decreases. The middle reach is located between the Qilian Mountains and the deserts. The elevation in this portion of the basin ranges from 2000 m to 1340 m and the mean annual precipitation decreases from 250 mm to <100 mm, respectively. Water scarcity is, therefore, mainly created by topographic characteristics of the Heihe River Basin.

The water consumption per GDP has had a decreasing trend over the period of 2000–2010 (Fig. 2). Among different sectors, agriculture is still the largest water-consuming sector in the basin, accounting for more than 90% of total water withdrawals. Also, prior to 2002, the water consumption per GDP was merely larger than the water consumption per industrial added value; however, the gap between them has widened after 2002 (Fig. 3). The water consumption per GDP is about 30 $m^3/10^3\$$, which is twice as much as that per industrial added value, indicating a very high amount of agricultural water consumption. In addition, urbanization and the other anthropogenic activities have been increasing in the river basin, aggravating the water insecurity.

Seven counties are located in the middle reach of the Heihe River Basin: Ganzhou, Linze, Gaotai, Sunan, Shandan, Minle, and Suzhou, all of which are typical oasis counties. The total area of these counties is about 42,000 km^2, and, in 2010, the total

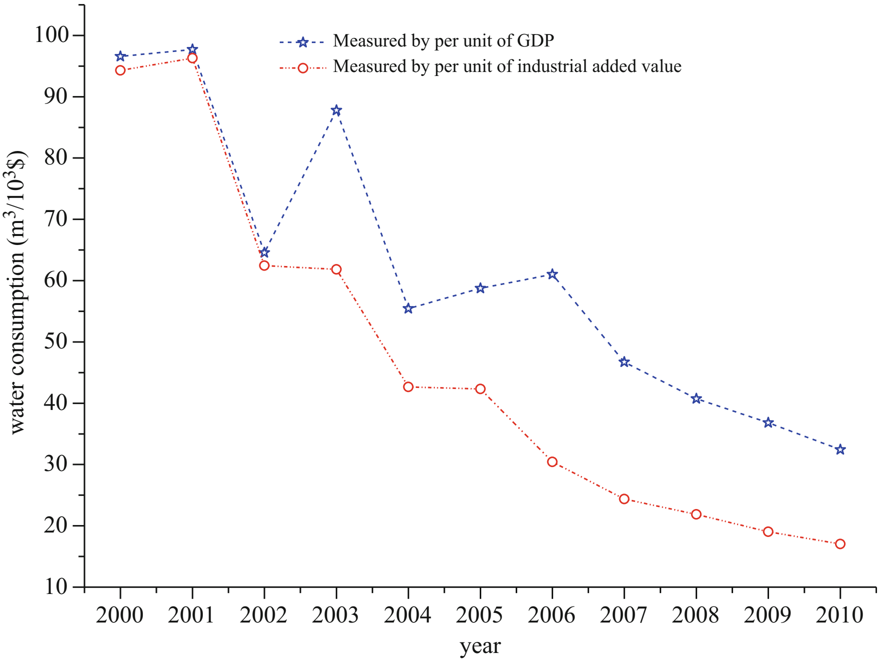

Fig. 2 Water consumption per unit of output (Data source: the Gansu Water Resource Official Reports) (Reprinted from Wu et al. (2015) with permission of Ecological Modelling)

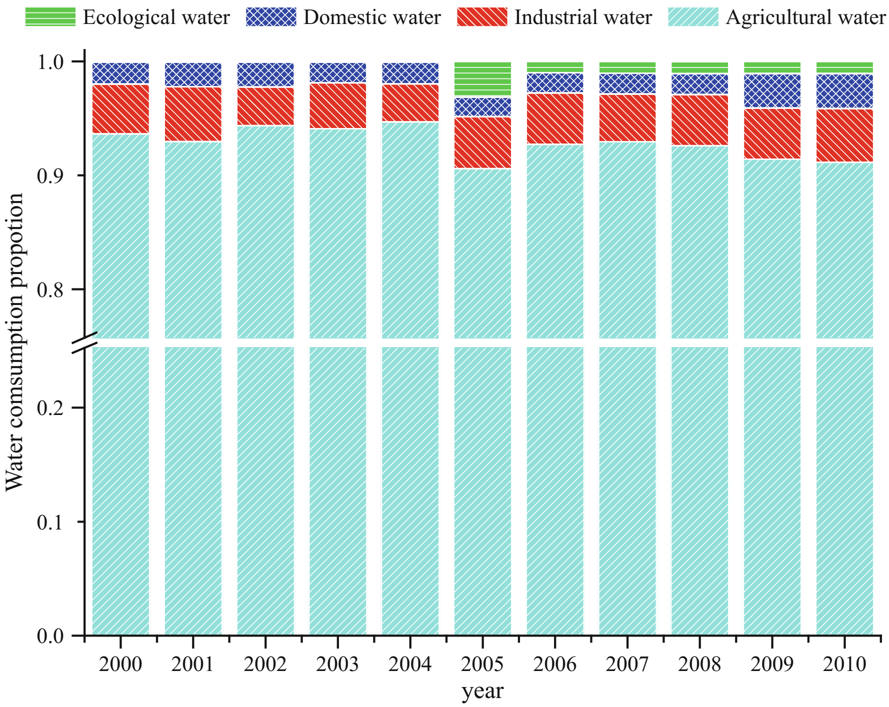

Fig. 3 The proportions of water use in different sectors (Reprinted from Wu et al. (2015) with permission of Ecological Modelling)

population is at 1.26 million, where the rural and urban populations account for 72.3% and 27.7% of the total, respectively (Wang et al. 2009). In 2010, the urbanization rate in the middle reach region was just below 30%. Overall, the total water use of the region is 2.46 × 109 m^3, 81.7% of which is supplied by the Heihe River and the rest (18.3%) is supplied by the Liyuanhe River (Li et al. 2001). Since 2001, when the integrated management and allocation strategy of water resources in the entire Heihe River Basin was implemented, the sources of water supply have been changed with a 13.0% decrease in the supply from Heihe River and a 157.6% increase in the supply from groundwater (Xiao et al. 2009). However, with the anticipated increase in urbanization and economic development, the need for freshwater will be exacerbated in the future.

Zhangye, a prefecture-level city of Gansu Province in Northwest China is located in the midstream of the Heihe River Basin and the middle part of the Hexi Corridor. As one of the most important areas during the national western development, Zhangye occupies 95% of cultivated land (2668 km^2), which includes 91% of the population, and generates more than 80% of GDP of the Heihe River Basin. Zhangye is rich in natural resources and is the main irrigated area in the Heihe River Basin. There are 26 rivers and streams in Zhangye, which contribute to annual runoff up to 2.66 billion m^3. The groundwater reserve is very abundant (Chen et al. 2014). Zhangye, with forest coverage reaching 9.2%, covers more than 217,333 km^2

grassland and 3867 km^2 woodland. Sunshine duration throughout the year in Zhangye is up to 3000 h. Zhangye is irrigated by the Heihe River, and its flat and fertile soil produces rich products, such as Wujiang rice and corn as for seed. It is one of the 12 key national commercial grain bases due to its abundant supply of wheat, corn, rice, oilseed rape, flax, and other crops. The government aimed to secure food production and economic growth; thus, irrigation agriculture became the largest user of water by far. Large investments were made in agricultural infrastructure and laws were established to protect the water rights of riparian farmers. Rapid industrialization, however, has been proved to be a significant competitor to the agricultural sector. To adjust the farming layout, transforming low-value grain commodities to high-value products is the major agricultural development goal.

Expanding agriculture and rapid economic development have induced the excessive use of water resources in Zhangye (Wang et al. 2009). According to the Zhangye Water Resource Bulletin (2008), the annual available water resources were 2.36 billion m^3 in 2007, including 2.02 billion m^3 surface water and 0.34 billion m^3 groundwater, while actual annual water utilization was 2.36 billion m^3, 99% of which was consumed by the socio-economic systems; 95% of this amount was used for agriculture (Fig. 4). Ecological and environmental water demands are severely restricted due to excessive water utilization in socio-economic systems. As a result, it seems that Zhangye has been caught in an environmental-economic dilemma due to increasing dependency on scarce water resources and further erosion of environmental quality. It is imperative to promote water use efficiency for the management of water demand in the region.

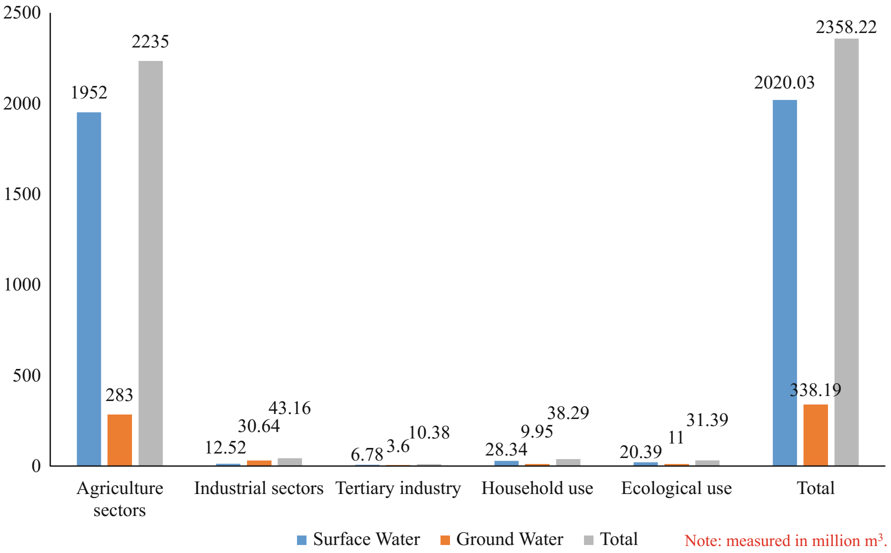

Fig. 4 Situation of water use in Zhangye 2007

In the Heihe River Basin, water supply hardly meets the demand as a whole. The extensive exploitation of water resources in the middle reach of the Heihe River has led to ecological damages in the downstream reach (Cheng and Zhao 2006). The water supply is mainly from the upstream runoff, local precipitation, and groundwater; and it is principally used for ecological, domestic, industrial, and agricultural purposes (Li et al. 2010). At present, water from the upstream and middle reaches is allocated to restore the ecological environment in the downstream reach. According to the water distribution plan imposed by the State Council of China in 1997, under normal circumstances (i.e., with a discharge of the upper reach 15.8×10^8 m^3), the middle reach should transfer 9.5×10^8 m^3 water to the downstream reach. The regulation also requires that if the discharge of upper reach is larger than 15.8×10^8 m^3, the middle reach should transfer water to the downstream reach based on the proportion of 15.8:9.5.

Methodology and Materials

Economic models of water use have been widely applied to analyze water-related policies and scenarios and their impacts on the allocation and use of water resources. These generally include partial and general equilibrium models. Partial equilibrium analysis at a catchment or basin scale is best suited for assessing sectoral policies of a region while assuming that the shifts in key parameters under alternative water scenarios will have little impact on other sectors and regions of the economy. For example, Rosegrant et al. use the IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) model to estimate demand and supply of water to 2025 at the global scale. While the IMPACT model simulates detailed future outcomes for a range of agricultural products and regions, nonagricultural sectors are excluded. However, efficient water resource management and water policy development require good understanding of inter-sectoral and inter-regional linkages and economy-wide effect of water scenario changes.

Water is widely regarded as one of the most valuable primary factors of production in economic activities. The intrinsic link between water and economies is usually ignored in most existing economic models. But without the water market, this important natural resource is usually used for free or at an underestimated price, which makes it difficult to efficiently conserve and allocate water. All the discrepancies between availability and demand, as well as sectoral and regional conflicts, bring water issues to the fore. Effective tools, such as partial and general equilibrium models, are frequently used to augment economic benefit and social welfare with limited water resources. The conceptual water flow in a CGE model is presented in Fig. 5. This water CGE model is an extended standard CGE model so that usually includes the components of factor market, consumption market, production market, government market, trade flow, and commodity exchanges as an intermediate input-output process. Commodity is produced by all firms in a sector that presents both market demand of consumption and market supply of production. Thereby, regional economic structure can be aggregated by a

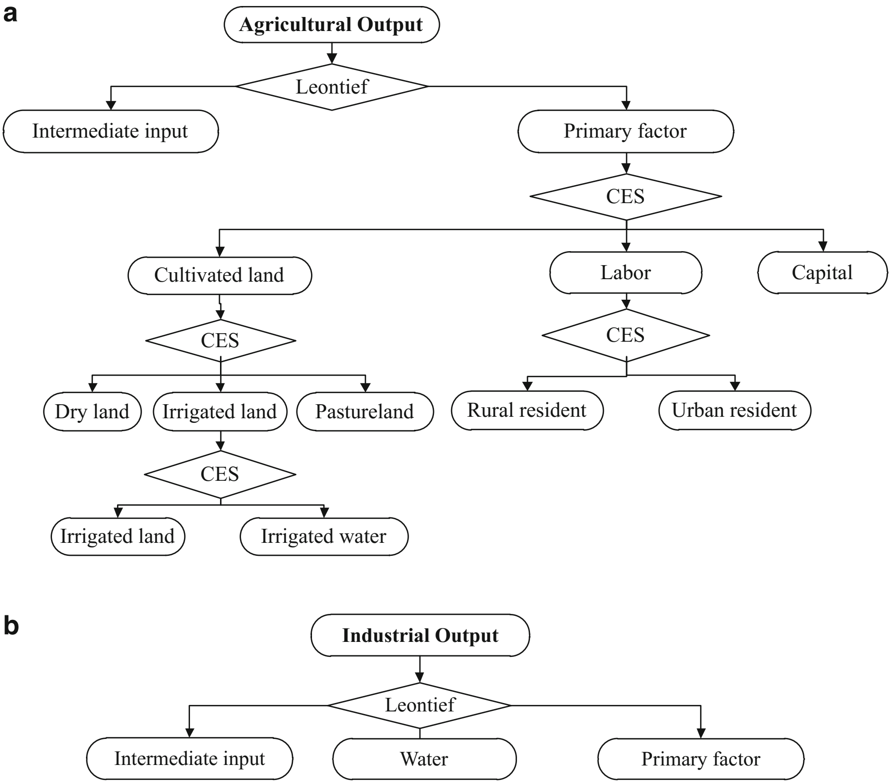

Fig. 5 Production function for embedding water resource factors. Panel (**a**) the production function of the agricultural sector; Panel (**b**) the production function of the industrial sector (Reprinted from Wu et al. (2014) with permission of Sustainability)

series of production functions to represent a practical and specific economic scale, and water may also be considered as a factor of production. The consumption markets are formed by all households which represent all family earnings and purchase. Their incomes are divided by two parts: one is from all factor income and the other one is from their salaries. For flowing money in a well-constructed circulation, households purchase connects factor market and commodity market. Water commodities purchased in the product market may not include all water use for all production process in every sector. However, it should be included into a framework of money flows the same as the other commodities. There are a wide range of models for analyzing issues of water use, such as the water pricing policy, water quality, water allocation, water markets, and irrigation policies. Most of them focus on describing agricultural sectors through a production function such as the nested constant elasticity of substitution (CES) function, the Cobb-Douglas function, and the Leontief function. These models distinguish between irrigated and rain-fed crops. In addition, some researchers have developed a multiregional CGE model to explore the impact of trade liberalization policy on water resource allocation. They proposed a theoretical framework that links trade reform with water market creation and further extended the model to distinguish surface water from groundwater.

To date, the GTAP-W model and the TERM-H_2O model are the two most renowned water-embedded CGE models. The GTAP-W model, first proposed by Berrittella (2007), is widely used to analyze related issues of agricultural water utilization at a global scale. Additionally, Glyn Wittwer (2012) has developed the TERM-H_2O model, a special version of the TERM model, to analyze the economic impacts of water shortage and water trading at a multiregional scale. In addition to the difference in scale, the GTAP-W model is a "top-down" model, while the TERM-H_2O model follows a "bottom-up" approach. In the GTAP-W model, the original land endowment has been split into pasture land, rain-fed land, irrigable land, and irrigated land. Irrigation water is nested into value-added part, which implies substitution possibilities with irrigable land and all other factors of production. By combining irrigated land and its water supply, production factors are set in a value-added nest through a CES function. The nest structure of GTAP-W is relatively simpler, but more flexible. However, in the TERM-H_2O model, water is combined with irrigable land to create irrigated land using the Leontief formulation, in which water is fixedly proportioned with irrigable land. Overall, these two models only focus on water consumption in agricultural sectors. In this study, water is considered as the primary factor of agricultural production and can be replaced with other factors. The CES function was used to analyze the factor distribution of production. In addition to the implementation of recycled waste water in the industrial sector, water serves as the intermediate input for the industrial sectors and is accounted for water supply sector. Therefore, water can be made a primary factor to flow across all sectors. In addition, capital, land, water, and labor are considered as the primary factors of production in our model. The research improved the general CGE model to consider the variance of water supply systems in different sectors, which included water in the agricultural sector and coupled water in industrial sector. The model can evaluate the effects of industrial transformation on water consumption across sectors.

As in Australia, water scarcity is a growing issue in China and China has several important river systems that support economic activities within respective watershed regions. Largely due to data limitation and model constraint, most modeling studies analyzing water issues in China focus on particular regions. On the contrary, studies about water issues in China at the national scale are scarce. In this case, treating the whole country as a single watershed region has obvious limitations in incorporating important regional variations and inter-regional linkages. Rather, a practical way is to model each watershed region of the country as a separate economy with links to other regions to account for product and factor mobility between regions. Feng et al. used a dynamic general equilibrium approach to assess the economic impacts of the South-North Water Transfer (SNWT) project. However, they divided China into only two regions – Beijing and the rest of China – and therefore provided simplified regional detail. The recent development of different versions of TERM for other nations including China and improved water accounts from the National Bureau of

Statistics of China make a more practical and complicated analysis of national water issues possible. This first requires construction and compilation of the multiregional database that includes water accounts linked to individual economic activities.

A challenge for incorporating irrigation water in the model is to identify the value of marginal product of water in agricultural production. As water is often not treated as a normal good, water prices do not necessarily reflect the marginal value of water, but may be administratively set and subject to subsidies or regulations. Inferring marginal productivity of water from water consumption levels and prices can be problematic. In this study, we value water as an input to production and use market output prices, output levels, and quantities of water consumed in each sector to determine the marginal productivity of water. The underlying rationale is that producers who use water as a variable input to their production processes choose how much to consume depending on the marginal value of that input to the value of outputs.

Modeling Urbanization

The study determines the growth in urbanization in the middle reach based on the trends in population and economic growth and water resource availability, which are the main determinants of the rate of urban growth in the Heihe River Basin. The government follows the basic principle of "developing industries which are water-saving and reducing industries which are water-consumptive"; and industrialization and urbanization are considered as the basic drivers of the socio-economic development. The capacity of available water resources has been reached and even exceeded under the changes in the industrial structure and economic development. By 2010, the resources have been utilized at a rate of 120% in Heihe River Basin, a level that is much higher than internationally recognized threshold of 40% (Falkenmark and Widstrand 1992). Hence, the limitation in water resources is one of the most important factors, which slowed down the growth of urbanization in the region and required adjustments in the region's economic structure to alleviate water scarcity and sustain its urban ecosystems.

Urban growth was characterized first by determining the urbanization of the seven counties in the middle reach of the Heihe River Basin for the period of 2000–2010 (Fig. 4) and then projecting it to 2050. Urban land growth at 2050 was predicted by allocating the land use changes determined at regional level to disaggregated grid cells using the Dynamics of Land System (DLS) model (Deng et al. 2008; Jiang et al. 2008). In addition, forecasted urban growth rate was calculated based on three different forecasting algorithms, including exponential smoothing (Huang et al. 2009), grey forecast, and regression forecast, which minimize forecast reciprocal error square sum as standard. Ordered weighted harmonic averaging (IOWHA) Operator Combination Model (Chen and Zhou 2011), with the combination of the above forecasting algorithms, was used to forecast the urbanization of the seven counties and then the results of forecast effectiveness were evaluated using the historical data from the period 2000 to 2010. The forecasts were repeated using each forecasting algorithm until a satisfactory accuracy was reached and then, the IOWHA model was used to forecast urbanization at 2050 (Fig. 4).

Modeling Water Allocation

CGE model was used to determine the future water demand and to optimize and assess the water allocation for the forecasted urbanization scenarios. In the model, the circular flow of the economy and water were represented by a set of financial transactions. The value of water changes substantially with time and space. The production and consumption functions were used to represent the economic activity of primary, secondary, and tertiary industries. In the nested structure of production function, land and water were considered as parts of the primary factors.

At the top level, the sectoral output was represented by a linear function of intermediate input and real value-added (Fig. 5). Intermediate inputs were demand with fixed input-output coefficients, which determine the heterogeneity in both technology and productivity. Real value-added was represented by a CES function of capital, labor, and an aggregate of land and water. At the lower level, the labor was represented by a CES function of rural and urban residents. The land and water aggregate was represented by a linear function of industrial land and cultivated land. In addition, the industrial land aggregate was assumed as a linear function of the land and water used in the industrial production. However, the cultivated land was a CES function of dry land, irrigated land, and pasture land. At the lowest level, the irrigated land was characterized by a CES function of land and water. Producers combine irrigable land and irrigation water according to a CES function. At this stage, only biased technical change was specified, and it represents the shift in the production technology that favors land or water by increasing its relative productivity. Thus, the demand for irrigable land and water was

$$QFE(i,j,r) = \frac{QLW(j,r)}{AFE(i,j,r)}\left[\frac{PFE(i,j,r)}{AFE(i,j,r)\times PLW(i,j,r)}\right]^{-ELLW(j,r)} \tag{1}$$

and unit cost of the irrigable land-water composite (Eq. 2) was determined as:

$$PLW(j,r) = \prod_{k\in ENDWLW}\left(\frac{PFE(k,j,r)}{AFE(k,j,r)}\right)^{SLW(k,j,r)} \tag{2}$$

where $QFE(i, j, r)$ denotes the quantity of total primary factor, $QLW(i, j, r)$ denotes the quantity of land and water aggregate, $AFE(i, j, r)$ denotes the technical change of primary factor, $PFE(i, j, r)$ denotes the price of total primary factor, $PLW(i, j, r)$ denotes the price of land and water aggregate, and ELLWjr denotes the elasticity of substitution. However, water is an intermediate input for production in secondary and tertiary sectors as follows (Fig. 3, Panel b).

$$Q_1(c,i) = X_1TOT(i) \times \left[\frac{P_0COM(c)}{P_1TOT(i)}\right]^{\sigma(i)} \tag{3}$$

where $Q_1(c, i)$ denotes the quantity of water used in the industrial sector, $X_1TOTi)$ denotes the quantity of total output, $P_1TOTi)$ denotes the price of total output, and $P_0COM(c)$ denotes the price of water in sector c.

Water supply data were collected from *Zhangye Water Resource Bulletin (2008)*, published by the Zhangye Water Resource Bureau. Water utilization data were collected from the Zhangye Water Resource Bureau and Water Supply Company and the input-output table published by the Statistics Bureau of Zhangye in 2002. The average water prices of different sectors, published by the Price Bureau of Zhangye, were used for calculating the initialized economic valuation of water use in each sector. See the following mathematical formulae.

For Water Consumption in Primary Industry (Deng et al. 2014):

$$\mathrm{WI}_{\mathrm{crop}} = \frac{\mathrm{GO}_{\mathrm{irrigated}} - \mathrm{GO}_{\mathrm{non\text{-}irrigated}}}{\mathrm{WA}_{\mathrm{irrigated}} - \mathrm{WA}_{\mathrm{non\text{-}irrigated}}} \tag{4}$$

where $\mathrm{WI}_{\mathrm{crop}}$ is the economic value of per unit water consumption in crop farming industry (CNY/m^3), GO represents the gross output of different cultivated land types (CNY), and WA is the amount of water consumption of different cultivated land types (m^3).

For Water Consumption in other industries (i):

$$WI_i = \frac{GO_i}{WA_i} \times C_i \tag{5}$$

where WI_i is the water consumption coefficient of per unit output in each industrial sector (CNY/m^3), C_i is the coefficient of water reuse in each industrial sector, GO_i is the gross output of each industrial sector (CNY), and WA_i is the water consumption of different sectors (m^3).

The main water source for Zhangye is the Heihe River, and water consumption is closely related to the category and development of industries. In Zhangye, the output values of all industries except other agriculture continued to increase during 2003–2008. The output value of the secondary industry increased significantly by 39.78% during 2003–2005 and 88.43% during 2005–2008, followed by that of the tertiary industry, which increased by 24.59% and 39.07%, respectively, during the same period. However, the output values of animal husbandry and the construction industry increased by 30% and 35%, respectively, during 2003–2005, whereas their growth rate during 2005–2008 was only 7% and 10%, respectively. Water consumption increases with the output growth, especially for the planting industry. The increase rate of water consumption was 30% during 2003–2005 and 7% during 2005–2008. At the same time, the marginal revenue of water in tertiary industry rose from 1.22 during 2003–2005 to 5.43 during 2005–2008 (Fig. 6). The abrupt decreased growth rate of water consumption

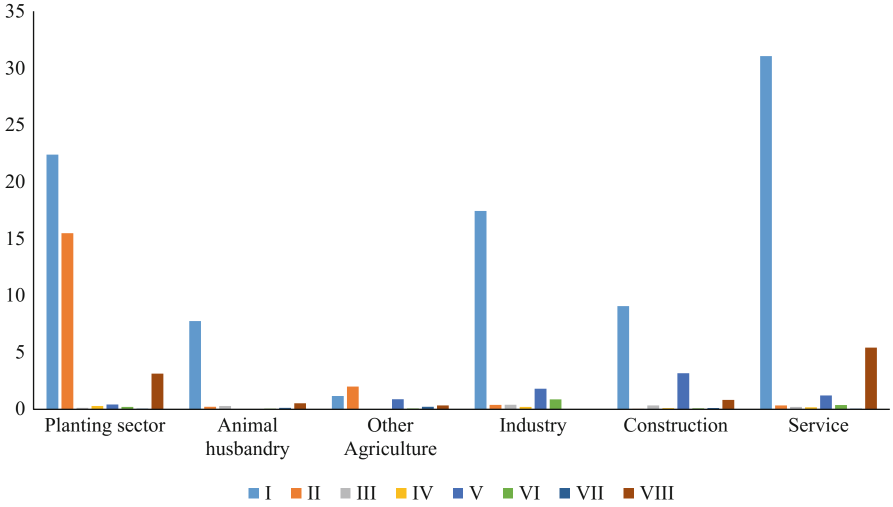

Fig. 6 Baseline of outputs, water consumption, and marginal revenue of water during 2003–2005 and 2005–2008. Note: at 2008 prices. I: output(Billion CNY) in 2003; II: Water consumption in 2003 (10^8 m^3); III: change of output during 2003–2005 (Billion CNY);IV: change of water consumption during 2003–2005 (10^8 m^3); V: marginal revenue of water during 2003–2005 (CNY/m^3); VI: change of output during 2005–2008 (Billion CNY);VII: change of water consumption during 2005–2008 (10^8 m^3); VIII: marginal revenue of water during 2005–2008 (CNY/m^3)

between the two periods, even as the irrigation water supply from precipitation held stable in Zhangye, can be explained by two factors. First, in pursuit of rapid economic development, a higher output of crops at a lower level of water consumption may occur. Secondly, improvement in water use technology led to lower water consumption.

In this model, water is the primary factor in the agricultural sectors and the intermediate input in the industrial sectors; therefore, water is embedded in the economic flow. The assumption that the data are obtained from an economy in some type of "equilibrium" is the primary condition for all CGE models (Deng et al. 2012). In the baseline simulation, the model operates in a reverse fashion with GDP, production, consumption, and international trade exogenous, and the corresponding technical and preference change variables endogenous. In the baseline simulation, the model operates according to changes in GDP, consumption, investment, and other observed variables during a historical period, and then it calculates the necessary changes in technology and preferences. Calibration is the procedure commonly used for parameter specification, which was carried out with the data from 2003 to 2008 based on the input-output table in 2002; the model is completed when parameters have been calibrated and are ready to evaluate the effects of three scenarios on water consumption. We followed the static calibration procedure to compute the baseline after determining the parameter values, applying the CGE model until all parameter values are correctly specified.

Modeling Watershed Hydrology and Water Supply

In general, surface runoff and river discharge increase when natural vegetation, especially forests, decreases (Foley et al. 2005). Impervious surfaces developed during urbanization contribute more surface runoff due to decreased infiltration. To characterize the impacts of urbanization on runoff, the watershed hydrology was modeled using the Soil and Water Assessment Tool (SWAT), which is commonly used in hydrological applications (Castillo et al. 2014). SWAT model was developed with a daily time step. The modeled area was divided into 116 subbasins and hydrological response units (HRUs), where the HRUs were determined based on land use land cover (LULC) over subbasin area (5%), soil over land use area (10%), and slope over soil area (10%) is the characteristics of the watershed. This consideration of limited set of factors was essential for keeping the model size manageable.

For each subbasin, the water balance was simulated for four storage volumes: snow and glacier, soil profile, shallow aquifer, and deep aquifer. Specifically, the surface runoff was simulated using a modified SCS (Soil Conservation Service) Curve Number (CN) method, which integrates a slope factor (Li et al. 2010). The modified CN method has been tested in the Loess Plateau (Huang et al. 2006) and provides an appropriate scheme for our study. In addition, snow and melting water in the alpine drainage of upstream reach was calculated using the energy balance equation (Arnold and Fohrer 2005).

SWAT input data included elevation, soil properties, LULC, temperature, precipitation, and stream flow (Table 1). These data were constructed using the ArcSWAT graphical user interface that runs in ArcGIS (Winchell et al. 2010). Elevation data were obtained from the Digital Elevation Model (DEM) created using Shuttle Radar Topography Mission (SRTM) data (CGIAR-CGI 2008). The Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) data (http://gdem.ersdac.

Table 1 Data used and sources information

Data type	Data source	Scale	Description
DEM	Shuttle radar topography mission (SRTM)	90 m	Elevation
Soil	Regional database (http://westdc.westgis.ac.cn/)	1:1000000	(Soil-plant-atmosphere-water) field and pond hydrology model was used to calculate some parameters
Weather	China meteorological administration (Daily)		13 weather stations
Hydrological observation	Hydrologic yearbook (Daily)		4 stations
River flow	Data Center of Chinese Academy of Science	1:250000	River network-diversion

jspacesystems.or.jp/) were also utilized to fill the missing SRTM data (i.e., a total of 3482 grids). The LULC data used in the study were developed by Chinese Academy of Sciences (CAS) (Table 1) for the years 2000, 2005, and 2010. The overall accuracy of the classification is 95% (Liu et al. 2005). The daily temperature and precipitation data were acquired from China Meteorological Administration (http://www.cma.gov.cn). The soil and glacier related data were obtained from latest regional database (http://westdc.westgis.ac.cn/) and the daily stream flow data collected at four hydrological stations.

Zhangye is one of the cities in the middle reach of the Heihe River Basin with the highest urbanization rate. Thus, the 2009 and 2010 observations of Yingluoxia hydrological station located at the upstream reach, where human activities are not intensive, were used as the calibration and validation data of the SWAT model. Since the middle reach of the Heihe River Basin is expected to experience the highest urbanization rate over the period from 2010 to 2050, Zhengyixia hydrological station located at the outlet of middle reach was used to examine the impact of urbanization on stream flows.

The ranges for the most sensitive model parameters were determined, and most appropriate values to be used in the model were selected (Table 2). The calibration and validation of model were performed by comparing the predicted daily stream flows against the measured stream flows on Yingluoxia hydrological station (Fig. 6) with the SWAT-CUP, which is a tool for the semi-automatic calibration and validation of SWAT models (Abbaspour 2007).The model performance in predicting the daily stream flows was evaluated using a set of goodness-of-fit (GOF) indicators, including the coefficient of determination (R^2) (Eq. 6) and Nash-Sutcliffe model efficiency coefficient (E_{ns}) (Eq. 7) (Nash and Sutcliffe 1970):

$$R^2 = \frac{\left[\sum_{i=1}^{n} \left(Q_{o,i} - \overline{Q}_o\right)\left(Q_{m,i} - \overline{Q}_m\right)\right]^2}{\sum_{i=1}^{n} \left(Q_{o,i} - \overline{Q}_o\right)^2 \sum_{i=1}^{n} \left(Q_{m,i} - \overline{Q}_m\right)^2} \tag{6}$$

Table 2 Ranges and Values of the most sensitive parameters in SWAT model

Parameters	Descriptions	Ranges	Values
CN_2	SCS curve number	−20%~20%	+6.32%
Sol_k	Saturated hydrological conductivity	−20%–20%	+11.56%
Escno	Evaporation compensation factor	0~1.0	0.83
SFTMP	Snowfall temperature	−2.0~2.0 °C	0.9 °C
Sol_z	Depth from soil surface to bottom of layer	−20%–20%	+3.65%
Sol_Awc	Available soil water content	−20%–20%	−0.35%
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur	0–500 mm	306.5
ALPHA_BF	Baseflow alpha factor	0.00~1.00	0.07

$$E_{ns} = 1 - \frac{\sum_{i=1}^{n} \left(Q_{o,i} - Q_{m,i}\right)^2}{\sum_{i=1}^{n} \left(Q_{o,i} - \overline{Q}_o\right)^2} \tag{7}$$

where $Q_{o,i}$ the observed data of runoff in i years; $\overline{Q}_o$ is the mean of observed data . . .., $Q_{m,i}$ the simulation data of runoff in i years; $\overline{Q}_m$ is the mean of simulation data . . .; and n is the length of the time series. The closer E_{ns} and R^2 are to 1, the more accurate the model prediction, an $E_{ns}>0.0$ indicates that the model is a better predictor than the mean of the observed data. The R^2 values of 0.87 and 0.89 were obtained for the calibration and validation periods, respectively, showing a high accuracy of the model. Also, E_{ns} values of 0.88 and 0.87 for the calibration and validation periods, respectively, correspond to “very good” modeling performance (Moriasi et al. 2007).

The effects of urbanization on basin hydrology were simulated using the projections of urban land use and climate. The high resolution precipitation and temperature forecasts for 2050 were simulated using Regional Integrated Environmental Model System (RIEMS 2.0) developed by START TEA-COM RRC and Department of Atmospheric Science of Nanjing University (Xiong and Yan 2013) and with the IPCC emission scenarios RCP4 of Geophysical Fluid Dynamics Laboratory (GFDL) dataset (http://nomads.gfdl.noaa.gov:8080/DataPortal/cmip5.jsp). These forecast data were input to SWAT to simulate the basin hydrology in 2050. Then, the differences in discharges between 2010 and 2050 were examined.

Results and Discussion

The Prediction of Urbanization and Industrial Transformation

The study performed the analysis in the changes in urbanization, total water utilization, total economic output value, industrial structure, and water utilization efficiency on the counties of middle reach of Heihe River Basin. The output percentage of three sectors changed from 32:34:34 in 2000 to 33:30:37 in 2010, indicating the output in 2010 declines in the sequence of the tertiary industry, and the primary industry and the secondary industry. However, the GDP value increased from 12.97 billion Yuan in 2000 to 234.58 billion Yuan in 2010. This structure is in accordance with the economic development level and indicates that the regional economy has stepped into service-based economy. That means traditional industries are giving way to knowledge-based industries.

According to the trend of urbanization rate during 2000–2010, the study constructed the IOWHA method to forecast the urbanization level of these counties over the period of 2010–2050. The results show that urbanization rate is higher in counties like Ganzhou and Suzhou. Specifically, the urbanization rate of each county in the middle reach is projected with the highest of which at 50% in 2050. The largest change value of urbanization is about 20% during 2010–2050. The county of lowest change value is Minle, which is almost 6% during this period. Though the predicted highest urbanization rate of Suzhou is 48% among the seven counties in 2050, it is far lower than that of other cities with abundant water resource in Northwest China (Bao and Fang 2012).The built-up area is about 1.53% of total land use area in 2010, which will increase 62% from 2010 to 2050.

Urbanization might boost the improvement of the labor resource and technical level, which drives the change in industrial structure because of the changes in the primary factors affecting the production activities. According to the overall results, the proportion of the primary industry is expected to decrease more than 10%, with the largest decrease being in the Gaotai with 22% decrease. On the other hand, the proportion of the tertiary industry is expected to increase some extent, with the expansion ranging from 5% to 11% depends on the county.

The Effect of Urbanization on Water Supply and Water Demand

Urban and rural settlements are fundamentally different, not only because of their difference in population size and thus density, but even more because of their differences in the way of living, in their cultural diversity and heterogeneous mix of activities. The urban life style is gradually spreading even in small and remote rural settlements. When urbanites are spreading more loosely into the countryside, they change the traditional life style there and make the distinction between urban and rural to become very diffuse.

The results show that although all the water consumptions per unit of output value of the primary, secondary, and tertiary industries have a decreasing trend, the absolute total water demand is expected to increase from 21.74×10^8 m^3 to 24.35×10^8 m^3 over the period of 2010–2050. The reason is various, but the key aspect is enlargement of industrial-scale. The GDP value is about 3500 million US $ in 2010. In the study, future GDP growth rate is fixed with the historical minimum value. But there is much uncertainty about what is the GDP growth rate in the future. The study aims to analyze the water balance scenarios for the integrated watershed management.

Population growth, urbanization, and industrialization not only impact the environmental conditions and hydrological processes, they also aggravate the water scarcity, which, in turn, put the water needs for agricultural activities at risk. Advancing understanding about how water is partitioned among diverse urban users, the economic output provided by the water, and the consumption amount associated with urbanization will be essential for ensuring sustainable development. The most significant pressures from rapid urbanization on water resources are the redistribution of limited water supplies and the increase in water consumption. Urbanization has serious economic, social, and political dimensions. It leads to a change in industrial structure and also increases the demand for resident live. City is an essential location for maintaining the health and comfort of the majority of human. Thus, migration from rural to urban area will increase water consumption in the Basin, which has direct relationship with residents' consumption propensity. On one hand, resident in urban consume more water than rural resident in their live. On the other hand, the change of consumption structure and pattern will increase the indirect water consumption. The use of urban water throughout a city is associated with a broad range of ecosystem services, including human health–related uses like drinking water and showering, industrial and commercial economic activity, and aesthetic and recreational benefits resulting from irrigated gardening and landscaping.

It is important to note that the future hydrological conditions hold some uncertainties resulting from the uncertainties in the urban expansion patterns or climatic changes. With the development of urbanization and industrial transformation, the water consumption per unit of output will declines because of the innovative technique. But the demand of water resources is still increasing with the enlargement of industrial scale. At the same time, the urban expansion patterns can unfold in unexpected ways, which cause the great changes in land use and land cover, and thus affect the change of regional climatic factors such as temperature, precipitation, etc. These are bound to affect the change of the Heihe River Basin runoff and cause the change of hydrological conditions. These uncertainties caused by urban expansion and industrial transformation can affect the results from the hydrological simulation performed using SWAT.

Certainly, some measures for balancing the water supply and demand should be taken into consideration for water sustainable utilization. At the same time, as centers for innovation, cities provide opportunities for more sustainable use of water, including treating used water to standards that enable it to be used again. They are well positioned to rapidly adopt conservation measures, and the concentration of people in compact settlements can reduce the cost of providing services such as water supply and sanitation. Furthermore, cities can connect with their hinterlands and support the protection of water resources in their surrounding areas by actively engaging in watershed management or providing ecosystem service function. Rapid urbanization, increased industrialization, and improving living standards generally combine to increase the overall demand for water in cities. These could include technical measures such as water saving, irrigation district renovation, farmland area reduction, and wastewater reuse, which have been proven to be useful to reduce the water demand, nontechnical demand management measure such as institutional reform, water pricing adjustment, and cropping pattern optimization. As future work, the corresponding integrated model considering the interactions between surface and groundwater should be carried out in practice. Then, as to the Heihe River Basin, policy recommendations are supposed to be summarized to identify the scales and patterns of urbanization and industrial transformation.

Industrial Transformation

It is challenging but necessary to boost economic development through the efficient use of water resources. The simulation results show that the output value of all the sectors increased under scenario 1 when the output value of the secondary industry increased by 5% (Fig. 7). However, the proportion of water consumption in secondary industry increased, while that of farming, animal husbandry, and the service sector decreased and that of other agricultures remained stable (Table 3). The analysis suggests that the output value of other sectors was driven by the industrial technical change. Food industry is the major secondary industry in Zhangye, and therefore the development of secondary industry may advance the primary and tertiary industries by raising prices. Specifically, GDP increased by 2.6% and total water consumption was reduced by 0.13%, indicating that the farming industry is the

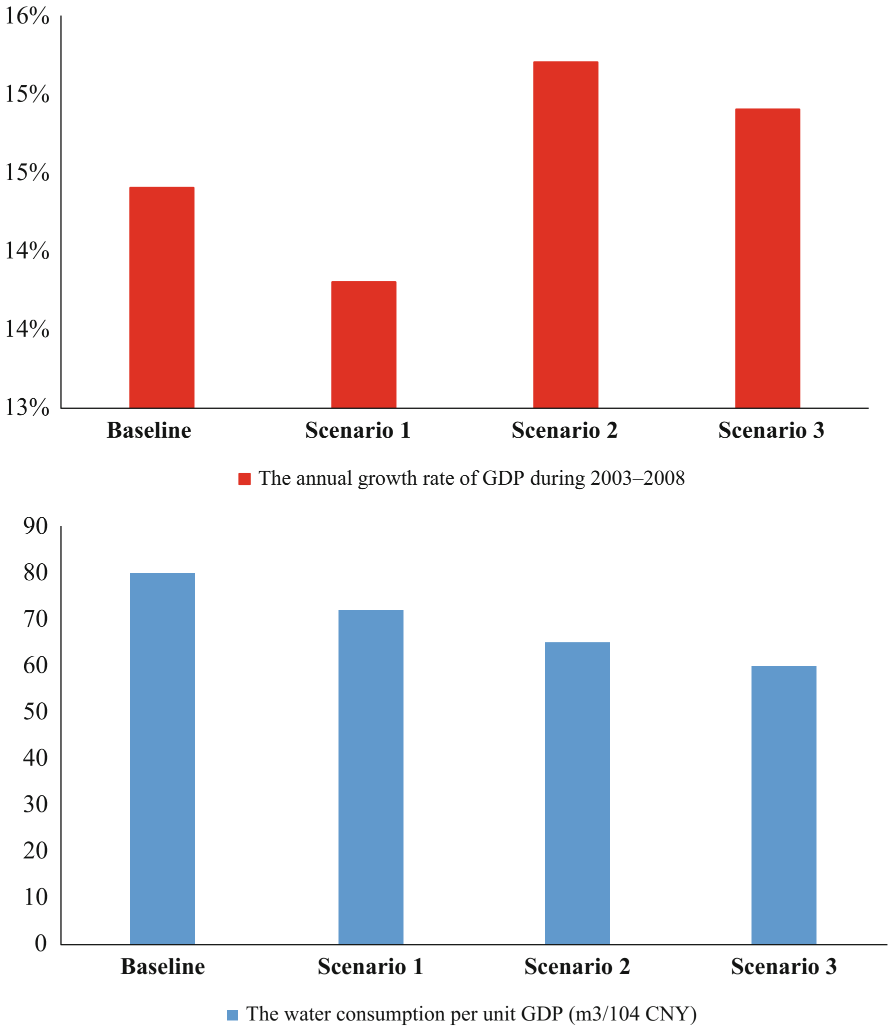

Fig. 7 Comparison of different scenarios' effects on economic development and water consumption

Table 3 Effects of industrial transformation on output value (**a**) and water consumption (**b**) under different scenarios

Planting industry	Animal husbandry	Other Agriculture	Industry	Construction	Service	Planting industry
(a) Change of output (%)						
Scenario 1	1.65	1.50	2.42	5.00	2.68	1.34
Scenario 2	−5.00	−0.31	−0.41	−0.11	−0.01	−3.00
Scenario 3	0.17	−0.34	0.45	1.89	2.87	5.00
(b) Change of water consumption (%)						
Scenario 1	−0.72	−0.80	0.00	2.61	0.39	−0.82
Scenario 2	−2.83	2.11	1.24	2.20	2.25	−0.79
Scenario 3	−2.46	−2.63	−3.20	−0.59	0.44	2.41

largest water-consuming sector in the region. Under the second scenario, outputs of almost every industry decreased, but the change of water consumption was different. The change of water consumption in secondary industry was contrary to that of the output value. Under the last scenario, the development of tertiary industry would promote the secondary industry, but the effect on agriculture was not significant. However, the water consumption of the planting industry decreased by 2.5%; therefore, it will be beneficial to promote the expansion of secondary industry and tertiary industry with lower water use intensity while advancing the development of the planting industry and other agricultural sectors.

The reduction in water consumption per unit GDP can be achieved through promoting technical change under the three scenarios. The industrial transformation of planting plays a key role in improving water use efficiency to achieve the goal of reducing water consumption. Under scenario 1, when the output value of the secondary industry increased by 5%, the annual GDP increased by 0.80%, while the water consumption per unit GDP decreased from 80 $m^3/10^4$ CNY under the baseline scenario to 65 $m^3/10^4$ CNY under scenario 1. Under scenario 3, the water consumption of per unit GDP decreased by 25% as the annual GDP increased by 0.50% (Fig. 7). This indicates that the secondary industries play an essential role in pushing economic development, while the development of the tertiary industries can greatly raise water use efficiency in Zhangye. The food industry in secondary industries can push the development of primary industry, which is also closely related to the development of tertiary industry. Therefore, the development of tertiary industries can drive the complete industrial chain in Zhangye's economic system. The proportion of industries with high water consumption in Zhangye is very large, which can cause serious environmental issues, so the development of these industries is against the goal of sustainable development. Therefore, municipal government and relevant institutions in this environmentally fragile region should cooperate to promote the coordinated development of both economic and ecological systems. For example, high water-consuming industries with a high direct water use coefficient should be limited to some extent in the future. Overall, according to the simulation results under three scenarios, we suggested that the third scenario should be adopted for water resource management reform.

It is challenging but necessary to boost economic development through the efficient use of water resources. The simulation results show that the output value of all the sectors increased under scenario 1 when the output value of the secondary industry increased by 5%. However, the proportion of water consumption in secondary industry increased, while that of farming, animal husbandry, and the service sector decreased and that of other agricultures remained stable. The analysis suggests that the output value of other sectors was driven by the industrial technical change. Food industry is the major secondary industry in Zhangye, and therefore, the development of secondary industry may advance the primary and tertiary industries by raising prices. Specifically, GDP increased by 2.6% and total water consumption was reduced by 0.13%, indicating that the farming industry is the largest water-consuming sector in the region. Under the second scenario, outputs of almost every industry decreased, but the change of water consumption was different. The change of water consumption in secondary industry was contrary to that of the output value. Under the last scenario, the development of tertiary industry would promote the secondary industry, but the effect on agriculture was not significant. However, the water consumption of the planting industry decreased by 2.5%; therefore, it will be beneficial to promote the expansion of secondary industry and tertiary industry with lower water use intensity while advancing the development of the planting industry and other agricultural sectors.

More than 90% of the water use in Zhangye city comes from the Heihe River. Because of ecological challenges aggravated by water shortages and over-exploitation of groundwater, water resource reallocation between the midstream and the downstream area of Heihe River Basin has been implemented since 2001. Zhangye city has taken many measures to reduce water use in several key economic sectors and to ensure enough water flow to the lower basin since 2002. Therefore, in the economic system, water consumption should be reduced and conversely, water use efficiency ought to be increased. However, in this study, we investigated the feedback between land-use dynamics and water-saving measures, with a strong focus on water use in irrigation. The water use efficiency increased from 8 CNY/m^3 in 2002 to 15 CNY/m^3 in 2012, but the total water use of the economic system increased by about 200 million m^3. A rebound effect of these water-saving measures occurred in Zhangye city, which indicates that there was no other use of water saving measures in the economic system. Integrated water resource management should be implemented to control the expansion of cultivated lands. Water and land resource competition and environmental degradation bring about severe problems for resource managers. In particular, managers must consider the ensuing tradeoffs between economic, environmental, and social factors and their spatiotemporal variability when implementing management policies.

Conclusions

In the Heihe River Basin, water scarcity has become a serious constraint hindering the economic development, giving rise to conflicts over water resources among ecology, agriculture, economy, and humanity. Therefore, the study focuses on the research on the effects of urbanization and industrial transformation for improved water management on the water balance in the basin. Where surface water–groundwater interactions are important processes controlling catchment hydrology, particular care has to be taken to understand this interaction prior to determining urban water management strategies for new urban developments.

Most analyses on the impact of urbanization on the water balance are based on reasonably simple models. The study studied the combined impacts of economic development and changes in urban land and climatic conditions on the water resource in the Heihe River Basin. The growth rate of total water demand will reach at 12%. The most significant pressures from rapid urbanization on water resources are the redistribution of limited water supplies and the increase in water consumption. In this study, we found that the direct water consumption coefficients of the planting sector and other agricultural divisions are much higher than that of other sectors, and changes in the corresponding output values have significant effects on the total water consumption. However, the marginal revenue of water use in the tertiary sector is the highest among all sectors. Then we evaluated the changes of water consumption caused by industrial transformation, using the CGE model under three scenarios designed with industries' technical changes in mind. The simulation results indicated that the water saving benefit from industrial structure transformation is significant when the output value of secondary industry and tertiary industry increases but the percentage of the planting sector in the total output value decreases. Enhancing water use efficiency through industrial transformation will be an effective way to meet water needs in the face of severe water scarcity in a typically arid region of Northwest China. The simulation results also suggested that encouraging the development of tertiary industry is a sustainable tradeoff scheme for raising water use efficiency, and moderating the development of the planting sector is also an important way to improve water use efficiency in the whole river basin.

This study only analyzed the impacts of industrial transformation on water consumption in multiple sectors, without considering the intraregional or interregional water trade in response to variability of seasonal allocation. Given that variability in seasonal allocation is a common phenomenon across the Heihe River Basin, the long-term benefits of industrial transformation in Zhangye are likely to be greater than these estimates. In spite of this limitation, the findings of this study can provide some suggestions for the sustainable use of water resources.

In this study, we pay more attention on exploring the coupling mechanism of hydrological process. In future, we should convert the conventional regional CGE model into one that takes into account physical boundaries of water resource. And we found that the direct water consumption coefficients of the planting sector and other agricultural divisions are much higher than industrial sectors, and changes in the corresponding output values have significant effects on the total water consumption. However, the marginal revenue of water use in the tertiary sector is the highest among all sectors. The simulation results indicated that the water saving benefit from industrial structure transformation is significant when the output value of secondary industry and tertiary industry increases but the percentage of the planting sector in the total output value decreases. Enhancing water use efficiency through industrial transformation will be an effective way to meet water needs in the face of severe water scarcity in a typically arid region of Northwest China. The simulation suggested that encouraging the development of tertiary industry is a sustainable tradeoff scheme for raising water use efficiency, and moderating the development of the planting sector is also an important way to improve water use efficiency in the whole river basin.

Summary

Urban ecosystems coupling social and biophysical processes require interdisciplinary effort. An integrated framework is explored by linking a hydrological model (SWAT) and an economic model (CGE) for allocating the water resource to maximize the water use efficiency in a river basin. A case study of the Heihe River Basin is presented to illustrate how the framework can be used to analyze the water supply and demand in the process of urbanization. The industrial transformation will happen along with the urbanization, both of which will lead to rapid increase of water consumption. In addition, the rate of urbanization mainly depends on the economic development, population growth and water resource limitations. Therefore the study analyzed the water demand of each county using the CGE model, with the population growth, capital accumulation and technical progress used as exogenous variables. Simultaneously, the land use/cover change with urbanization will back to influence water supply through the hydrological process. The results indicate that the total water consumption in the middle reach of the Heihe River Basin will increase from 21.74×10^8 m^3 in 2010 to 24.35×10^8 m^3 in 2050. In addition, the results indicate that the runoff in the lower reach of urban will increase by 9.14% and the groundwater infiltration will decrease in 2050, indicating that more water can be withdrawn from Heihe River to meet the increasing water demand due to urbanization in the middle reach on condition that the ecological water demand in the lower reach remains unchanged.

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Impacts of Land Use and Cover Changes on Water Balance in River Basin

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Contents

Introduction 92
Study Area and Data 94
  Study Area 94
  Data Source and Handling 96
Water Scarcity of the Heihe River Basin 98
  Water Scarcity along with Serious Contradiction between Supply and Demand of Water 98
  Irrational Water Consumption Structure along with Low Water Efficiency 101
  Deficient Systems and Institutions on Water Management 104

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Methods 105
WRF Model and Simulation Schemes 105
Energy Balance and Water Balance 106
The Impacts of LUCC on Surface Energy 107
The Impact of LUCC on Water Balance 110
Summary 113
Discussions 113
Conclusions 115
References 116

Abstract

It is well known that there are huge land use and land cover changes (LUCC) all over the world in recent decades, and plenty of instable effect appeared on the energy and water balance. This study aims to analyze the impacts of land use and land cover changes on the energy and water balance in the Heihe River Basin of China during 2000–2010, and four key study sites with representative hydrological stations and dramatic LUCC in the past decades were selected to illustrate the responses of the energy and water balance to LUCC. First, LUCC of the Heihe River Basin from 2000 to 2010 was analyzed based on the interpretation of remote sensing images. Then a series of indicators of the energy and water balances were simulated with the Weather Research and Forecasting (WRF) model and corresponding land use and land cover data. Thereafter the impacts of LUCC on the surface energy and water balance were detected and analyzed. The spatial–temporal variance of the impacts of LUCC on energy and water balance in a typical arid inland river basin was specifically presented in the following analysis. The land use conversions can lead to the fluctuation of energy balance, and among those changes, the most significant impacts on surface energy balance occurred when grassland was converted to barren or sparsely vegetated land. As for water balance, the impact is measured with variations of precipitation, runoff, and evapotranspiration induced by LUCC, which were also remarkable, although seasonal trends of the effects are similar among various land use/cover conversions during 2000–2010. At last, policy suggestions, e.g., shifting the water balance by LUCC to improve the water management, are given to conclude this study.

Keywords

LUCC · Energy and water balance · Heihe River Basin · Policy suggestion · Water management

Introduction

Water nowadays not only plays avital role in the formation, development, and stability of desert oasis, but also is a key component of the ecosystem environment and services. The fact is that most of the inland rivers in China are faced with severe water resource shortage and serious ecological deterioration. The north and north-west of China account for half of the total area of China but have less than 20% of total national available water resource. Meanwhile, as one of the major constraints on sustainable development, water is the determining factor to maintain social production and livelihoods of the arid and semiarid region. The water issue in arid and semiarid inland areas is thus receiving considerable attention worldwide.

With the development of theory and methodology for studying the motivations behind the dynamics of water balance, researchers have increasingly realized the close relationships between water balance and the dynamics of land system change (Deng 2011; Deng et al. 2012, 2014). There have been tremendous changes in global land use and land cover in the past decades (Foley et al. 2005; Lambin and Meyfroidt 2011), especially in countries with rapid development, such as China (Deng et al. 2006a; Seto et al. 2011). Land use and land cover changes (LUCC), which are expected to continue in the future, have enormous influence on global and regional climate and water balance (Anav et al. 2010; Kueppers and Snyder 2012; Deng et al. 2013). In this sense, the impacts of LUCC on global and regional climate change have attracted great attention (Chen et al. 2005; Seneviratne et al. 2006). For example, recent studies have shown that anthropogenic LUCC have dramatically altered the earth’s land surface (Ramankutty et al. 2008; Margono et al. 2012) and played a vital role in reshaping the global patterns of energy and/or water balances (Chen et al. 2005; Seneviratne et al. 2006). Previous studies showed that the large-scale land use/cover dynamics exerted huge impacts on the surface energy and water balance through biochemical and biophysical processes (Twine et al. 2004; Ardli and Wolff 2009; Jiang et al. 2011; Liu and Deng 2011; Deng et al. 2012; Huang et al. 2013). Besides, some research indicated that surface roughness, albedo, and other properties, which affect exchanges of water and energy between the land surface and the atmosphere, will be altered by the conversion of natural ecosystems to irrigated agriculture, leading to various changes of the surface energy and net radiation in different seasons (Kueppers and Snyder 2012). In addition, some studies of the urban expansion showed that the conversion to built-up area may result in a rapid increase of impervious surface area, and affect the runoff generation and groundwater recharge. By changing the permeability of surface land, there will be more water flows over impervious surfaces or through runoff networks, which consequently increases the speed of flows and results in more significant urban heat island effects (Oke 1982; Gregory et al. 2006; Yadav et al. 2012). In summary, most of the previous studies focused on the impacts of a certain kind of land use conversion on the energy and water balance in a certain region. In this study, we not only refine the land use categories but also focus on all kinds of land use conversions.

There have been several models to quantify the impacts of LUCC on surface energy and water balances (Rwasoka et al. 2011), which can be generally divided into two categories. One is based on the hydrological models or regional climate models, such as International Center for Theoretical Physics (ICTP), Regional Climate (Reg-CM3) model (Kueppers and Snyder 2012), Davis Regional Climate (DRCM) model (Kanamaru and Kanamitsu 2008), and Soil and Water Assessment Tool (SWAT) model (Schilling et al. 2008). It is quite popular and mature to separately analyze the water balance with hydrological models and analyze the energy balance with regional climate models (Jothityangkoon et al. 2001; Shindell et al. 2001; Döll et al. 2003; Gerten et al. 2004; Fettweis 2007). However, not all of these studies quantified the impacts of LUCC on energy and water balance from a comprehensive view (Sakai et al. 2004; Twine et al. 2004; Schilling et al. 2008). The other is based on the combination of land use simulation model with hydrological models or regional climate models, such as the combination of Integrated Biosphere Simulator (IBIS) model and Hydrologic routing model (HYDRA) (Lenters et al. 2000), and the combination of Simple Biosphere Model (SiB2). The basic thought of the latter category is to firstly simulate the LUCC with the land use simulation model and then simulate the energy balance and water balance based on the simulated LUCC (Bormann et al. 2007; Fohrer et al. 2005). However, there is a major technical challenge in the latter category, i.e., the transformation of parameters (Romanowicz et al. 2005; Li et al. 2007).

It is more persuasive to analyze the impacts of LUCC with the real historical land use/cover data since it is feasible to verify the simulated results with the observed records. In this study, the impacts of LUCC on the energy and water balance have analyzed with the historical land use/cover data used as the input parameters of the WRF model as follows. First, we analyzed the land use/cover dynamics in the Heihe River Basin (HRB) from 2000 to 2010, and four key study sites within HRB were selected, which have experienced dramatic LUCC and possess representative hydrological stations. Then two sets of simulation schemes were designed to analyze the changes of energy and water balances with the WRF model. Thereafter, the results simulated with the WRF model were compared with the observation records from hydro-logical stations to verify the simulation capability of WRF model. The simulation results can provide a better understanding of the influencing factors of water and energy balances in the HRB and assist local managers in formulating proper land use planning to offset the LUCC-induced negative impacts on the surface energy and water balance.

Study Area and Data

Study Area

HRB is the second largest inland river basin of China, covering an area of 143,000 km^2. It is located in the northwest region of China (90°E–102°E, 37°50’ N–42°40’ N) and expands across Qinghai Province, Gansu Province, and Inner Mongolia Autonomous Region (Fig. 1). The Qilian Mountains lie in the southwest part of this basin, and Badain Jaran Desert lies in the east part, with the elevation ranging from 980 m to approximately 4000 m. The HRB belongs to the semi-arid and subhumid temperate continental monsoon climate zone, with significant temperature variation among seasons. Besides, the precipitation and evaporation show significant spatiotemporal heterogeneity under the influence of geographic factors and atmospheric circulation. Therefore, we chose this specific study site to explore the impact of LUCC on energy and water balance. In addition, the whole basin is

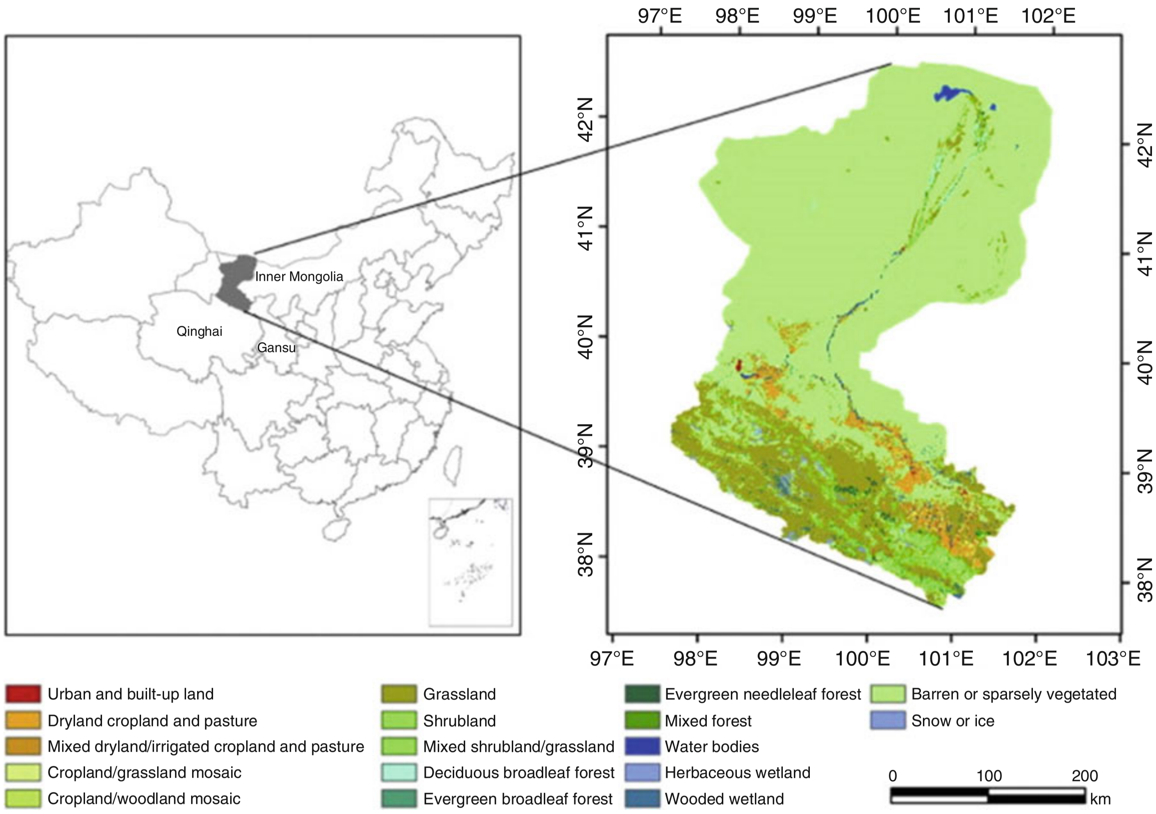

Fig. 1 Location and land use and land cover in 2010 of the HRB (Reprinted from Deng et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

divided into the upper, middle, and lower reaches, which are featured by different natural conditions and social economic development status. The upper reach is the water source area, where the mean runoff coefficient is up to 0.85 and the cumulative proportion of runoff reach to 68%. The middle reach is the water consumption zone, where most of the land has been reclaimed for oasis agriculture, and it accounts for 95% of the cultivated land, 91% of the population, and more than 80% of the GDP of the whole HRB. The lower reach is the tail-end zone, with a huge evaporation capacity and very fragile ecological environment.

Human activities have been the dominant factor for environmental problems of the HRB. The grassland has degraded severely due to long-time overgrazing and overcultivation in the upper reaches, while water holding capacity has decreased greatly. Meanwhile, water consumption has increased steadily, especially in the middle reaches where it is featured with remarkable economic growth. Consequently, the hydrological processes of these areas have been deeply modified by human activities, such as the expansion of irrigation, rapid population growth, and socioeconomic development. On one hand, due to the high intensity of water usage in the upper and middle reaches in the HRB, the lower reaches have dried up and groundwater levels have decreased severely. On the other hand, with the implementation of national Policy on Integrated Development of Western China, plenty of water previously used by natural ecosystems and irrigation agriculture will be saved and used into industrial and urban systems to maintain the economic development. Generally, it has caused the imbalance in the whole interrelated system of human beings and natural resource, as well as environment, thus leading to sever ecological and socioeconomic problems in the whole region.

The sustainable development of an arid area largely depends on the availability of water from the inland rivers like the HRB of China. A number of studies analyzed the hydrological process and the water problems of the HRB. These researches have put forward some approaches and schemes for water management. However, some knowledge gaps on the spatial variability of water and water efficiency in the HRB ought to be stressed. Meanwhile, the institutions and successful practices of water management for improving water efficiency need to be integrated in the arid basin research.

Data Source and Handling

Three kinds of data are used in this study, including land use/cover data, climate forcing data, surface energy, and hydrological data. The 1 km resolution land use/cover data, which are obtained from the interpretation of remote sensing images, are provided by Data Center for Resources and Environmental Sciences, Chinese academy of sciences (CAS) (Liu et al. 2009; Wu et al. 2013). The land use/cover of the US Geological Survey (USGS) classification system has been used in this study (Table 1) since it has been widely used in the simulation with modern land surface and distributed hydrological/ecological models (Chen and Dudhia 2001; Wu et al. 2013). Besides, the geographically segmented (GEOG) climate forcing data used in

Table 1 Land use/cover types of USGS land classification system

Code	Land use/cover	Description
100	UBL	Urban and built-up land
211	DCP	Dryland cropland and pasture
212	ICP	Irrigated cropland and pasture
213	MCP	Mixed dryland/irrigated cropland and pasture
280	CGM	Cropland/grassland mosaic
290	CWM	Cropland/woodland mosaic
311	GL	Grassland
321	SL	Shrubland
330	MSG	Mixed shrubland/grassland
332	SA	Savanna
411	DBF	Deciduous broadleaf forest
412	DNF	Deciduous needleleaf forest
421	EBF	Evergreen broadleaf forest
422	ENF	Evergreen needleleaf forest
430	MF	Mixed forest
500	WB	Water bodies
620	HW	Herbaceous wetland
610	WW	Wooded wetland
770	BSV	Barren or sparsely vegetated
820	HT	Herbaceous tundra
810	WT	Wooded tundra
850	MT	Mixed tundra
830	BGT	Bare ground tundra
900	SI	SI snow or ice

this study, which are updated every 6 h, were downloaded from NCEP FNL (Final) Operational Global Analysis. This dataset with the spatial resolution of 1 × 1 and the vertical height of 27 layers has been constructed and updated since July 1999 with the data assimilation of observation data (e.g., the remote sensing data and ground-based observation data). The time period of the climate forcing data was truncated from January 2000 to December 2010 in this study. Both the climate forcing data and land use/cover data were used as the input data of the WRF model. In addition, the climate data, energy flux data, and hydrologic records were obtained from the hydrological stations and meteorological stations. The 20 km × 20 km resolution temperature data were obtained by interpolating the monthly average temperature data derived from the 57 meteorological stations in the HRB with the Kriging interpolation method. The historical meteorological data in 2000 were put into the WRF model. To validate the simulation accuracy, we collect the observed records on climatic data, energy flux, and hydrological data in 2010 from the certain hydrological and meteorological stations and compared them with the results simulated with the WRF model.

There are 17 types of land use/cover in HRB according to the USGS classification, indicating complex land surface characteristics. Observed from Fig.1 and based on the dataset developed by CAS, the barren or sparsely vegetated land cover accounts for more than 70% of the total area and approximately 20% of the land is covered by grassland, with the rest being other types. Previous study shows that

Table 2 The main land use/cover changes in the HRB, 2000–2010

Land use/cover in 2000	Land use/cover in 2010	Area in 2000 (km^2)	Conversion area(km^2)	Conversion as percentage of area in 2000(%)	Conversion as percentage of total conversion area (%)
GL	BSV	22,083	1529	6.9	20.0
GL	SL	22,083	1029	4.7	13.5
BSV	DCP	91,798	853	0.9	11.2
MSG	SL	1536	631	41.1	8.3
CGM	DCP	711	529	74.4	6.9
BSV	SL	91,798	525	0.6	6.9
MCP	BSV	2892	500	17.3	6.5

Note: Land use/cover codes are listed in Table 1.

cultivated land, saline and alkaline land, and built-up area increased before 2000, while the forestry area, grassland, river, and glacier decreased (Deng et al. 2010). Besides, the land use/cover has changed dramatically after 2000. The LUCC during 2000–2010 was analyzed by calculating the transition matrix in this study, and Table 2 shows the major land use/cover changes during 2000–2010 in the HRB.

Since there is great difference in the energy conditions and water conditions among the upper, middle, and lower reaches of the HRB, four case study areas (Fig. 2) were selected for a further analysis, where there are representative hydrological stations. The selected representative hydrological stations include Qilian Station (S1) in the upper reaches, Liqiao Reservoir (S2) and Jiayuguan Station (S3) in the middle reaches, and the Langxin Mountain Station (S4) in the lower reaches (Fig. 2). Besides, the selected case study areas are characterized by different types of LUCC. In the case study area in the upper reaches, a lot of grasslands have changed into shrub land due to the implementation of soil and water conservation policies. There are mainly two types of LUCC in the middle reaches. For example, in the case study area with S2, plenty of cropland/grassland mosaic land changed into dry cropland, while in the case study area with S3, the water area increased significantly due to conversion from the barren or sparsely vegetated land. By comparison, the case study area with S4 in the lower reaches is mainly characterized by the conversion from grasslands to barren or sparsely vegetated land (Table 3).

Water Scarcity of the Heihe River Basin

Water Scarcity along with Serious Contradiction between Supply and Demand of Water

Water scarcity is a long-standing and widespread problem in the HRB, and there is unevenly temporal and spatial water distribution. Based on our survey results, research findings, and statistical analysis, there are a series of reservoirs (one large reservoir, 9 medium size reservoirs, and 89 small reservoirs) in the basin and the total capacity is 416.9 billion m^3. Influenced by topography, altitude, and atmospheric

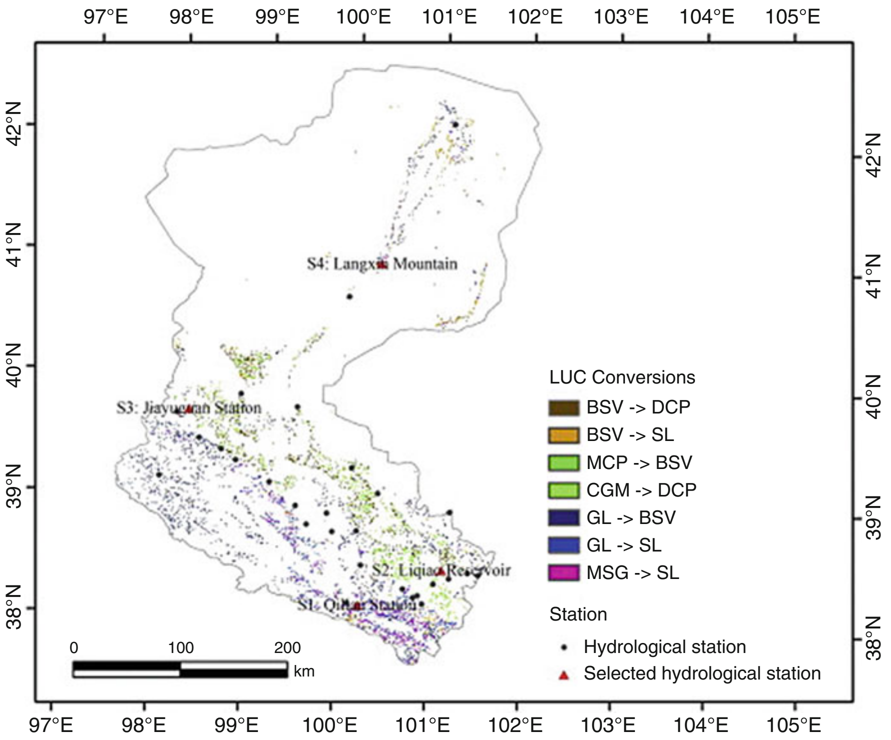

Fig. 2 Major LUCC in the HRB (2000–2010) and the hydrological stations (Reprinted from Deng et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

Table 3 LUCC matrix of the for key study sites in the HRB during 2000–2010

Station	Name	LUCC in 2000	LUCC in 2010
S1	Qilian Station	Grassland	Shrubland
S2	Liqiao reservoir	Cropland/grass mosaic land	Dryland cropland and pasture
S3	Jiayuguan Station	Barren or sparsely vegetated land	water area
S4	Langxin Mountain	Grassland	Barren or sparsely vegetated land

circulation at different scale, the spatial distribution of precipitation is extremely uneven in the middle reaches and lower reaches. Generally, the annual average precipitation decreases from southeast to northwest (Fig. 3). The maximum precipitation zone mainly concentrated in the upper reaches with an altitude of 2200–3000 m and an annual precipitation of 400–750 mm. In contrast, the minimum precipitation zone is the desert area of Ejina which administratively belongs to the Inner Mongolia, with an annual precipitation of 15–50 mm.

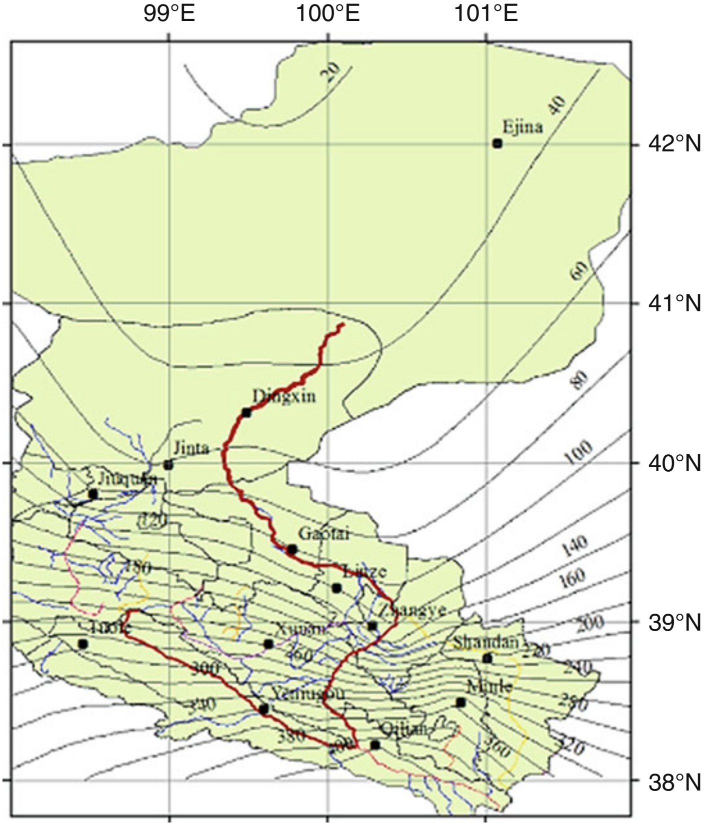

Fig. 3 Spatial distribution of the average precipitation (mm) in the Heihe River Basin for the year 1960–2006 (Reprinted from Deng & Zhao (2015) with permission of Advances in Meteorology)

Aside from precipitation, water resource is mainly supplied by springs, subsurface flow, and solid glacier in Qilian Mountain. There are 298 million m^3 water resource formed by ice and snow melting from the Qilian Mountain, accounting for 8% of the total amount of runoff. The previous studies have concluded that the yearly based rate of glacial retreating was around 0.60% in the HRB from 1960s to the year 2010, and this speed was significantly faster than Tianshan Mountain (0.49%/a), Geladandong (0.05%), and Naimona Nyi region (0.26%). In this sense, water scarcity is induced not only by the natural process, but also by irrational damage. The landscape structure and composition in the upper reaches of the HRB have been seriously changed, which inevitably reduced water availability in the lower reaches.

Meanwhile, water demand in HRB has increased considerably over the past half century. Since the year 1949, the China government has paid much attention to the development of irrigation infrastructure. By the year of 1985, the number of reservoirs (the small plain reservoirs and embankments with a volume less than 100 thousand $m^3$are not accounted) in the middle reaches has come to 95, and the total storage capacity is up to 360 million m^3, 20 times more than that in the year 1949. As a result, the hydrology changed radically in the middle reaches, which is highlighted by the fact that the utilization rate of surface water increased by 19 times, the area of irrigated oasis expanded by 89.5%, and the area of desertification land increased by 4% to 11% since the year 1949. Along with utilization of the surface water, the groundwater was also explored, and the number of motor-pumped well had doubled from the year 1985 to the year 1994. The groundwater table had been steadily decreasing due to the over pumping and the decreasing of recharges. In fact, there is a very close interconnection between the surface runoff and groundwater in the HRB because of the water distribution characteristics of HRB, which partly determined the hydrological process. Last but not least, as the intermediate linkage between the surface water and the groundwater, the volume of springs also shows a decreasing tend. In addition, the average reducing rate had increased by 6.8% in the year 1981–1991 compared to the year 1960–1980.

Consequently, the exploitation on surface runoff water and groundwater dramatically changed the hydrological situation of the HRB in the long historical period. All the 33 tributaries in the middle reaches no longer joined into the mean stream after 1980s, and they gradually disappeared and formed some in dependent irrigation oasis. The water volume of the runoff through the Zhengyixia decreased sharply in recent decades, from 1.19 billion m^3 in 1950s to merely 691 million m^3 in 1990s, and the main stream became the seasonal river below the Zhengyixia. In arid region, large-scale development of irrigation agriculture induces dramatic increase of water demand. The excessive water consumption by humans has resulted in continued environmental deterioration, which has become a serious threat to sustainable development.

Irrational Water Consumption Structure along with Low Water Efficiency

Currently, the overall water consumption of all sectors in the HRB is about 3.36 billion m^3. Among them, industrial and domestic water consumption is fairly less, and agricultural water use accounts for about 95%, posing a great threat to the ecological water consumption. Indeed, groundwater has become the dominant source of water supply for irrigation in Northern China. Taking the year 2000 as an example, the annual water consumption in the HRB is 2.65 billion m^3. Specifically, the farmland irrigation consumption is 2.03 billion m^3, and the water consumption in the forestry, stock raising, and fishing sector is 489 million m^3 totally, industrial water consumption is 86 million m^3, livestock water consumption is 15 million m^3, people living consumption is 32 million m^3 (including urban public consumption), and the urban environment water consumption is two million m^3.

In terms of the spatial distribution of water consumption, it is mainly concentrated in the middle reaches, accounting for 84.1%. The water consumption in the lower reaches accounts for 13.6%, and the water consumption in the upper reaches merely accounts for 2.3% of the total water consumption. When water moves from mountains in the upper reaches to oases in the middle reaches and then disappears in the desert in the lower reaches, it causes significant differences in economic development, natural environmental bearing capacity, and ecological stability among the three reaches. The fact that population and economy mainly concentrate in the middle reaches results in the high water consumption in Shandan, Minle, Linze, Gaotai, and other regions (Table 4). Meanwhile, utilization of water resource in the year 2006 reached 95% (statistical data from the water resource department of Gansu Province), which far exceeds the rational exploitation warning line of 40% set by international consensus.

Globally, agricultural water use including irrigation accounts for about 70% of the global water and irrigated agricultural land comprises less than one-fifth of the total cultivated area of the world but produces about two-fifths of Advances in Meteorology the world's food (Postel 1999). Similarly, the irrigation farming in the middle reaches of the HRB has greatly contributed to the increase of food production historically and supported the large number of population of the northwestern China. In the HRB, large-scale development of irrigation farming induces dramatic increase of water demand. However, from the global perspective, food production relying on "irrigation miracle" gives significant impacts on water. China's agricultural water consumption was much higher than other countries all over the world. For the ratio of daily life water usage, industrial water usage, and agricultural water, Russian is 17:60:23, Canada is 18:70:12, America is 13:45:42, and Brazil is 22:19:59, while China is 6:7:87. Therefore, there is a lot of works to do on agricultural water saving strategies in terms of water resource management.

In the HRB, agricultural water use accounted for about 94% of the total social and economic water consumption in the year 2006, but the water efficiency and the water productivity were very low. Due to people's unawareness of implementation of water-saving projects, the water-saving renovation project cannot be effectively promoted, and thus the water demand for farmland irrigation is hard to decrease. This phenomenon is extremely predominating in the middle reaches of the HRB, where there are too many irrigation gates and plain reservoirs and where high technical irrigation engineering and exploitation of groundwater cannot be supported. All of these lead to low water efficiency and lower GDP output of per unit of water. Water resource of the HRB can not only generate economic benefits, but also provide the ecological service function. Some scholars put forward the generalized water efficiency and point out that it not only represents the social and economic water consumption, but also represents natural ecological water consumption; it not only focuses on a single department's or unit's water utilization process, but also pays attention to the water utilization of the whole region. A river basin is not only characterized by natural and physical processes but also related to man-made projects and management policies. In this sense, the lower reaches are rich in natural resources, but the ecological sustainability is extremely vulnerable because of limited water. The oasis is the most concentrated area of human activities in arid regions and the disturbances are happening on a large scale in this area. Therefore, the desertification process of the lower reaches of HRB exacerbated the deterioration of the ecological environment, causing the area to become a source of dust storms and threat environmental safety in northern China.

Table 4 Statistic of water consumption (1000 m^3) of the Heihe River Basin by countries in the year 2000

Region	Domestic living in cities	Domestic living in countryside	Industry	Farmland irrigation	Forest and fishing	Stock raising	City environment	Total
Qilian	417.8	353.3	1246.0	7815.6	5154.6	3305.9	38.8	18331.9
Shandan	1435.5	2702.9	15573.0	214360.0	20214.3	1300.0	138.5	255724.2
Minle	1968.3	3099.6	8771.0	404498.1	27034.0	1162.3	183.5	446716.7
Ganzhou	6371.4	6086.4	28222.1	640706.5	49352.0	4312.6	723.0	735774.0
Linze	1300.6	1993.0	13102.8	380011.4	57492.0	1109.6	119.1	455128.4
Gaotai	1591.5	2103.8	8609.9	278336.0	45154.0	1367.5	148.0	337310.7
Sunan	335.2	279.4	2434.4	24108.0	13844.4	1134.2	32.9	42168.6
Jinta	461.7	684.2	4669.2	68783.4	21100.0	418.4	41.0	96157.7
Ejina	390.9	62.9	2981.1	10136.5	249421.0	810.7	78.2	263881.2
Total	14272.8	17365.5	85609.4	2028755.5	488766.3	14921.0	1503.0	2651193.5

Deficient Systems and Institutions on Water Management

Along with Unreasonable Water Allocation Scheme, in the inland river basin, rising the water security and efficiency is of great significance, which can guarantee the water supply for livelihood and production. The situation about the low water efficiency in the HRB is far from being satisfactory. The deficiency of systems and institutions on water management as well as the unreasonable water allocation scheme becomes the primary cause of the severe water consumption in agriculture.

There are two main kinds of management strategies for community irrigation in the HRB: the collective management strategy and Water User Associations (WUAs) management strategy. For the collective management strategy mode, village leaders are in charge of the village water allocation, channel maintenance, water charges, and other relevant issues to fulfill their water management duties. In contrast, WUAs is independent water management organizations which take over the village leaders to be responsible for water allocation, channel maintenance, water charges, and other relevant issues in a specific village. In terms of the policies and measures on water demand management, there are three modes: water price, water tickets, and water rights. For the water price mode, the government would charge some fees for water services. For the water tickets mode, the farmers need to purchase water tickets from village leaders or WUAs before the farmland irrigation activities. The water rights mode refers to the water right card issued to farmers to guarantee their water consumption rights.

From the year 1992 onward, a series of water resource allocation and management policies have been implemented in China to alleviate the conflicts between natural water shortage and the high water consumption. In the year 1997, the Heihe River Basin Bureau was established for special management of water resource in the HRB. With the support of scientific research from Chinese scholars, it has allocated the water resource for five times among the HRB. Unfortunately, different counties have their own management focuses and time schedules, which leads to another form of water waste.

The difficulty for a rational water allocation scheme is also constricted by the fact that the supply volume and the annual distribution of water in the lower reaches are completely subjected to the human activities in the middle reaches. In the long history, people living in the middle reaches performed irrigation agriculture (settled culture) and the people living in lower reaches performed nomadic husbandry. Even though conflict on water use between the middle reaches and lower reaches has a history of 200 years, it reached to an unprecedented situation. Since 1950s, intensive agricultural practices in the middle reaches have resulted in drastic environmental degradation in the lower reaches.

In addition, Heihe River dries up in May, June, and July and is flooded in August to October, and the water volume would reduce and even stops flowing sharply in December till the next March or April. At that time the river will be recharged. Consequently, there is a prominent contradiction between the water supply and demand in the lower reaches timely and spatially, which deteriorated by the fact that the high water demand just happens in the dry periods. Meanwhile, the water quality and water pollution caused by severe human activities cannot be ignored. In the past decades, the water scarce conditions and water quality situation have been aggravated dramatically in the lower reaches because of the large increase in agricultural fertilizer and pesticide use in the middle reaches.

Methods

Observational analysis and model-based simulation are both adopted in this study. Firstly, we conducted data analysis of the HRB, where Geographic Information System technologies are frequently used to process and analyze data. This step is the basis of the simulation process that followed. Then under certain designing of simulation and the prepared input parameters, model-based simulation could be done accordingly, and the output variables could be obtained to identify the influence of the two kinds of balances caused by land use/cover changes. The main method used in this step is the WRF model. The two steps mentioned above are designed to serve the subsequent analysis phase, which is also the most important part of the study. Next by analyzing the output variables of the simulation according to certain balance equations, general and empirical interpretation could be done in regard to the impact of the two kinds of balance caused by LUCC.

WRF Model and Simulation Schemes

The analysis of the energy balance and water balance in the HRB was based on the simulation with the WRF model, a regional climate model that has been widely used in the global climatic studies (Seneviratne et al. 2006; Ramankutty et al. 2008; Anav et al. 2010; Jiang et al. 2011; Margono et al. 2012). The WRF model is a meso-scale numerical weather prediction system designed to meet the needs of both atmospheric research and operational fore-casting. Besides, there are two dynamical core versions of WRF, including the Advanced Research WRF (ARW) and the WRF-NMM (NMM), and the former one was adopted in this study. The ARW module includes the Preprocessing System (WPS), main program and postprocessor, and Post-processing System; it provides many physical parameterization schemes and has strong robustness for predicting the climate change with various parameters such as the temperature, precipitation, radiation, and heat flux.

Two sets of tests were designed and performed in this study, namely, the control test and the sensitivity test. The two tests differ in the land cover types of the underlying surface, the land cover data of the year 2000 served as a reference in the control test, while that of the year 2010 were included in the sensitivity test. The input parameters and parameterization scheme of the physical processes except the land cover data were the same in the two tests in order to analyze the impacts of LUCC on the energy and water balances. The two tests were implemented with the same climate forcing data between October 2008 and December 2010. The simulation period of the control test ranged from January 2000 to December 2010, and the land cover data of the year 2000 were used as underlying surface data, while the simulation period in the sensitivity test ranged from January 2010 to December 2010, with the land cover data of the year 2010 used as the underlying surface data. The experiment was designed in this way to eliminate the influence of the climate forcing data and simultaneously focus on the impacts of LUCC on the surface energy balance and the water balance.

Energy Balance and Water Balance

The WRF model was used to simulate the change of the parameters to represent the energy balance and water balance, and then the energy balance equation and the water balance equation were used to analyze the impacts of LUCC on the energy and water balance. The following simplified equations were used to examine the energy balance (Seto et al. 2011). It should be noted that the energy balance generally only refers to the surface energy balance.

$$H + E = Rn - G \tag{1}$$

$$H = \rho C_p K_h \Delta t / \Delta z \tag{2}$$

$$L = (1 - \gamma)\rho C_p K_w \Delta e / \Delta z \tag{3}$$

$$\beta = \frac{H}{E} = \gamma \Delta t / \Delta e \tag{4}$$

where R_n is the net energy flux at the interface, representing the total energy absorbed by the ecosystem (W/m^2), which is redistributed into H, E, and G; H refers to the sensible heat, E is the latent heat (W/m^2), G refers to the soil heat flux (W/m^2), γ is wet and dry bulb constant, K_h and K_w are the diffusion coefficients of the sensible heat and the latent heat, respectively, and it is generally assumed that $K_h = K_w$ since the two exchange processes rates are similar; Δt, Δe, and Δz are the temperature difference, pressure of water vapor difference, and altitude intercept of two heights, respectively; ρ is the density, ρC_p means the heat a subject needs when its temperature rises by one degree per volume, and β is the ratio of H to E, which is called the Bowen ratio. The change of Bowen ratio indicates the variation of evaporation and reflection ability, which are directly associated with LUCC.

It is necessary to specify some terms with regard to the water balance at first. Altogether, there are three types of water balance, i.e., the natural water cycle balance which is characterized by precipitation–runoff balance, social water cycle balance, and the balance between the supply and demand of water resources. In this study, we focused on the natural water cycle balance, which is also the foundation for analyzing the social water cycle as well as the supply and demand of water resources at the watershed scale. In some sense, the analysis of the natural water cycle balance is sort of analysis of the water yield cycle balance, which is the relationship among precipitation, evaporation capacity, and runoff in a watershed. The water balance in a closed watershed is expressed as follows if the change in water storage and interbasin water transfer were neglected (Halihan et al. 1998; Sahu et al. 2013).

$$P - ET - R = \frac{dW}{dt} - U \tag{5}$$

where P is the precipitation of the watershed in the period (mm/day), ET is the total evapotranspiration of the watershed in a period, including water surface evapotranspiration, soil evapotranspiration, vegetation transpiration, and phreatic water evaporation (mm); R is the total runoff of the watershed export section in a period, which includes surface runoff and subsurface runoff (mm); W is the total surface water volume, including soil moisture, snow, and groundwater (mm); and U is the climatological soil moisture nudging term used in the NCEP/NCAR reanalysis, and $\frac{dW}{dt}$ refers to the variable quantity of water storage of the watershed in the period (mm). Note that U is a source term (positive denoting addition of water to the soil) and that $U = 0$ in the simulations. Also although changes in the groundwater level from the lowest layer into runoff are included in $\frac{dW}{dt}$(in the observations), we did not pay much attention to the groundwater. In addition, the water withdrawal process of the socioeconomic system has been taken into account in this analysis.

The Impacts of LUCC on Surface Energy

The simulation results indicate that the LUCC exerted significant impacts on the energy balance in the study area. For example, in S4 (Fig. 4), the significant increase of albedo, which was generally associated with the conversion of grassland to barren or sparsely vegetated land, increased the net energy in regions with high vegetation coverage. Besides, the change in the net energy flux affected not only the magnitude of all fluxes, but also the partitioning of energy into different surface fluxes in different seasons. For example, the simulation results in S4 showed that the sensible heat fluxes decreased in winter and increased in other seasons, while the evapotranspiration only experienced a slight increase in spring and decreased in summer and autumn (Fig. 4, S4). Land cover of S1 in 2000 was similar to that of S4, but the vegetation coverage of S1 increased slightly during the simulation period, resulting in slight decline of sensible heat flux and increase of evapotranspiration in summer and autumn. Nevertheless, there was minor change in the vegetation coverage in S1 in spring and winter, which are not the growing seasons of vegetation, and as a result there was minor change in both the sensible heat flux and evapotranspiration in these two seasons (Fig. 4, S1). A lot of cropland/grassland mosaic land changed into dryland Cropland and pasture in S2, which is a drying reservoir, and as a result the sensible heat flux increased, but there was no significant change in the evapotranspiration (Fig. 4, S2).

The annual mean Bowen ratios in S1, S2, and S3 in the sensitivity test (8.88, 12.76, and 21.96) are slightly lower than that in the control test (9.11, 12.86, and 22.07), while the situation in S4 is on the contrary, where the annual mean Bowen

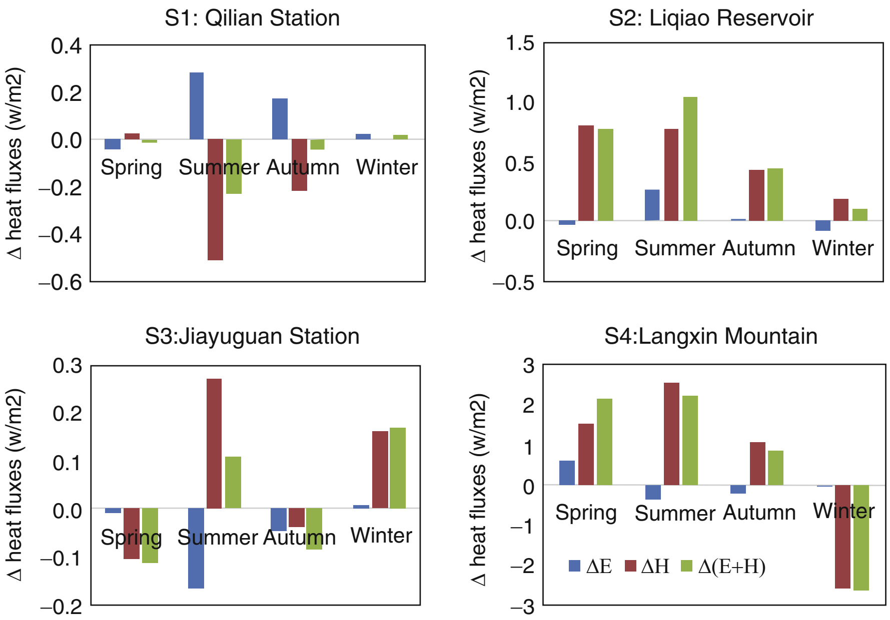

Fig. 4 Seasonal differences in the changes of evapotranspiration (E), sensible heat flux (H), and their sum (4(E + H) caused by LUCC in the four study areas listed in Table 3. *Note*: Seasons are divided as follows: Spring (March, April and May), Summer (June, July, and August), Autumn (September, October, and November), and Winter (December, January, and February) (Reprinted from Deng et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

ratio in the sensitivity test is 0.34 higher than that in the control test (Table 5). The Bowen ratio is the ratio of H to E, and its change indicates the variation of evaporation and reflection ability, which are directly associated with LUCC (Table 3). As S1, S2, and S3 were all characterized by the conversion from land types with low evaporation and high reflection to land types with high evaporation and low reflection, these areas demonstrated the same changing pattern in the Bowen ratio. By comparison, the LUCC of S4 was from high evaporation and low reflection to low evaporation and high reflection, which led to the different change in the Bowen ratio.

As for the seasonal variation, there were similar changing trends of the Bowen ratio in the S1, S2, and S3 in both the sensitivity test and the control test, which was higher in summer and lower in winter and moderate in spring and autumn. By comparison, the highest Bowen ratios appeared in winter and the lowest ones appeared in spring in S4 in both the sensitivity test and the control test. Besides, in all of the four areas, the evaporation and reflection ability were generally higher in summer and lower in winter. However, in the first three areas, the net decrease of evaporation in winter was more significant than the net decrease of reflection in summer, while S4 demonstrated the opposite trend. Consequently, there were certain effects of LUCC on the Bowen ratio, but the seasonal variation trends of the Bowen ratio nearly remained unchanged.

Table 5 Seasonal differences in the changes of Bowen ratio caused by LUCC in the four case study areas listed in Table 3

	S1		S2		S3		S4	
	Control test	Sensitivity test	Control test	Sensitivity test	Control test	Sensitivity test	Control test	Sensitivity test
Spring	5.83	5.56	6.23	6.18	11.45	11.72	17.78	17.74
Summer	18.43	17.66	24.33	24.88	31.11	30.48	43.78	43.74
Autumn	7.7	7.99	13.89	13.53	20.69	20.83	32.07	32.94
Winter	4.48	4.32	7	6.83	25.03	24.79	71.49	72.05
Mean	9.11	8.88	12.86	12.76	22.07	21.96	41.28	41.62

The Impact of LUCC on Water Balance

The simulated water budget components include the monthly changes of precipitation (P), evapotranspiration (ET), runoff (R), the difference between precipitation and evapotranspiration (P–ET), and the water storage terms including surface water and groundwater (P–ET–R = dW/dt – U). The simulation results indicate that P, ET, and R in all of the four case study areas showed obvious seasonal variation (Fig. a–c), with a general similar variation trend of P in two tests, but their values were different between the two tests, which showed the impacts of LUCC on precipitation, evapotranspiration, and runoff. Meanwhile, the simulated P–E curves in four case study areas showed a distinct seasonal cycle, with precipitation exceeding evapotranspiration (Fig. 5d). The water storage terms (P-ET–R) are depicted with the P–ET–R curve (Fig. 5e), which also showed significant seasonal variation in

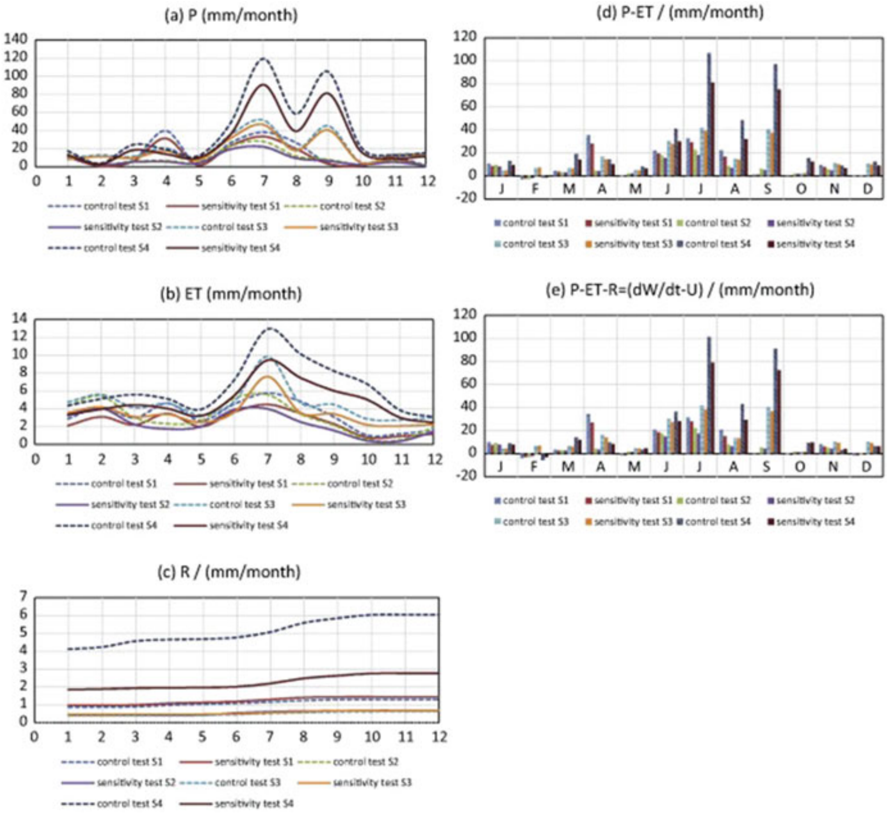

Fig. 5 Simulated P (a), ET (b), R (c), P–ET (d) and P–ET–R = ($\frac{\mathrm{dw}}{\mathrm{dt}}$ − U) (e) in the control test and the sensitivity test of the four study areas. *Note*: Simulation results without LUCC refers to the simulation based on the LUCC data of the year 2000, whiles those with LUCC means the simulation are based on the LUCC data of the year 2010 (Reprinted from Deng et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

both the sensitivity and control tests. The P–ET–R values in the sensitivity test are higher than those in the control test in the four key study sites, which indicated corresponding higher water storage in different degree is caused by LUCC in these areas.

Figure 5 illustrates the simulation results of water budget components in the four case study areas in the sensitivity test and the control test, the differences between which are considered as the impacts of LUCC on the water balance. In S1 in the river source area in Qilian Mountain, there is obvious seasonal variation of P in both tests, with the peak appearing in April when the snow starts to melt. The runoff will increase in S1 due to the increased vegetation coverage rate, which leads to more rainfall and decline of evapotranspiration. The P–ET–R curve is very similar to the P–E curve, with higher than annual storage from June to August in both of the two tests, but the water storage is higher in the sensitivity test than that in the control test. In S2, both the precipitation and evapotranspiration decline due to the LUCC, however, the overall runoff increases. The P–E curve also shows notable seasonal variation, with the highest value occurring during June and August in both tests. The P–ET–R curve is very similar to the P–E curve, with higher than annual mean storage from June to August in both of the two tests, but the water storage value is higher in the sensitivity test than that in the control test. In S3, the precipitation decreases slightly due to LUCC, which further leads to the decline of evapotranspiration. Meanwhile, the runoff value is higher in the sensitivity test than that in the control test, which exactly reveals the increasing effects LUCC on the surface runoff in this area. Then it is self-evident that the P–E value in the sensitivity test is higher than it is in the control test. The P–ET–R curves in both tests show that insufficient water is stored between October and May and excessive water is stored between June and September. However, the monthly water storage in the sensitivity test is more than that in the control test, which indicates that the total water storage increases due to LUCC in this area. In S4, the simulation results indicate that the precipitation and evapotranspiration both decline due to the decreased vegetation coverage, so as to the runoff increases since there is less water that is absorbed by soil or gets into the underground water. Consequently, the monthly average water storage increases slightly due to LUCC in this study area. Besides, the most significant changes occur during June and September. Meanwhile, the variation trends of P, ET, R, P–ET, and P–ET–R are quite similar in S4 in the two tests.

The results of this study are consistent with some previous research in the same study area (Gao et al. 2008), i.e., there are obvious seasonal changing trends of the surface energy balance and water balance. Besides, the general conclusions about the impacts of LUCC on energy and water balance in this study are similar to that of previous similar research that has taken LUCC into account (Boulain et al. 2009; Ramier et al. 2009; van der Meijden et al. 2010). However, the results of this study differ from previous research due to the difference in the study areas and the classification system of land use and land cover. For example, one empirical study in USA concludes that the runoff and ET decreased when the grassland changed into crop land (Sun et al. 2010), which is consistent with the results of this study; however, their study indicates the heat flux increased all year round due to land use change, which is different from the results of this study. Simulation results suggested that it will take a long time to restore the ecological environment and improve the water and soil conservation in the HRB. Therefore, this study supports the notion that it is much easier to destroy an ecosystem than to restore it, which raises the alarm for local land managers.

Figure 6 shows the average daily observation value and simulated value of evapotranspiration. The simulated values of ET are larger than the observation values in the Langxin Mountain station (S4) covered by high quality grassland, where the largest ET occurs (Fig. 6), while in the Qilian Station (S1) where ET is the lowest among these four stations, the simulated value of ET is a little higher than the observation values, even though there is some grassland and it belongs to alpine meadow. Besides, Fig. 6 shows that ET will fluctuate more drastically in Liqiao Reservoir (S2), especially during April and August when it is the growing season of vegetation. Overall, the simulated ET responds well to the observation records, indicating that the simulation method is reliable. However, it is still necessary to take more factors into consideration when simulating and analyzing the impacts of LUCC on the surface energy and water balance since the energy balance and water balance are complex processes that are related to the atmosphere and the soil system. For example, the groundwater circulation is an important component in the water balance, and it should be considered in the simulation scheme in the future.

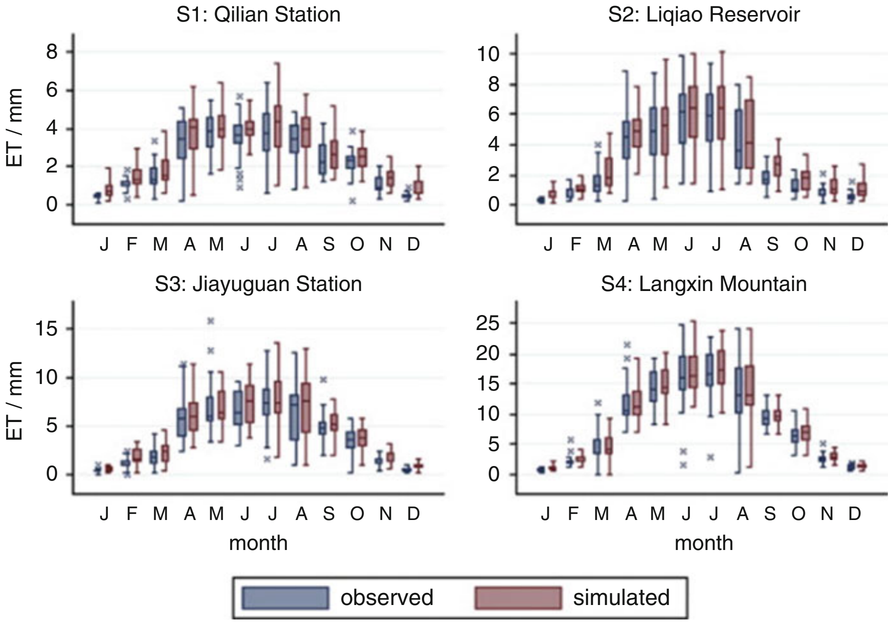

Fig. 6 Comparison between the daily observed and simulated ET in the four stations of year 2010. *Note*: Boxes represent the 25th percentile to the 75th percentile of both the observed records and simulated values of ET, the lines include the upper adjacent value to the lower adjacent value, and the cross means the outside values (Reprinted from Deng et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

Summary

Discussions

Considering the water scarcity character of the HRB, it is important to clarify the coupling relationship between water, ecology, and social economy, reveal the driving mechanism of the socioeconomic system on the evolution of water resource, improve the systems and institution designs for water management, and explore innovative approaches on optimal water allocation.

Based on the modeling and integration analysis, the Decision Support System (DSS) is vital to achieving the adaptive water management in the HRB. At present, there have been two types of DSS: research-oriented DSS and application-oriented DSS. Research-oriented DSS for the HRB is a scientific model integrating "Water-Soil-Gas-Biology-Human." It tries to integrate the expert knowledge and experience of the HRB to build a spatially explicit model with scenario analysis method. For the development of the research-oriented DSS, it has integrated multiple hydrologic models and coupled many GIS functions to support coupled work of multi-disciplinary model. Also, it has made technical breakthroughs on the mismatch of the models at different spatial-temporal scales. Through providing scenario-driven decision making strategies graphically and multiobjectively and providing various auxiliary decision tools, it is expected to be a new generation of DSS for river basin integrated management. For the application-oriented DSS, some water management DSS can analyze the climate and human activities at the middle reaches of the HRB. It is also able to study the planting structure of different crops and spatial-temporal distribution of water requirement with different hydraulic engineering conditions. Finally, it can realize the simulation of water resource allocation process at multi-level (the whole basin, administrational district, and irrigation region) and evaluate the influence of varied water resource management strategies.

Taking the arid climate and the unique relationship among the three reaches of the HRB into consideration, there should be an innovative framework and research components for DSS for the HRB based on the existing studies (Fig. 7). Spatially, water consumption of the HRB mainly concentrated in the middle reaches, where industrialization and urbanization are evident. Institutionally, there is a history of water right and water price system and institutions in the HRB, especially in the middle reaches where irrigation agriculture is preformed widely. Naturally, the desertification process exacerbated the deterioration of the ecology and change of oasis area. Also the future climate change will greatly influence the hydrological process and water supple, that is, the precipitation as well as the solid glacier in the upper reaches. Therefore, we should firstly comprehensively consider and make multiple scenarios analysis on the impacts of water right system reform, industrialization and urbanization, land use change, change of oasis area, and climate change on the HRB. This work can be conducted on the basis of exciting knowledge, data, and regional models. The scenarios analysis results would help to deepen and widen the recognition of the mechanism and linage of a series of factors within the ecology and economy of the arid area.

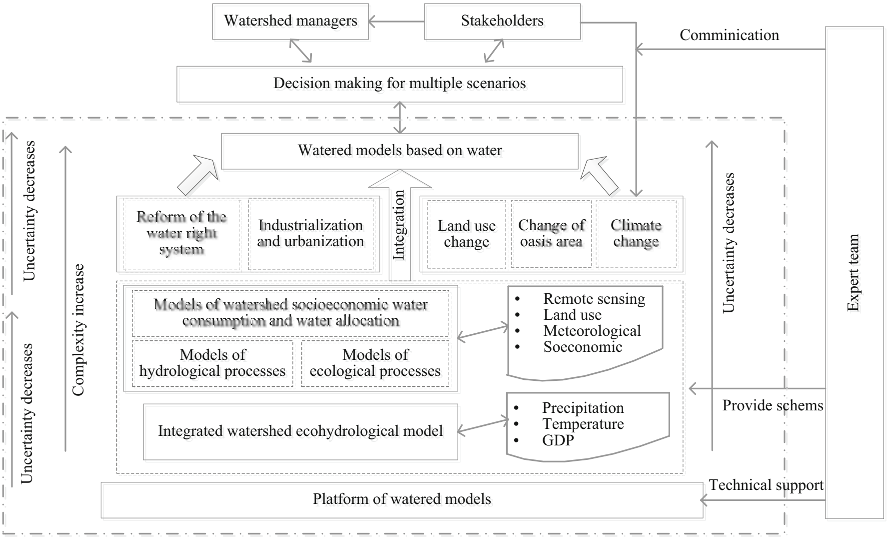

Fig. 7 Framework and components for a DSS for the integrated water management in the Heihe River Basin

Secondly, the water resource utilization in the HRB is often confronted with the contradiction between ecological service and social and economic development. Therefore, it is necessary to realize the modeling integration between the social-economic model and ecohydrological model for the optimization of watershed management. Also Millennium Ecosystem Assessment puts forward the idea that "regulating water supply service on ecosystem by means of economy and market is the preferred method of management." The balance between the water supply and demand is the core to integrate the social-economic model and ecohydrological model as separate module (Fig. 7). The work on model integration needs to analyze the water supply capacity, water consumption structure, water efficiency, and water demand trend at multilevel (whole basin, administrational district, and irrigation region). Specifically, it needs to clarify the interaction mechanism among the water supply in the upper reaches, the industrial water consumption in middle reaches, and ecological water consumption in the lower reaches.

Further, the water management system is indispensable for the whole framework of the DDS. In practice, due to the absence of proper water management system, the conflicts among counties often arise because of competition on water use and jurisdictional mandates of the related stakeholders. An integrated watershed water management system should comprehensively consider the ecology, hydrology, and socio economy in the basin, in order to provide scientific support for the water security, ecological security, and sustainable development of the inland river basin. Last but not least, water optimal allocation strategies should be involved to explore the regulation measures under different natural and social scenarios. In recent years, a series of studies have been carried out on understanding the impact of human activities (irrigation, livestock activities, and institutional change) on water.

Throughout studies on the HRB and other inland rivers, it can be identified that promoting water management from water demand management to water consumption management is an important direction for scientific and sustainable development of the HRB. Furthermore, from the institutional perspective, a spatially and dynamically effective water allocation scheme is a strategic need for rational and efficient use of water in the HRB. A pressing matter of the moment for reforming the water management systems in the HRB is to improve the water system based on the water demand in production, human living, and natural ecology.

Conclusions

This study explored the impacts of LUCC on the surface energy and water balance in the HRB during 2000–2010 based on the simulation with the WRF model. LUCC during 2000–2010 was first analyzed, and the dominant LUCC types were identified, according to which four typical case study areas were selected. Then the climate change was simulated with the WRF model on the basis of the land use/cover data in 2000 and 2010. Simulation results indicated that LUCC in the HRB exerted remarkable impacts on the regional surface energy and water balance, which was characterized by significant spatiotemporal variance, and the evapotranspiration was higher than sensible heat flux in summer, while it was on the contrary in winter. Besides, the simulation results showed that the conversion from grassland to barren or sparsely vegetated land led to the most significant changes in the latent, sensible, and total heat flux in all seasons in comparison to other types of land use/cover dynamics. This indicated that grassland degradation which was one of the most severe ecological and environmental problems in the HRB exerted the most significant impacts on the surface energy balance. By contrast, the conversion from barren or sparsely vegetated land to water area led to the slowest and the minimum variation of heat flux in the whole year.

The simulation results in this study also indicated that the conversion from grassland to barren or sparsely vegetated land decreased the available energy for evapotranspiration, which correspondingly elevated the runoff. Besides, the simulation results showed that effects of grassland degradation on the water balance are more prominent in summer and winter than in the other seasons. In addition, severe droughts can have significant influence on the surface soil moisture and plant growth and consequently greatly affect the evapotranspiration. Therefore, it is necessary to consider the soil water conditions in the analysis of the effects of LUCC on albedo, energy, and water balances at large scales. In addition, the simulation results in the four selected case study areas in the HRB showed that there were profound impacts of LUCC on the water balance, and the energy balance and the water balance interacted with each other. Therefore, we put forward a suggestion of shifting the water balance by LUCC to improve the water management, which can shed light on the land use planning to offset the LUCC-induced negative impacts on the surface energy and water balances.

The sensitivity test of this research mainly focused on testing whether the WRF is applicable to this study area, and as for the data limitation, we can only conduct the controlling test using one-year data, and this is also one of the major limitations of this research. In the future research, we can conduct the controlling test based on the panel data of multiple years, and it can be used not only in the examination of the effects of model setting on simulation results, but also to examine the effects of index selection on simulation results. In summary, it is necessary to establish an integrated water management system based on the water carrying capacity in order to provide support for the strategic decision making at watershed scale for sustainable development of the HRB. In addition, establishing an integrated model on river basin with clear physical process, powerful functions, and strong applicability has universal significance. It can also be applied to many inland basins in China, as well as other inland river basins which are distributed in all continents of the world, account for 11.4% of the global land area, and provide significant support for sustainable development of regions with severe water shortage, fragile environment, and rapid development demand.

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Adapting Water Scarcity for River Basin: Optimization of Land Uses

Zhihui Li, Xiangzheng Deng, Aisha Arowolo, Qunou Jiang, and Haiming Yan

Contents

Introduction 120
Identification of Water Scarcity in the Heihe River Basin 122
  Water Scarcity with Imbalance Between Water Supply and Demand 122
  Irrational Water Consumption Structure with Low Water Efficiency 124
  Deficient Systems and Institutions for Water Management Along with Unreasonable Water Allocation Scheme 125
Water Resource Availability and Land Use/Cover Change 127
  Water Yield Variation Due to Forestry Change in the Head-Water Area of the Heihe River Basin, Northwest China 128
  Water Resources in Response to Land Use Change in the Middle and Upper Reaches of the Heihe River Basin 134
Summary 147
References 149

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Abstract
Water scarcity is a hot issue in river basin management, especially in ecologically fragile areas with arid climate, such as the Heihe River Basin (HRB) in Northwest China, where water availability is at the core of sustainable socioeconomic development and ecological conservation and the effects of land use changes on the hydrological process are crucial to rational allocation of water resources. In this chapter, first, we identified that the severity of water scarcity problems can be associated with imbalance between water supply and demand, irrational water consumption structure and low water efficiency, deficient systems and institutions for water management, as well as unreasonable water allocation scheme. Further, we investigated the hydrological responses to land use changes in the upper and middle reaches of the HRB based on scenario analysis. In one case, the results indicated that the forest land has "sponge" effects on the water resource in the upper reach of the HRB; in the other case for the upper and middle reaches, the results showed that the forest land and grassland will expand with increase in water utilization ratio, and further the quick-response surface runoff would decrease significantly due to forest and grassland expansion, which may cause an overall decreasing trend of the water yield. This indicated that water resources should be reasonably allocated for different land use demand, which is critical for sustainable development. The results of this chapter will be informative to decision-makers for sustainable water resource and land management.

Keywords
Water scarcity · Water constrain · Water yield · Surface runoff · Forestry change · Land use changes · Hydrological process · SWAT · DLS · Heihe River Basin

Introduction

Water is one of the most critically limited resources for sustainable development and natural ecosystem conservation, especially in the arid and semiarid regions (Vörösmarty et al. 2000). Its scarcity is further triggered by the unsustainable use, rapid population growth, and economic development, which results in deterioration of the natural ecosystem, land degradation, and decrease in agricultural production.

In view of this, the issue of water scarcity and stress have increasingly attracted more attention, and how to improve water provision to adapt for water scarcity becomes a key issue in the river basin management in order to reconcile water availability and demand. The water resource management and land use patterns are intrinsically linked. On the one hand, the provision of water resources is closely related with the hydrological processes, which are considered to be affected mainly by climate and land use/cover changes in the river basins (Al-Bakri et al. 2013). Better understanding of the impact mechanism of climate and land use/cover changes on hydrological processes is crucial for sustainable water resource management. At a catchment level, forest cover and agricultural cultivation have significant impacts on the water resources and can affect the availability of water for other users. While climate and land use/cover change interact with each other, it is important to apply consistent climate or land use conditions when trying to investigate the separate impacts of land use/cover change and climate change on the hydrological processes (Bierwagen et al. 2009). For example, Van Ty et al. (2012) and Kim et al. (2013) investigated the impacts of climate and land use/cover change on hydrological processes, respectively, and their results showed that both changes in climate and land use/cover have significant impacts on streamflow in the basins. On the other hand, water resource is the determinant factor that will affect the land use structure since different land use types have different water demands (Deng et al. 2014) and land use/cover change in arid region is strongly restricted by water resources. For example, Li et al. (2011) found that after the implementation of the water allocation scheme in the HRB between Gansu Province and Inner Mongolia in 2000, water use in the middle reach region was further limited, which significantly affected the land use structure changes in the middle reach region of the HRB. Besides, for long-term water resource planning and management, scenario analysis has become an efficient method to predict the responses of hydrological process to climate and land use/cover change. For example, Menzel et al. (2009) designed two intermediate land use/cover change scenarios, with projected developments ranging between optimistic and pessimistic futures (with regard to social and economic conditions in the region) and climate conditions remaining unchanged; the simulation results showed that both increase and decrease of water availability depend on the future pattern of natural and agricultural vegetation and the related dominance of hydrological processes.

The HRB, as a typical inland river basin located in the semiarid region of Northwest China, is facing increased water scarcity issues, which have become the major bottleneck of socioeconomic development and ecological security, especially where agricultural production and natural ecosystems are closely linked and compete for the water use. The water from the Heihe River is important to agricultural production and ecosystem stabilization in the middle and lower reaches of the HRB and is highly sensitive to climate change and human activities in this area. The climate in the HRB has remained in a relatively stable warm-wet state since the 1960s and has not experienced strong changes due to global warming (Qin et al. 2010). Therefore, human activities, such as land use changes and economic development, have become the dominant driver of changes in the water resources of the HRB over the last 60 years. Especially between the 1960s and 1990s, with the rapid expansion of farmland, a large increase in the quantity of water used for irrigation had directly lead to the decrease in the amount of water for ecosystems, resulting in devastating environmental and ecological problems in the arid river basin (Hu et al. 2015).

In this chapter, we firstly aim to identify the water scarcity condition of the HRB; following, in order to come up with adaptation strategies that may release the pressure from water scarcity and minimize the water conflicts between agricultural production and natural ecosystems from the perspectives of land use optimization, we investigated the relationship between water availability and land use changes in the typical area of the basin: we firstly analyzed the effects of forestation on the hydrological process in the upper reach of the river basin, which is the water source area of the whole basin and crucial to protecting water resources; further taking the upper and middle reaches of the HRB as the study area, we aimed to investigate the changes in the hydrological processes under different land use scenarios based on the degrees of water constraints. The research results in this chapter are meant to provide valuable information and implications for future sustainable water and land management in the HRB.

Identification of Water Scarcity in the Heihe River Basin

Water plays an important role in economic development and ecological balance of the HRB, especially in the middle and lower reaches. During the 1960s–1990s, intensive agricultural activities in the middle reaches and lack of effective coordinated water management system have drastically reduced the amount of water that flows into the lower reach. As a result, the rivers and lakes dried up intensively in the lower reach, the groundwater table declined, and the level of water mineralization increased, leading to substantial deterioration of the ecosystems (Deng and Zhao 2015). In addition, along with the rapid climate and land use/cover changes, water scarcity and stress faced by the HRB increasingly becomes severe and thus is a critical issue that should be addressed for sustainable development.

Water Scarcity with Imbalance Between Water Supply and Demand

Water scarcity is a long-standing and widespread problem in the HRB, with the characteristic of unevenly temporal and spatial water distribution. There are a series of reservoirs (1 large reservoir, 9 medium-sized reservoirs, and 89 small reservoirs) in the basin, and the total capacity is 416.9 billion m^3. Influenced by topography, altitude, and atmospheric circulation at different scales, the spatial distribution of precipitation is extremely uneven in the middle and lower reaches. Generally, the annual average precipitation decreases from the southeast to the northwest (Fig. 1). The maximum precipitation zone mainly concentrated in the upper reach with an altitude of 2200–3000 m and an annual precipitation of 400–750 mm. In contrast, the minimum precipitation zone is the desert area of Ejina, which administratively belongs to the Inner Mongolia, with an annual precipitation of only 15–50 mm.

Aside from precipitation, the available water resource mainly depends on the amount of water from the upper and middle reaches, supplied by springs, subsurface flow, and solid glacier in the Qilian Mountain. There are 298 million m^3 of water resource formed by ice and snow melting from the Qilian Mountain, accounting for 8% of the total amount of runoff. However, due to irrational human activities that seriously changed the landscape structure and composition in the upper reach of the HRB, available water resources inevitably reduced. It has been concluded that the yearly based rate of glacial retreating was around 0.60% in the HRB from the 1960s to 2010,

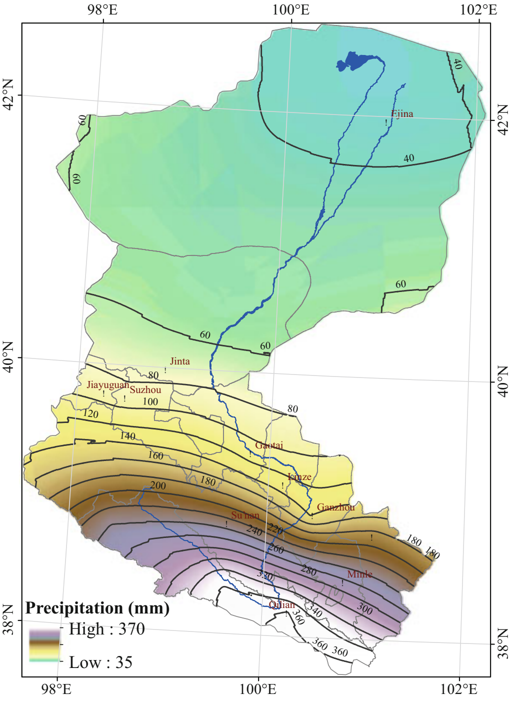

Fig. 1 Spatial distribution of the average precipitation (mm) in the HRB for the year 1960–2006 (Reprinted from Deng and Zhao (2015) with permission of Advances in Meteorology)

and this speed was significantly faster than that of the Tian Shan Mountain (0.49%/a), Geladaindong (0.05%), and Naimona'nyi region (0.26%) (Huai et al. 2014).

Meanwhile, water demand in the HRB has increased considerably over the past half century. Since 1949, the Chinese government has paid much attention to the development of irrigation infrastructure, and by 1985, the number of reservoirs (the small plain reservoirs and embankments with a volume less than 100,000 m^3 are not accounted) in the middle reaches had reached 95, and the total storage capacity had been up to 360 million m^3, more than 20 times of that in 1949. As a result, the hydrology changed radically in the middle reach, which was highlighted by the fact that the utilization rate of surface water increased by 19 times, the area of irrigated oasis expanded by 89.5%, and the area of desertification land increased by 4–11% since the year 1949. Along with utilization of the surface water, the groundwater was also extensively explored, and the number of motor-pumped well had doubled from 1985 to 1994 (Wang and Cheng 1998). The groundwater table had been steadily decreasing due to the overpumping and the decreasing of recharges. In fact, there is a very close interconnection between the surface runoff and groundwater in the HRB because of the water distribution characteristics of the HRB, which partly determined the hydrological process. Last but not least, as the intermediate linkage between the surface water and the groundwater, the volume of springs also showed a decreasing tend. In addition, the average reducing rate had increased by 6.8% in 1981–1991 compared to 1960–1980 (Wang and Cheng 1998).

Consequently, the exploitation on surface runoff water and groundwater had dramatically changed the hydrological situation of the HRB during the long historical period. All the 33 tributaries in the middle reach no longer joined into the main stream of the Heihe River since the 1980s and gradually disappeared and formed some independent irrigation oasis. The water volume of the runoff through the Zhengyixia hydrological station decreased sharply in recent decades, from 1.19 billion m^3 in the 1950s to merely 691 million m^3 in the 1990s, and the mainstream became a seasonal river in the downstream of the Zhengyixia station (Fig. 2). In this arid and semiarid river basin region, large-scale development of irrigation agriculture induces dramatic increase of water demand. The excessive water consumption by humans has resulted in continued environmental deterioration, which has become a serious threat to sustainable development.

Irrational Water Consumption Structure with Low Water Efficiency

Currently, the overall water consumption of all sectors in the HRB is about 3.36 billion m^3, among which industrial and domestic water consumption is fairly less and agricultural water use accounts for about 95%, posing a great threat to the ecological water consumption. Taking the year 2000 as an example, the annual water consumption in the HRB was 2.65 billion m^3, among which the farmland irrigation consumed 2.03 billion m^3; the water consumption in the forestry, stock raising, and fishing sector was 489 million m^3 in total; the industrial water consumption was 86 million m^3; the livestock water consumption was 15 million m^3; the human living

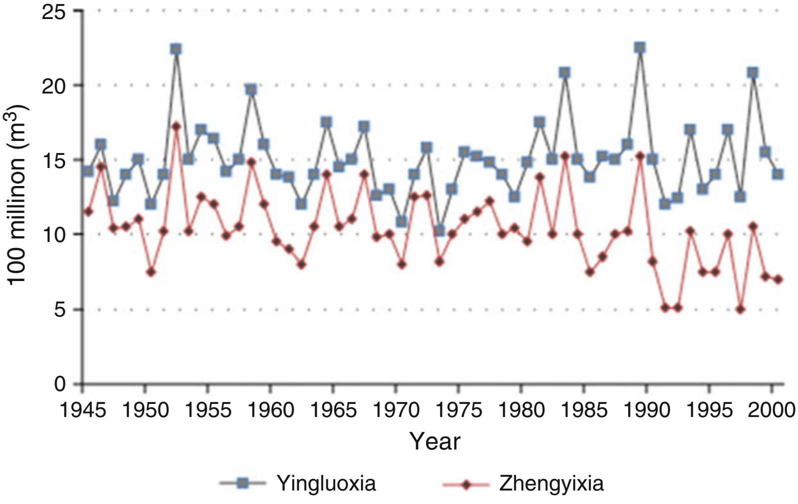

Fig. 2 Change of the surface runoff through the Yingluoxia hydrological station in the upper reach and the Zhengyixia hydrological station in the middle reach (Reprinted from Deng and Zhao (2015) with permission of Advances in Meteorology)

consumption was 32 million m^3 (including urban public consumption); and the urban environment water consumption was 2 million m^3. In terms of the spatial distribution of water consumption, the water consumption in the upper and lower reaches accounts for 2.3% and 13.6%, respectively, while the water consumption in the middle reach accounts for 84.1% of the total. The water consumption is high in the middle reach because human and economic activities mainly concentrate in this region, which results in high water consumption in the counties located in the middle reach, including Shandan, Minle, Linze, and Gaotai (Table 1).

The irrigation agriculture in the middle reach of the HRB has greatly contributed to the increase of food production historically and supported the large number of population of the Northwest China. In the HRB, large-scale development of irrigation agriculture induces dramatic increase of water demand, agricultural water use accounted for about 94% of the total social and economic water consumption in the year 2006, but the water efficiency and the water productivity were very low. Therefore, agricultural water-saving strategies are necessary in terms of water resource management. However, due to people's unawareness of implementation of water-saving projects, as well as the restriction on the crop types, planting technologies, crop rotation, land management patterns, and unguaranteed maintenance costs, the water-saving renovation projects cannot be effectively promoted, and the water demand for farmland irrigation is hard to decrease. This phenomenon is extremely predominant in the middle reach of the HRB, where there are lots of irrigation gates and plain reservoirs and high technical irrigation engineering and exploitation of groundwater cannot be supported. All of these lead to low water efficiency and lower GDP output of per unit of water, which further accelerate the water scarcity problems.

Deficient Systems and Institutions for Water Management Along with Unreasonable Water Allocation Scheme

In the inland river basin, improving the water security and efficiency is of great significance, which can guarantee the supply of water for livelihood and production. The water efficiency in the HRB is beyond the satisfactory level. The deficiency of systems and institutions for water management as well as the unreasonable water allocation scheme are the primary cause of the huge water consumption in agriculture.

There are two main kinds of management strategies for community irrigation in the HRB, including the collective management strategy and Water User Associations (WUAs) management strategy. For the collective management strategy mode, village leaders are in charge of the village water allocation, channel maintenance, water charges, and other relevant issues to fulfill their water management duties. In contrast, WUAs are independent water management organizations that take over the village leaders to be responsible for water allocation, channel maintenance, water charges, and other relevant issues in a specific village. In terms of the policies and measures on water demand management, there are three modes, including water

Table 1 Statistics of county-level water consumption (1000 m^3) in the HRB, 2000

Region	Domestic living in cities	Domestic living in countryside	Industry	Farmland irrigation	Forest and fishing	Stock raising	City environment	Total
Qilian	417.8	353.3	1246.0	7815.6	5154.6	3305.9	38.8	18331.9
Shandan	1435.5	2702.9	15573.0	214360.0	20214.3	1300.0	138.5	255724.2
Minle	1968.3	3099.6	8771.0	404498.1	27034.0	1162.3	183.5	446716.7
Ganzhou	6371.4	6086.4	28222.1	640706.5	49352.0	4312.6	723.0	735774.0
Linze	1300.6	1993.0	13102.8	380011.4	57492.0	1109.6	119.1	455128.4
Gaotai	1591.5	2103.8	8609.9	278336.0	45154.0	1367.5	148.0	337310.7
Sunan	335.2	279.4	2434.4	24108.0	13844.4	1134.2	32.9	42168.6
Jinta	461.7	684.2	4669.2	68783.4	21100.0	418.4	41.0	96157.7
Ejina	390.9	62.9	2981.1	10136.5	249421.0	810.7	78.2	263881.2
Total	14272.8	17365.5	85609.4	2028755.5	488766.3	14921.0	1503.0	2651193.5

price, water ticket, and water right. For the water price mode, the government would charge some fees for water services. For the water ticket mode, the farmers need to purchase water tickets from village leaders or WUAs before the farmland irrigation activities. The water right mode refers to the water right card issued to farmers to guarantee their water consumption rights.

Since 1992, a series of water resource allocation and management policies have been implemented in China to alleviate the conflicts between natural water shortage and the high water consumption (Cai 2008). In 1997, the Heihe River Basin Bureau was established for special management of water resource in the HRB. With the support of scientific research from Chinese scholars, it has adjusted the water resource allocation schemes among the HRB for five times. Unfortunately, different counties have their own management focuses and time schedules, which lead to another form of water waste.

The difficulty for a rational water allocation scheme is also on by due to the fact that the supply volume and the annual distribution of water in the lower reaches are completely subjected to the human activities in the middle reaches. In the long history, people living in the middle reaches performed irrigation agriculture (settled culture), and the people living in lower reaches performed nomadic husbandry. Even though conflicts on water use between the middle and lower reaches has a history of 200 years, it reached an unprecedented situation. Since 1950s, intensive agricultural practices in the middle reaches have resulted in drastic environmental degradation in the lower reaches. In addition, Heihe River dries up in May, June, and July and is flooded from August to October, and the water volume would reduce and even stops flowing sharply in December till the next March or April. Consequently, there is a prominent contradiction between the water supply and demand over time and space, which is deteriorated by the fact that the high water demanding just happens in the dry periods (Wang and Cheng 1998).

Water Resource Availability and Land Use/Cover Change

The HRB has been facing serious water scarcity problems, as water and land resources in the arid inland river basin have been intensively used due to population increase and economic expansion. In this section, we aim to investigate the impact of land use/cover changes on water resource availability for sustainable water resource management in the HRB. The main economic activity in the HRB is traditional agriculture, which is mostly concentrated in irrigated oasis regions in the middle reaches. Such an economic pattern necessitates a close relation between water resources and land use in the HRB. It has been long recognized that changes in land use and land cover are important factors affecting water circulation and the spatial-temporal variations in the distribution of water resources. Such impacts on hydrological processes are reflected in fluctuations in the supply-and-demand relation of water resources, which in turn will significantly affect the ecosystem, environment, and economy (Wang et al. 2007). With the continuous exploitation of both water and land resources in the middle reach, the runoff in the lower reach had been decreasing, and terminal lakes had dried up, resulting in a series of severe eco-environment problems in the HRB (Hu et al. 2015). The effects of land use/cover changes on the runoff process in the upper and middle reaches of this arid inland river basin are a key factor in the rational allocation of water resources to the middle and lower reaches. Thus, it is critical to clarify how land use/cover changes impact the hydrological processes in such an arid inland river basin to promote effective measures for sustainable water and land resources management in the HRB.

Water Yield Variation Due to Forestry Change in the Head-Water Area of the Heihe River Basin, Northwest China

The HRB is the second largest inland river basin in China, which can be divided into the upper, middle, and lower reaches, differing significantly in their natural and socioeconomic characteristics. For example, the average annual precipitation in the upper, middle, and lower reaches are 200–600 mm, less than 200 mm, and less than 50 mm, respectively, while the annual evaporation ranges from 500 mm in the upper reach to over 3000 mm in the lower reach (Feng et al. 2001).

The water resource in this basin mainly originates from the Qilian Mountains in the upper reach of the HRB, where the grassland and forest are the main land use types, accounting for about 21% and 50% the total land area, respectively. The relationship between forests and water resources is a critical issue which must be accorded with high priority. A key challenge faced by the land, forest, and water managers is how to maximize the wide range of forest benefits without detriment to water resources and ecosystem functions. To address this challenge, there is an urgent need for a better understanding of the interactions between forests/trees and water, also for awareness raising and capacity building in forest hydrology and for embedding this knowledge and the research findings in policies. Forestation in the upper reach of the basin is deemed as the most effective measure to enhance water availability for agriculture, industrial, and domestic uses (Singh and Mishra 2012). A quantitative assessment of the hydrological effects of forestation, especially on the water yield, is therefore crucial for improving the forestation and water resource management to guarantee the sustainable water and land management within the arid or semiarid regions.

The hydrological effects of forestation of degraded land in the dry region have important implications for local and regional hydrological services, but such issues have been relatively less studied when compared to the issue of impacts of forest conversion (Yu et al. 2013). Scientists from forestry and environmental science disciplines emphasized the significance of forests in regulating runoff and controlling soil erosion (Huaxing et al. 2009; Chen et al. 2010), while scientists from other fields, for example, geography, climatology, and agriculture, argued that forests only have limited effects on water budgets and controlling flood (Yu et al. 2013). Overall, the relationship between forestation/reforestation and water yield is still a controversial issue. A central concept in the “traditional” view of the role of forests is the "sponge" effect of the tree roots, forest litter, and soil. It has been ever claimed that the tree roots soak up water during wet periods and release it slowly and evenly during the dry season to maintain water supplies (Myers 1983). The debate was endless because there were no convincing field data from research on forest hydrology, especially in China. Most literature suggested that the effects of forestation on annual flow are largely on the base flow, which is an important component of annual water yield for most forested watersheds. Some may conclude that forests increased base flow because the trees help to increase infiltration (Scott et al. 2004), while others may argue that forests used more water and thus reduced the base flow (Wang et al. 2014). However, the hydrological consequences of forestation on degraded lands are not well studied in the forest hydrology research (Huaxing et al. 2009; Wang et al. 2014).

Catchment parameters have great influence on responses of the water budget and runoff to forestation. The magnitude of effects of forestation on annual water yield varies as a function of vegetation, climate, soil, and management practices (Calder 2003). Hydrological models, for example, the soil and water assessment tool (SWAT), allow for simulating the hydrological effects of these catchment parameters, which can help to understand the effects of forestation on water yields in the entire basin. The SWAT has been widely used in the water quantity and quality assessments at a wide range of scales and environmental conditions (Faramarzi et al. 2009; Castillo et al. 2014) and has also been successfully used to simulate the hydrological processes in the small upstream watershed of the HRB (Yao et al. 2009). In this section, the SWAT model, which includes the components such as soil and vegetation, is used to analyze the effects of forestation on the water yield.

Data and Methodology

SWAT is a semi-distributed hydrological model based on geography and natural hydrological processes at the watershed scale. SWAT subdivides an entire watershed into sub-watersheds connected with a river network and into smaller units that is called hydrological response units (HRUs). Each HRU represents a combination of land use, soil, and slope. HRUs are assumed to be nonspatially distributed with no interaction or dependency (Neitsch et al. 2011). Major model components of SWAT include weather, hydrology, temperature and properties of soil, plant nutrients and growth, pesticides, bacteria, and land management (Neitsch et al. 2011). The meteorological variables in SWAT include precipitation, temperature, wind speed, solar radiation, and relative humidity in daily or sub-daily time steps. The model uses readily available inputs efficiently for computing the large watersheds and is capable of simulating long-term yields for determining impacts of land management practices (Arnold et al. 1999). SWAT allows a number of different physical processes to be simulated in a basin. The hydrological routine of SWAT actually and also potentially consists of discharge, snow melting, and evapotranspiration.

We aim to address the processes related to vegetation interception, infiltration, transpiration, and evaporation in the dry watersheds, and the corresponding data used in the model are presented in Table 2. The 30 m resolution Landsat TM images in 1980 were downloaded from the US Geological Survey (USGS) website

Table 2 Data used and sources information (Reprinted from Wu et al. (2015b) with permission of Advances in Meteorology)

Data type	Data source	Scale	Description
DEM	Shuttle radar topography mission (SRTM)	90 m	Elevation
Soil	Regional database (http://westdc.westgis.ac.cn/)	1: 1000000	Soil-plant-atmosphere-water (SPAW) field and pond hydrology model was used to calculate some parameters
Weather	China Meteorological Administration (daily)		13 meteorological stations
Hydrological observation	Hydrologic yearbook (daily)		4 hydrological stations
River flow	Data Center of Chinese Academy of Science	1: 250000	River network diversion

(http://earthexplorer.usgs.gov/) for mapping the land cover types in the upper reach of the HRB in 1980. The collected images have already been georeferenced, and we radiometrically corrected them using the calibration utility for Landsat in ENVI 4.7 software package. The preprocessed images were subsequently clipped with the boundary of the study area. Supervised classification method was used to classify the land cover types in 1980. The Chinese Land Resource Classification System, from Data Center of Chinese Academy of Sciences, was used as the classification scheme to categorize the pixels of the image (Deng et al. 2008). The classification system includes cultivated land, forest land, grassland, water, urban and/or built-up area, and unused land. Further, a baseline scenario of forestation was designed on the basis of the land cover in 1980, in which the forestry proportion is 21%. Then a scenario was established with the simulated land cover data in 1980, in which the forest area increases by 12% compared to the actual land cover data in 1980. The regions with land use conversion are mainly located in the middle and western part of the study area (Fig. 3). The precipitation data of Qilian weather station was also used to analyze the trend of precipitation. From 1980 to 2010, the precipitation showed a significantly upward trend, increasing at an average rate of 1.79 mm year^{-1}, and the annual average temperature significantly increased by 0.06 °C year^{-1} (Fig. 4).

Impacts of Forestation on Water Yield

We simulated the effect of forestation on water yield using the SWAT model which couples the vegetation and physical processes. The SWAT model was calibrated based on the daily observation data records of 1980–1990 from Yingluoxia hydrological station, which is an outlet of the upper reach area, and the simulation results were validated with the daily observation records of 1990–2000. Some parameters were updated after the calibration. The Nash-Sutcliffe coefficient (E_{ns}) and coefficient of determination (R^2) of 0.72 and 0.70 and 0.80 and 0.79 for the calibration and

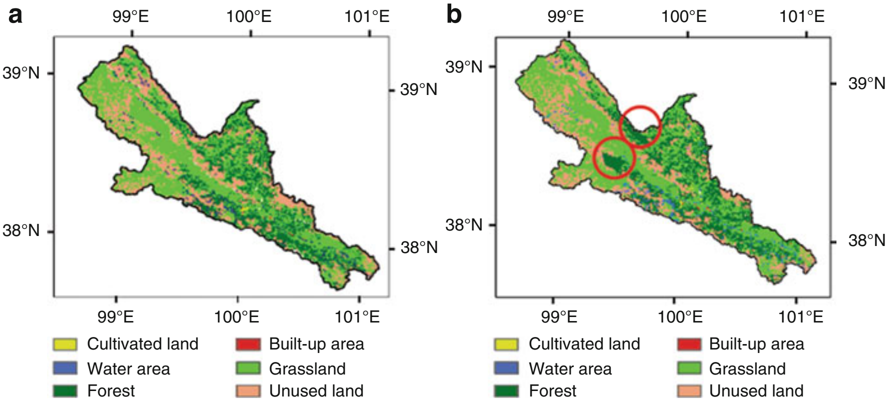

Fig. 3 The land use map in the upper reach of the HRB: (**a**) 1980 and (**b**) scenario-based simulated map (Reprinted from Wu et al. (2015b) with permission of Advances in Meteorology)

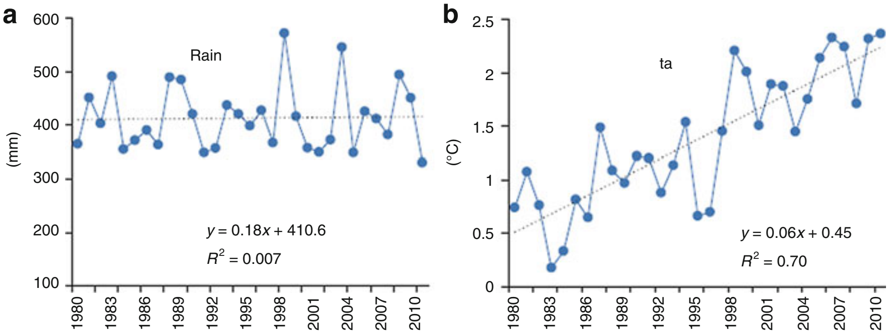

Fig. 4 The change trend of precipitation and temperature at Qilan meteorological station during 1980–2010 (Reprinted from Wu et al. (2015b) with permission of Advances in Meteorology)

validation period, respectively, showed that the SWAT model performed well in simulating the hydrological process in the upper reach area of the HRB (Fig. 5). The two coefficients of validation period were lower than the calibration period, the reason being that we used the land use map of the year 1980. Moreover, comparing the simulation results with the observation records from Yingluoxia hydrological station, we failed to reject the significance of the parameters of the SWAT model, indicating the model is suited for simulating the water balance in the upper reach area of the HRB.

The intervals of the most sensitive parameters were identified, and the most appropriate values are eventually shown in Table 3. The temperature lapse rate (TLAPS) is the most sensitive parameter, and it is directly related to the melting process of snow and glacier. Snow melting occurs mostly from March to June in a sub-watershed. The snow-melting factor on June 21 was parameterized to be SMFMX, which is the maximum melting rate; any increase of SMFMX drives

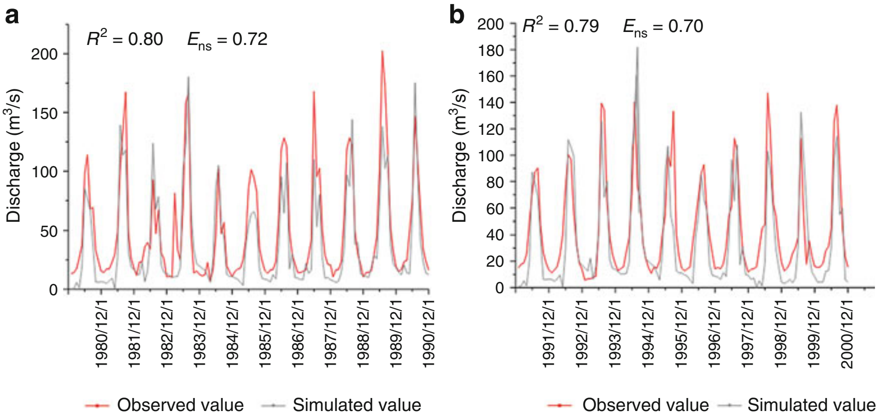

Fig. 5 The calibration and validation of monthly discharge at the Yingluoxia hydrological station, observed versus simulated using the SWAT (Reprinted from Wu et al. (2015b) with permission of Advances in Meteorology)

Table 3 Ranges and values of the most sensitive parameters in SWAT model (Reprinted from Wu et al. (2015b) with permission of Advances in Meteorology)

Parameters	Descriptions	Ranges	Values
CN_2	SCS curve number	−20%~20%	+6.32%
Sol_k	Saturated hydrological conductivity	−20%–20%	+11.56%
Escno	Evaporation compensation factor	0~1.0	0.83
SFTMP	Snowfall temperature	−2.0~2.0 °C	0.9 °C
Sol_z	Depth from soil surface to bottom of layer	−20%–20%	+3.65%
Sol_Awc	Available soil water content	−20%–20%	−0.35%
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur	0–500 mm	306.5
ALPHA_BF	Base flow alpha factor	0.00~1.00	0.07

rapid snow melting. The snow temperature lag factor TIMP is also linked with SMFMX because it is based on the previous situation. Along with TIMP surface water lag time, SURLAG plays an important role in influencing the model performance as a melted snow routing process is related to the geology of the watershed, where the melted water mainly flows to the surface runoff covering the impervious rock formations. SMTMP is sensitive since it indicates the starting and ending of snow and glacier melting, the availability of snow melting on a specific day, and the model-simulated streamflow, especially their peak values that are significantly influenced by the variation of SMTMP. Some parameters were updated after the calibration, and both calibration of the model and validation of the simulation results show that the model performed well in simulating the runoff variation due to glacier melting and climate change in upper reach of the HRB.

Streamflow production may be related to the differences in climatic pattern, meteorological conditions, species composition, canopy structure, and morphological characteristics of tree leaves, branches, and bark. Canopy rainfall interception varied from 14.7% to 31.8% of total rainfall, depending on the stand characteristics of different land cover type. Forest canopy interception was also affected by rainfall characteristics, which generally decreases with the rainfall amount and intensity. Evapotranspiration (ET), including physical evaporation and biological transpiration, is a significant component of forest water budgets, ranging from 80% to 90% of the total rainfall in the region. As expected, the actual amount of ET raised due to the increase of temperature and rainfall, whereas the amount of ET is relatively low in the mountainous watershed. ET from a forest is generally higher than that from pasture or bare land. However, ET is about 600 mm in the forest cover in the upper reach area of the HRB, which is far lower than that in those regions covered by grassland or unused land. The ET/PET ratio of native grasslands was the fastest to decline, followed by pine woodlands, shrub lands, alfalfa, and croplands. Pine woodland's low ET/PET ratios were mainly caused by its higher runoff due to soil compaction resulting from soil desiccation.

Previous studies have shown that the effect of forestation on water yield may differ among regions due to the difference in the topography, soil properties, and climate conditions (Deng et al. 2010). The simulation results in this study suggest that the monthly average water yield has generally increased under the forestation scenario, with an increment of 15.7 mm during 1980–2010 (Fig. 6). The increase of water yield mainly occurred in summer, while the decrease of water yield was mainly in winter. This may be due to the water conservation function of the forests. The study area is located in the mountain area having an altitude of approximately 3000 m, about 600 mm annual rainfall and a generally very high slope with the forests intercepting a large proportion of rainfall. The forest has a more powerful conservation function compared to the grassland, and it is more difficult to generate runoff in the forest than in the grassland. The results of the two simulation experiments show that the monthly average runoff decreased by 22.12 mm when the forest area increased during 1980–2010. In addition, the simulation results show that the interflow declined dramatically, the monthly average value of which decreased by approximately 500 mm during 1980–2010. This may be due to the difference in the

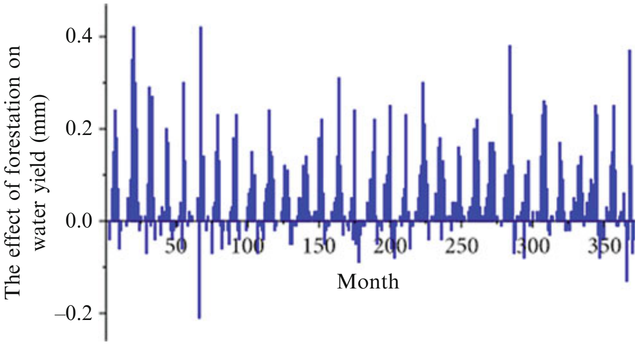

Fig. 6 The difference of water yield between forestation scenario and baseline during 1980–2010 (Reprinted from Wu et al. (2015b) with permission of Advances in Meteorology)

moisture infiltration of the forests and grasslands. The surface roots of forests can absorb more surface moisture and keep the shallow soil moist, and that of grasslands are generally very shallow, thus promoting the infiltration of rainfall into the soil.

The results of this study on the relationship between forestation and water yield differ from that obtained in some other studies. For example, Scott et al. (2004) showed that forestation can cause a reduction in water yield. However, the belief is based on the assumption of a constant relationship between precipitation and ET; that is, a reduced ET can logically lead to a gain of water yield. However, if this assumption is not true or if the relationship between precipitation and ET varies over time and space, the simple logic may be not tenable. Besides, forestation practices may cause the decrease of annual water yield due to the increase of ET. For any statistical tests, streamflow data must be first naturalized to account for other water uses. Moreover, the majority of the statistical studies are experiments at the plot scale, whereas there are few watershed-scale studies. Therefore, using ET information to infer water yield may not always be correct.

It is difficult to accurately simulate the hydrological processes because they are influenced by a myriad of biophysical factors. The results of this study suggest that the effect of forestation on water yield is area specific and forestation has positive effects on the water yield in the mountainous area. Several inferential studies have also demonstrated the uncertainty and variability of forestation on potential hydrological responses across China due to the large differences in climate and soil conditions (Wei et al. 2005). At the same time, most studies have focused on understanding whether forests are important in influencing water protection and soil erosion, and almost none of them have aimed at determining what percentage of forested land in a watershed or a landscape must be protected in order to minimize negative impacts on water resources. This question is important and must be answered in order to provide reference information for designing and implementing sustainable water and forest management practices.

Water Resources in Response to Land Use Change in the Middle and Upper Reaches of the Heihe River Basin

The HRB covers an area of approximately 130,000 km^2, which can be divided into three parts: (a) the upper reach region, including most part of Qilian County of Qinghai Province and some parts of Sunan County, where the supply of water mainly comes from the Qilian Mountains in the upper reach; (b) the middle reach region, including Zhangye city (Zhangye district, Sunan, Gaotai, Linze, Minle, and Shandan county) and Jiuquan and Jiayuguan cities, which is the main water consumption area as an irrigation agriculture economic zone; and (c) the lower reach region, including parts of Jinta county and Ejin Banner of Inner Mongolia Autonomous Region, which is mainly dominated by the desert animal husbandry (Fig. 7). Among the three parts, the upper reach is the main source of water, while the middle reach region (especially Zhangye city) is a highly developed irrigation agriculture zone in the HRB, with an agricultural history of about 2000 years, where about 90%

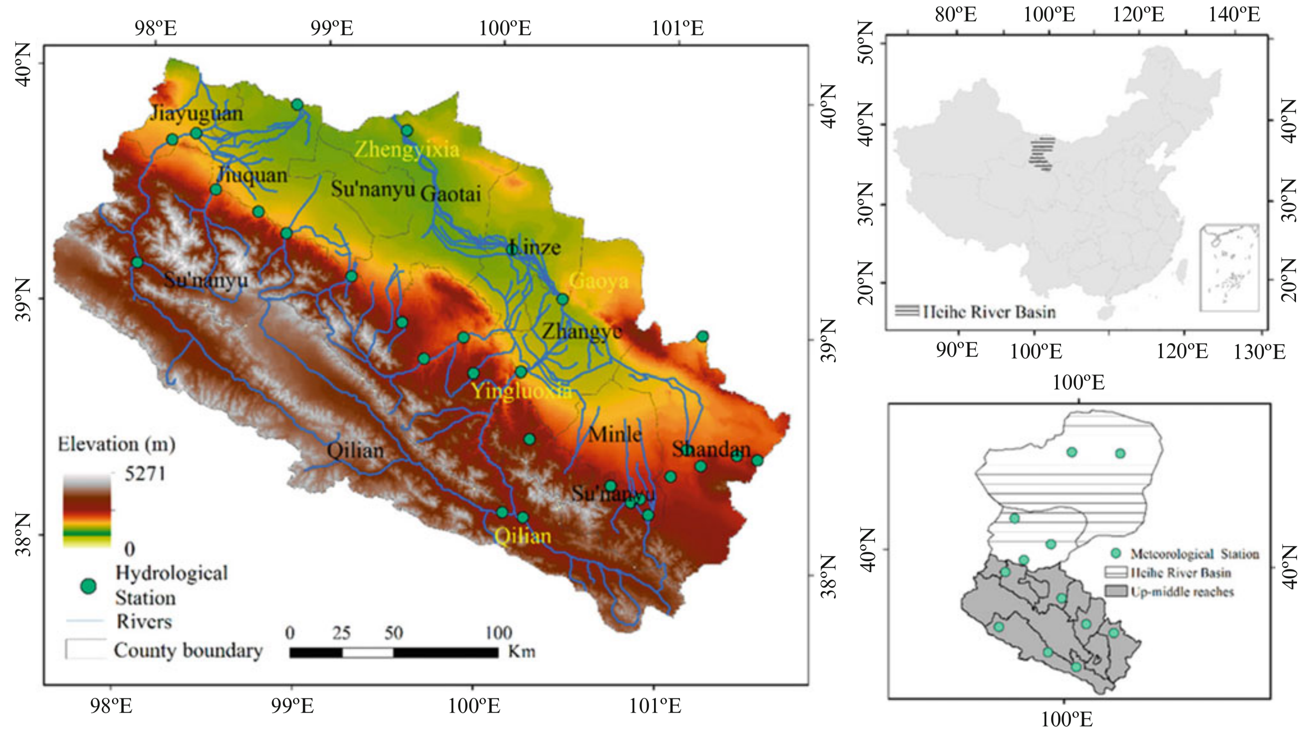

Fig. 7 Geographic location of the upper and middle reach of the HRB (Reprinted from Li et al. (2015) with permission of Sustainability)

of the available surface water are used for agricultural irrigation, leading to strong competitions for water between irrigation agriculture and natural ecosystems (Hu et al. 2015). In this case, we selected the upper and middle reach as the study area to detect the impacts of scenario-based land use/cover change on hydrological process, with the aim of figuring out the relationship between water availability and land use changes, and the optimal land use for adapting to water scarcity.

Model Inputs

In this section, we aim to investigate the relationships between water resource availability and land use changes, mainly based on the clarification of the hydrological process responses to land use changes that are simulated with different water constraint scenarios. We apply the SWAT model within the upper and middle reaches of the HRB to quantify the corresponding hydrological processes. The following inputs were prepared and used for the simulation.

1. Topographic and Soil Data
   The topographic data include elevation, slope and aspect, flow direction, and flow accumulation. The topographic data were obtained from a digital elevation model (DEM) of Shuttle Radar Topography Mission (SRTM) with 90 m resolution. The soil data mainly include soil texture, soil depth, and soil drainage attributes. The soil data with the resolution of 1 km were derived from the Harmonized World Soil Database (HWSD) provided by the Environmental and Ecological Science Data Center for West China (WestDC) (Table 4).
2. Hydrometeorological Data
   To simulate the daily hydrological processes with the SWAT model, meteorological data are required, including daily precipitation, minimum and maximum air temperatures, solar radiation, wind speed, and relative humidity. In general, the historical daily meteorological observation data sets of the HRB were collected from meteorological stations maintained by China Meteorological Administration (CMA) (Table 6). The meteorological data were obtained from 12 meteorological stations located within the HRB, and the data were available for 1980–2010. In addition, the historical hydrological data for the SWAT model calibration and validation, including the river flow data and discharge data of the hydrological stations, were obtained from the People’s Republic of China Hydrological Yearbook-Inland Rivers Hydrological Data. The hydrological data of 2007 and 2008 were used for SWAT calibration and validation, respectively (Table 4).
3. Land Use Data
   The historical land use data with a resolution of 1 km used in this study were derived from the database of the Resources and Environment Scientific Data Center, Chinese Academy of Sciences (Table 4). The land use data covers four periods: the late 1980s, mainly including the data from 1986 to 1989; the middle of the 1990s, including the data from 1995 to 1996; the late 1990s, including the data from 1999 to 2000; and the late 2000s, including the data from 2005 to 2008. In the late 1990s, the Chinese Academy of Sciences organized 8 research

Table 4 Input data used in the SWAT model (Reprinted from Li et al. (2015) with permission of Sustainability)

Data	Data sources	Information	Date/ period	Description
Digital elevation models (DEM)	Shuttle radar topography mission (SRTM) http://srtm.csi.cgiar.org/	Raster, 90 m	2000	
Land use	Resources and environment scientific data center (RESDC), Chinese Academy of Sciences	Raster, 1 km	2000, 2008	Including six land use types
Soil data	Environmental and ecological science data Center for West China (WestDC) http://westdc.westgis.ac.cn/	Raster, 1 km	1995	Parameters including saturation, texture, and hydraulic condition are calculated using a soil-plant-atmosphere-water (SPAW) field and pond hydrology model
Meteorological data	China Meteorological Administration (CMA)	Daily	1980–2010	Daily temperature and precipitation data from the weather stations at Tuole, Yeniugou, Qilian, Shandan, and Zhangye
Hydrological data	People's republic of China hydrological yearbook-inland rivers hydrological data	Daily	2007, 2008	Discharge data, at hydrological stations Zhengyixia and Yingluoxia
Glacier	Environmental and ecological science data Center for West China (WestDC) http://westdc.westgis.ac.cn/	Raster, 1 km	2000	Attributes including width, length, and depth

institutions, comprising about 100 scientists, to conduct its second nationwide land cover and land use classification project. The research team developed the national land use database by visual interpretation and digitalization based on remotely sensed digital images by the US Landsat TM/ETM satellite with a spatial resolution of 30 m. Further the interpretation of TM images and land cover classifications was validated through extensive large-scale field surveys. After the ground truthing, the results showed that the average interpretation accuracy for land cover classification were higher than 90% for each period (Liu et al. 2014). The land use data used in this study were composed of six land use types, including cultivated land use, forest land, grassland, water area, built-up land, and unused land. We adopted the land use data of years 2000 and 2008, among which the land use data of the year 2008 were adopted for the accuracy assessment of the simulation with the Dynamic Land System (DLS) model. Land use properties were obtained directly from the SWAT model database, and the glacier data were obtained from WestDC (Table 4).

Scenario-Based Land Use Simulation

1. Land Use Scenarios

Facing water scarcity, it is of great significance to integrate water and land use management. In the HRB, contradictions among water and land resource utilization for agricultural production, economic development, and ecological construction will be an outstanding issue for a long period in the future. The water constrains will be the key factor of land use/cover changes in the basin. Especially, in the middle reach region, which is characterized by irrigation agriculture, the water supply is critical to the regional development. According to the “water allocation scheme” in the HRB, the water amount for the middle reach will be strictly controlled to assure the supply of water for ecosystem conservation in the lower reach region. In this regard, it is urgent to improve the water utilization ratio in the middle reach; the water availability will be increased if the water utilization ratio were improved, which will significantly influence the land use pattern. Thus, we aim to detect how water resource constrain will affect the land use pattern and further how such land use/cover change will affect the hydrological process.

Particularly, Zhangye city covers about 90% of the middle reach, and more than 80% of artificial oasis, 92% of the population, 83% of GDP, and 95% of the arable land of the HRB concentrated in the Zhangye city (Shi et al. 2011). The water resource in Zhangye city is the main constrain of the socioeconomic development. According to the water amount from the upper reach of the Heihe River, Zhang et al. (2007) designed three scenarios of available water amount used in Zhangye city, which are 18.0×10^8 m^3, 26.5×10^8 m^3, and 35.0×10^8 m^3, respectively, related to 68%, 100%, and 132% of water utilization ratio, with circulation and repeat utilization between surface water and groundwater taken into account within the study area. In each scenario, the water resources for ecological utilization are considered according to ecological environmental conditions and total amount of available water, designed as 2.636×10^8 m^3, 4.967×10^8 m^3, and 7.625×10^8 m^3, respectively. Further aiming to maximize the total socioeconomic utility of water resources, the changing trend of six land use types from 2001 to 2020 under three water resource constraint scenarios using linear programming was calculated, with the constraint conditions of water quantity, total land areas, total population, and macro-scheme of regional development and ecological balances in Zhangye city.

In this section, taking the land use data of the year 2000 as baseline, we simulated the land use till the year of 2020 under the three land use structure change scenarios which correspond to three water utilization ratios (low-level water utilization ratio scenario (S1), middle-level water utilization ratio (S2), and high-level water utilization ratio (S3)).

2. Land Use Simulation

   The DLS model is a collection of programs that simulate the pattern changes in land uses by conducting scenario analysis of the area of land use/cover change (Deng 2011). The model analyzes causes of the dynamics of land use patterns, simulates the process of land use/cover change, and assists land use planning and land management decisions. The DLS model can export a macroscopic pattern change map of land uses at high spatial and temporal resolution by estimating the effects of changes in the spatial pattern of driving factors, formulating land use conversion rules and scenarios of land use change and simulating dynamic spatiotemporal processes of land use/cover change. The simulation process includes the analysis on driving mechanism, scenario design, and spatial allocation of land cover, and the DLS model has been proved to be robust to simulate the land cover change at the pixel scale (Deng et al. 2010).

   The analysis of the driving factors aims to estimate the statistical relationship between land use pattern successions and driving factors, which theoretically provides the response function for each land use types. All the driving factors are endowed with corresponding weights according to certain principles which can be assumed not to change during a short period, while the driving factors vary with time. In this case study, after collinearity diagnosis, we selected 17 driving factors to conduct the logistical regression analysis and got the relationships between the frequency of each land use type and the driving factors (Table 5). The results showed that the 17 driving factors can reasonably explain the spatial patterns of the six land use types. Specifically, the driving factors at the significant level and the driving mechanisms were different for each land use types. For example, the change of cultivated land was significantly driven by 16 driving factors, while the changes in the water area and built-up land were significantly affected by less driving factors. For each land use type, we selected those specific significant driving factors for land use pattern simulation. Base on the driving mechanism, spatial disaggregation module in the DLS model can spatially explicitly convert the land demands into land use/cover change at various locations of the study area under different scenarios.

3. Performance of the DLS Model

   Land use change models have widely been used to analyze the possible land use dynamics, which helps to support land use management and relevant policy-making. For further scientific application of land use change models, results obtained from these models are often assessed by comparing the simulated and actual spatial land use patterns, and one of the most commonly used methods is the Kappa coefficient of agreement (Congalton 1991). As land use datasets are

Table 5 Relationships between the frequency of each land use type and the driving factors base on logistical regression (Reprinted from Li et al. (2015) with permission of Sustainability)

Driving factors	Cultivated land	Forest land	Grassland	Water area	Built-up land	Unused land
Slope	$-2.95 \times 10^{-3***}$	$1.15 \times 10^{-3***}$	$-0.49 \times 10^{-3***}$	$-0.74 \times 10^{-3***}$	$-1.44 \times 10^{-3***}$	$0.20 \times 10^{-3***}$
Aspect	$-1.52 \times 10^{-5***}$	0.22×10^{-5}	0.13×10^{-5}	-0.33×10^{-5}	-0.59×10^{-5}	$0.22 \times 10^{-5**}$
Elevation	$-2.54 \times 10^{-3***}$	$-0.47 \times 10^{-3***}$	0.039×10^{-3}	$-0.73\text{E-}05^{***}$	$-2.07\text{E-}05^{***}$	$1.29\text{E-}05^{***}$
Rain	$-1.32 \times 10^{-3***}$	$-0.93 \times 10^{-3***}$	$0.546 \times 10^{-3***}$	-0.17×10^{-3}	0.59×10^{-3}	$-0.88 \times 10^{-3***}$
Sun radiation	$-1.9 \times 10^{-2***}$	$-0.52 \times 10^{-2***}$	$0.15 \times 10^{-2***}$	$-0.69 \times 10^{-2***}$	-0.28×10^{-2}	$-0.24 \times 10^{-2***}$
>0 °C accumulated temperature	-0.0426×10^{-4}	$1.45 \times 10^{-4***}$	$1.48 \times 10^{-4***}$	$-2.007 \times 10^{-4***}$	-0.93×10^{-4}	$-1.72 \times 10^{-4***}$
>10 °C accumulated temperature	$-2.02 \times 10^{-4***}$	$-2.36 \times 10^{-4***}$	$-1.55 \times 10^{-4***}$	$1.40 \times 10^{-4***}$	0.32×10^{-4}	$2.88 \times 10^{-4***}$
Soil depth	-0.11^{***}	0.07^{***}	-0.027^{***}	0.092^{***}	−0.089	-0.0099^{*}
Soil organic	-1.09^{**}	2.52^{***}	0.42	−0.83	−3.08	-1.47^{***}
Soil pH	-0.72^{***}	-0.25^{***}	0.039	−0.20	−0.17	0.036
Population density	$1.97 \times 10^{-4*}$	$-9.45 \times 10^{-4***}$	-1.4×10^{-4}	4.58×10^{-4}	0.50×10^{-4}	$7.00 \times 10^{-4***}$
GDP	$2.74 \times 10^{-3***}$	$-8.30 \times 10^{-3***}$	$-7.66 \times 10^{-3***}$	$-4.52 \times 10^{-3***}$	$7.72 \times 10^{-3***}$	$-24.05 \times 10^{-3***}$
Distance to express way	$-5.60 \times 10^{-2***}$	$-1.80 \times 10^{-2***}$	$-0.66 \times 10^{-2***}$	0.33×10^{-2}	$-1.86 \times 10^{-2***}$	$1.20 \times 10^{-2***}$
Distance to highway	$1.2 \times 10^{-2***}$	$0.41 \times 10^{-2***}$	$-0.46 \times 10^{-2***}$	0.38×10^{-2}	0.45×10^{-2}	$0.69 \times 10^{-2***}$
Distance to province way	$-0.83 \times 10^{-2***}$	$-1.714 \times 10^{-2***}$	$-0.25 \times 10^{-2***}$	$-1.39 \times 10^{-2***}$	0.52×10^{-2}	$1.09 \times 10^{-2***}$
Distance to water source	$-0.73 \times 10^{-2***}$	$1.42 \times 10^{-2***}$	$1.35 \times 10^{-2***}$	$-1.06 \times 10^{-2***}$	0.19×10^{-2}	$-1.22 \times 10^{-2***}$
Distance to province capital	$-0.95 \times 10^{-2***}$	$-01.26 \times 10^{-2***}$	$0.55 \times 10^{-2***}$	$-0.15 \times 10^{-2***}$	$-1.42 \times 10^{-2***}$	$-0.59 \times 10^{-2***}$
Cons	71.36	4.73	−2.35	8.38	22.94	2.71

t statistics in parentheses: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 6 The contingency table of actual and simulated land use in 2008 (Unit: %) (Reprinted from Li et al. (2015) with permission of Sustainability)

Actual land use in 2008	Simulated land use in 2008						Total
	1	2	3	4	5	6	
1	8.3	0.0	1.2	0.3	0.7	1.1	11.6
2	0.2	5.9	2.8	0.1	0.0	0.8	9.8
3	1.4	2.6	25.2	0.4	0.1	5.2	34.8
4	0.3	0.0	0.4	0.3	0.0	0.5	1.7
5	0.6	0.0	0.0	0.0	0.2	0.1	0.9
6	1.1	1.3	5.2	0.5	0.1	33.0	41.2
Total	11.9	9.9	34.8	1.6	1.1	40.6	100

Table 7 Accuracy of DLS land use simulation results assessed with Kappa statistics (Reprinted from Li et al. (2015) with permission of Sustainability)

Agreement	Expected agreement	Kappa	Std. err.	Z	Prob >Z
72.83%	31.25%	0.605	0.003	182.830	0.000

categorical, Kappa can be used for accuracy assessment of the results of spatial simulation models (Hagen-Zanker and Lajoie 2008). In this study, the land use data of 2000 was used as the base data to simulate the land use data of 2008, and the agreement between simulated and actual land use pattern of 2008 was accessed using the kappa coefficient.

Table 6 gives the contingency table from the comparison of the actual and simulated land use of 2008, and the fields indicate the fraction of cells that occupies a particular land use type. Based on Table 6, the agreement and Kappa value were calculated, the results shown in Table 7 indicated that the agreement between the actual and simulated land use pattern is 72.83%, and the corresponding Kappa is 0.605. According to the classification criterion based on Kappa coefficient (Saraux et al. 2013), the Kappa value above 0.6 indicated that the agreement between the actual data and simulation results was good, and the DLS model was suitable for simulating the spatial pattern of land use in the upper and middle reaches of the HRB.

4. Simulated Land Uses
   Grassland, forest land, cultivated land, and unused land are the four major land use types in the upper and middle reaches of the HRB. Under the three water utilization ratio scenarios, the changing trend of the land uses are shown in Fig. 8 and Table 8. It mainly shows that the increase of water utilization ratio will mitigate the decrease of cultivated land. The increase of forest land and grassland shows a positive relationship with the water utilization ratio. As for the built-up land, it will expand more significantly if the water resource is more strictly restricted. In other words, with lower water availability, to get the optimal utilization and maximum utility, water resources will be more diverted to built-up land. In addition, the unused land greatly decreases along with the increase of water utilization ratio.

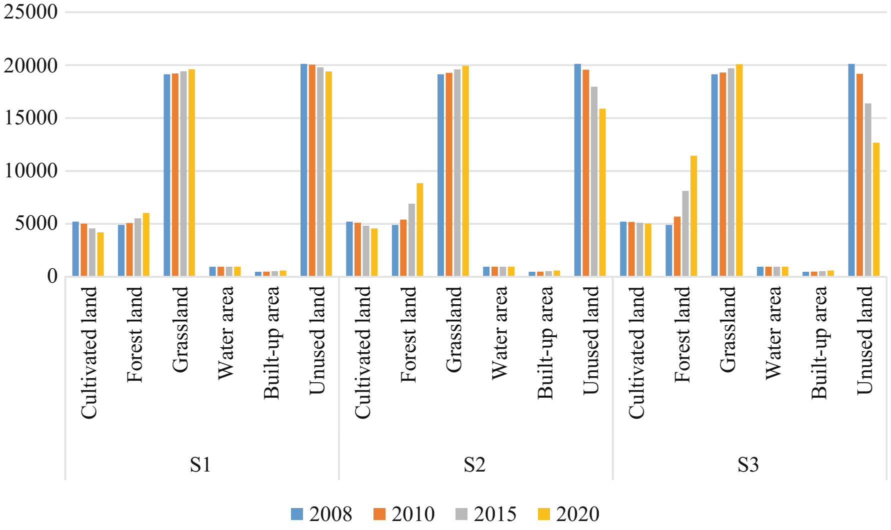

Fig. 8 Land use structure changes under S1, S2, and S3 scenarios (Reprinted from Li et al. (2015) with permission of Sustainability)

Figure 9 shows the land use patterns under each scenario for 2008–2020, which was simulated with the DLS model based on logistic regression analyses in Table 5. During the simulation processes, the land use structure data of the whole Zhangye city was applied as the input data, and the development-restricted areas and other counties were taken as restricted region. The simulation results indicated that land use/cover change in the arid area is strongly constrained by water resources, especially for the forest lands. The land use/cover change during 2008–2020 was mainly dominated by substantial expansion of forest land and grassland and the shrinkage of the cultivated land and unused land, which would exert significant impacts on water quantity in this basin.

Impacts of Land Use Change on Hydrological Process

1. SWAT Model Calibration and Validation

   The SWAT model was performed on a daily time step to predict the impacts of land use/cover change on water flow. In the SWAT model, a basin is divided into multiple subbasins, which were then further divided into two or more hydrological response units (HRUs) on the basis of unique combinations of land use, soil, and slope class. These HRUs are defined as homogeneous spatial units characterized by similar geomorphological and hydrological properties (Neitsch et al. 2011). To generate the HRUs, we used two slope classes (0–25% and >25%), and we also used a threshold of 25% for slope class and 38 soil types. That is, slope classes and soil types that covered more than 25% of a subbasin area would become their own HRUs. Furthermore, we incorporated land use/cover into the SWAT model to generate the HRUs, as the study

Table 8 Simulated areas of land use types under different scenarios (Unit: km^2) (Reprinted from Li et al. (2015) with permission of Sustainability)

Land use types	2008	2020					
		S1		S2		S3	
		Area	Percent change (%)	Area	Percent change (%)	Area	Percent change (%)
Cultivated land	5217	4413	−15.4	4807	−7.9	5217	0
Forest land	4894	6031	23.2	8807	80	11,420	133.3
Grassland	19,135	19,525	2	19,866	3.8	20,029	4.7
Water area	957	917	−4.2	923	−3.6	911	−4.8
Built-up land	500	601	20.2	588	17.6	573	14.6
Unused land	20,113	19,329	−3.9	15,825	−21.3	12,666	−37

selected multiple HRUs in a subbasin to simulate and the HRU threshold is determined by the threshold percentage of land use/cover over subbasin area (5%) and soil over land use area (10%). Finally, 113 subbasins and 1171 HRUs were generated in the upper and middle reaches of the HRB. For each subbasin, a modified soil conservation service (SCS) curve number (CN) method, which integrates a slope factor, was applied to simulate the surface runoff (Wu et al. 2015a).

The SWAT model was calibrated for streamflow at the subbasin level for 2005–2007 based on the daily observed streamflow from Yingluoxia hydrological station in the upper reach of the HRB, where human activities are not intensive. With the first 2 years (2005–2006) used as a warm-up period, which were not considered in the calibration analysis, the data of 2007 were actually applied to calibrate the model. Validation of the model was conducted using the data of 2008. The model performance was evaluated using goodness-of-fit statistics such as the Nash and Sutcliffe model efficiency coefficient (E_{ns}) and the coefficient of determination (R^2). Figure 10 shows the calibration and validation results. During the calibration period, the E_{ns} was 0.88, and the value of R^2 between the simulated and observed daily streamflows was 0.87. During the validation period, the E_{ns} was 0.87, and the value of R^2 was 0.89. The simulated streamflow was considered to be accurate for values of $E_{ns} > 0.75$ (Motovilov et al. 1999). These results suggest that the calibrated model can accurately simulate the streamflow in the HRB and confirm that the calibrated model with the set of optimized parameters can be used to examine the responses of hydrological processes to land use/cover change in the upper and middle reaches of the HRB.

2. Effects of Land Use Changes on Hydrological Processes

The influence of land use/cover change on the hydrological processes is a key factor in the rational allocation of water resources in the study area. It has been

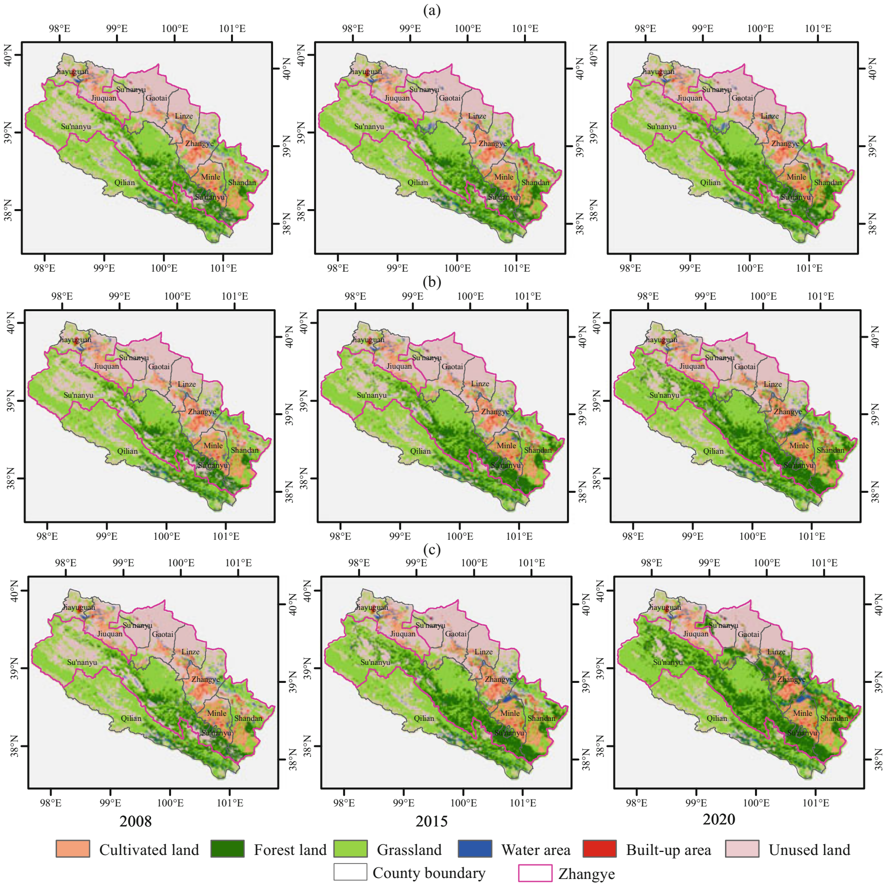

Fig. 9 Simulate land use patterns under the (**a**) S1 scenario, (**b**) S2 scenario, and (**c**) S3 scenario in the upper and middle reaches of the HRB for the years 2008, 2015, and 2020 (Reprinted from Li et al. (2015) with permission of Sustainability)

widely reported that land use/cover change can affect the quantity of water resources. The data of Zhengyixia hydrological station located at the outlet of middle reach were used to examine the impact of land use/cover changes on hydrological processes. We choose surface runoff and water yield to analyze the impacts of land use/cover change. The monthly average values of the surface runoff, water yield, and precipitation were calculated (Fig. 11). The results showed that the impacts of land use/cover change on the surface runoff and water yield varied with the precipitation and seasons, and the changing trend of surface runoff and water yield were similar to that of the precipitation.

The simulated surface runoff and water yield in 2020 under the three scenarios were compared to the corresponding values in 2008 (the baseline year). Figure 12

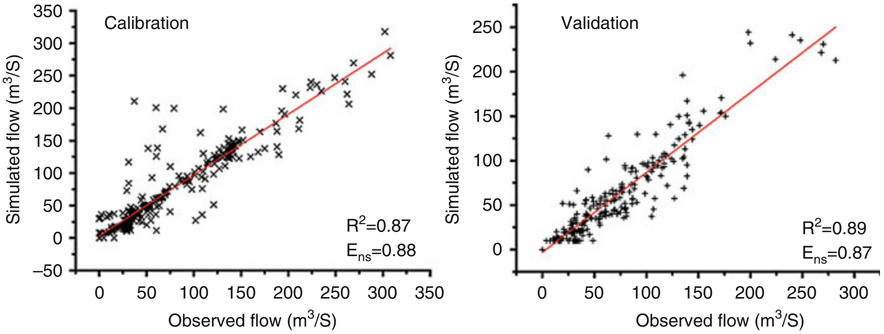

Fig. 10 Scatter plot of observed and simulated flow for the calibration and validation periods (Reprinted from Li et al. (2015) with permission of Sustainability)

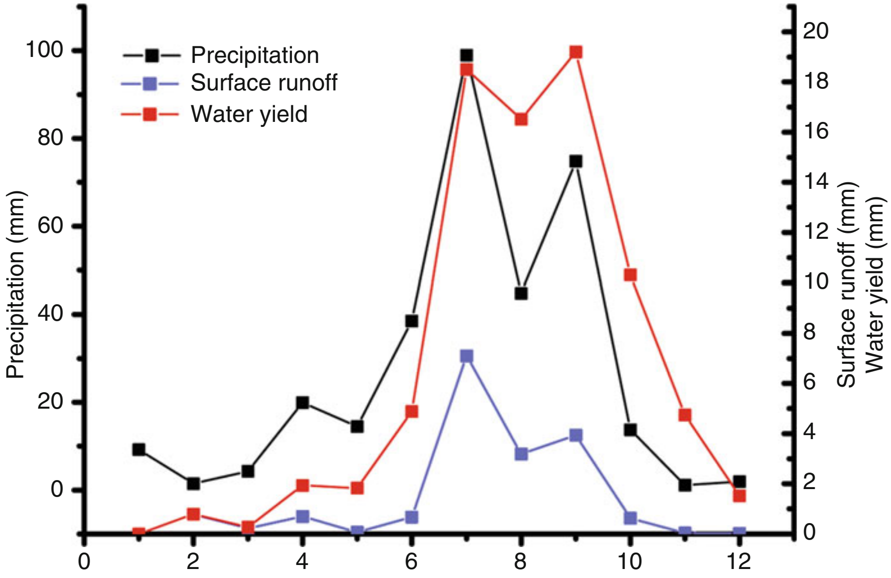

Fig. 11 Multi-year averaged monthly precipitation, surface runoff, and water yield in the upper and middle reaches of the HRB (Reprinted from Li et al. (2015) with permission of Sustainability)

shows the changes in monthly surface runoff and water yield under different land use/cover change scenarios. Surface runoff is one of the major pathways contributing to the water yield. The monthly quick-response surface runoff showed a decreasing trend, with the relative changes ranging from −55.5% to −1.6% (Fig. 12a) under the three scenarios. The water yield would increase in May and June and decrease in all other months in scenarios S2 and S3, while the water yield will increase during August to November in scenario S1 (Fig. 12b). The overall changing trend of the surface runoff is consistent with the water yield in scenarios S2 and S3, both revealing a decreasing trend due to land use/cover change.

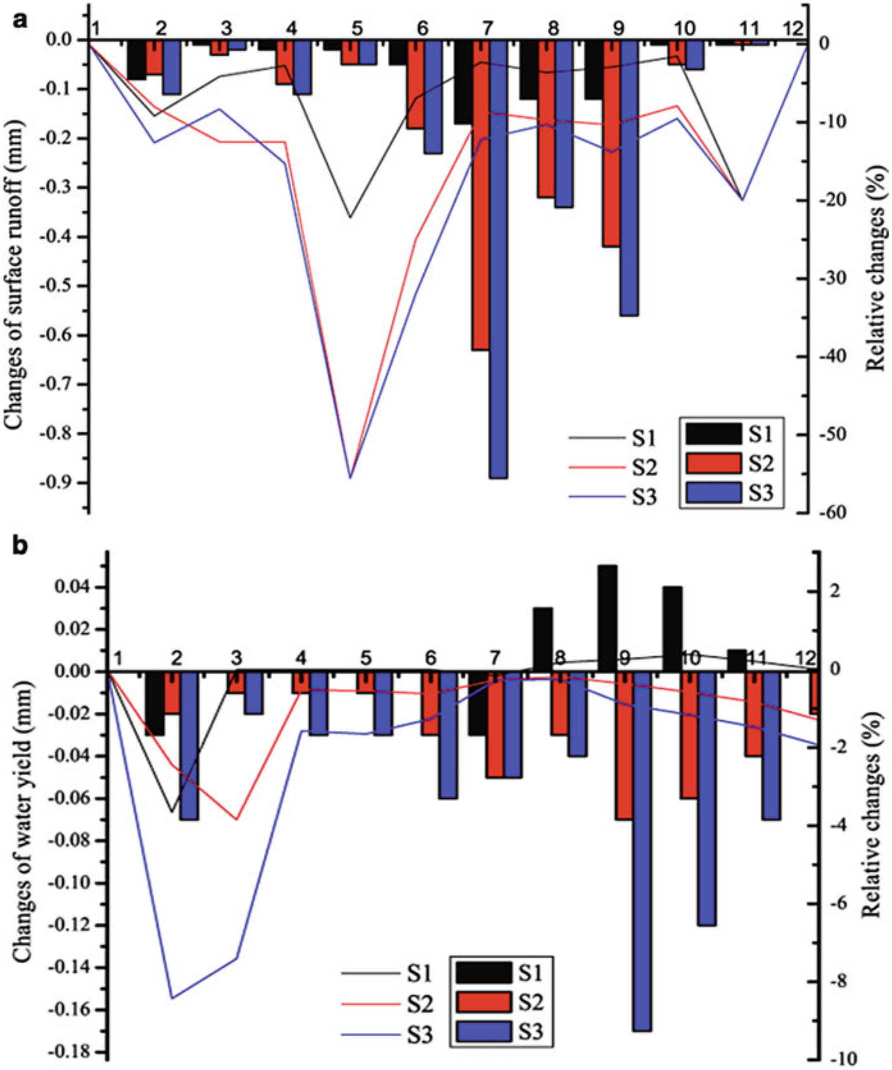

Fig. 12 Changes in monthly surface runoff (**a**) and water yield (**b**) under S1, S2, and S3 scenarios for the year 2020 relative to 2008 (Reprinted from Li et al. (2015) with permission of Sustainability)

The major causes of the decrease in surface runoff are the expansions of forest land and grassland. There is a broad agreement among researchers that the streamflow change is likely to be caused by different kinds of forestry activities, such as afforestation, which may lead to lower runoff generation and reduction of water yield. Sahin and Hall analyzed empirical data from 145 sites around the world and found that increase in scrub cover decreased annual runoff, and a reduction in deciduous hardwood cover leads to an increase in runoff (Huang et al. 2003).

Yin et al. (2009) identified the order of runoff rate of different land use types as unused land > cultivated land > grassland > forest land. In this case study, forest land and grassland land were mainly converted from unused land, which inevitably led to the reduction of surface runoff, and the more intensive forest land and grassland expansion are, the more the reduction and fluctuation of surface runoff. As shown in Fig. 12a, surface runoff reduced most significantly under the S3 scenario, especially in July, August, and September, when the precipitation is much more intensive and the impacts of land use/cover change on the absolute runoff amount changes will be significantly higher.

As for the water yield, the scenario S1, with less grassland and forest land expansion compared to scenarios S2 and S3, showed an increasing trend of the water yield during August to November even though the surface runoff is decreasing. Different land use types have different characteristics of the soil water infiltration, and the infiltration rate of forest land is higher than grassland and unused land (Liu et al. 2013). As both surface runoff and base flow are the major two parts contributing to water yield, with unused land being converted to grassland and forest land, the infiltration will increase and further lead to an increase of base flow. The impacts of vegetation coverage on the base flow are complex. On the one hand, infiltration rates increased strongly with the increase in vegetative coverage, leading to more generation of base flow (Loch 2000). On the other hand, vegetation evaporation and transpiration will consume a large amount of water, and vegetation coverage change will alter and improve the water storage capacity of soil, which is not conducive to supplement the base flow (Li 2000). In addition, vegetation roots, especially the larger deep-rooted vegetation that increased absorption, may make base flow absorbed by vegetation, and consequently, the water yield declines (Walker et al. 1993). The smaller the rainfall and rainfall intensity, the greater the capacity of vegetation to intercept precipitation. During July to October, the rainfall is much larger than for other months, leading to a lower capacity of vegetation to intercept precipitation. Under S1 scenario, the vegetation coverage density is much lower than that under S2 and S3 scenarios, resulting in less decrease of surface runoff and less absorption of vegetation, and the positive effect on base flow overwhelmed the negative effect on surface runoff, finally resulting in an increase in the water yield during August to November under S1 scenario (Fig. 12b). While under the S2 and S3 scenarios, with much higher vegetation coverage, the negative impacts on surface runoff overwhelmed the positive impacts on base flow, finally leading to the increase of water yield. In particular, during the winter season (October to December), the decrease of water yield is even larger than the decrease in surface runoff, which means that the base flow during the winter season has also been negatively affected by the forest and grassland expansion in the basin.

Summary

Water scarcity and stress have attracted increasing attention as water is one of the most critical limited resources for sustainable development of the world. The HRB, a typical arid inland river basin in Northwest China, had experienced serious water scarcity problems particularly during the 1960s–1990s, resulting from the extensive human activities and lack of effective management system, and consequently suffered a substantial deterioration of the ecosystem. In the HRB, there exist imbalances between the water supply and demand, with the characteristic of irrational water consumption structure, low water efficiency, and uneven temporal and spatial water distribution. In order to deal with the water scarcity problems, it is of great significant to consider the relationships between land use changes and water availability for sustainable water management.

Water resource constraints are a critical factor affecting land use demand for socioeconomic development and ecological conservation and further resulting land use/cover change, which will affect the water supply through influencing the hydrological processes. Understanding the interactions between water resources and land use change is crucial for sustainable water resource and land use management. The upper reach of the HRB is crucial for the basin's water supply, as it is the water source area of the whole basin. In the upper reach region, it is of high priority to identify the relationship between forests and water yield. It is shown that there was a significant positive relationship between forestation and water yield in the upper reach of the HRB during 1980–2010. The annual water yield increased by 1.31 mm when the forest cover increased by 1%, and the surface runoff reduced 1.84 mm for every 1% increase in the forest cover, which indicated that the forest land has "sponge" effects on the water resource in the mountainous watershed. Further, we chose the upper and middle reaches of the HRB, which is the major region of water consumption, to clarify the relationship between water availability and land use changes. First, we examined the possible land use/cover changes under different water utilization levels, with the higher water utilization ratio implying more water available for socioeconomic development and ecological conservation, which can further ease the decreasing trend of cultivated land in the irrigation agriculture area and stimulate the expansion of forest land and grassland. Further, based on the simulated land use data with unchanged climate conditions, we conducted quantitative analyses of the impacts of land use/cover change on the surface runoff and water yield in the upper and middle reaches of the HRB for the year 2008–2020. The results indicated the surface runoff and water yield both changed when there was forest and grassland expansion. The impacts of land use/cover change on hydrological processes is complex, and the surface runoff showed a decreasing trend along with increasing forest land and grassland under the three scenarios, while the water yield generally showed a decreasing trend. Exceptionally, the water yield showed an increasing trend during August to November under S1 scenario, in which the expansion of forest land and grassland was much lower than that under S2 and S3 scenarios, and the decreasing trend in water yield under S3 scenario is significantly higher than that under the S1 and S2 scenarios. With the higher water utilization ratio and the aim to maximize the socioeconomic utility of water resources, the higher water availability would lead to the expansion of forest land and grassland, which will in return exert negative impacts on the water yield, resulting in less water availability. This indicates that even if the water utilization ratio increases, the unreasonable allocation of water resources may exert negative impacts on the water resource, and therefore it is very necessary to reasonably allocate the water resources for different land use demand.

The water and land use planning should consider not only the current socioeconomic utility of water resources but also the future possible response of hydrological processes to the land use/cover change, and it is essential to carry out integrated water and land use management and consider the responses of hydrological process to land use/cover change resulted from water and land use management. The long-term water resource planning should be flexible and adaptable to changes due to these responses, and there is still considerable potential to improve the integrated modeling and analyses of water resources in the HRB and other basins with similar conditions.

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Water and Land Effects on Agricultural Development for River Basin: Resource Restriction and Sustainable Development

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Contents

Introduction 152
Identification of Water and Land Situations in the Heihe River Basin 156
Water and Land Effects of Agricultural Production in Heihe River Basin 158
  Methods 158
  Data Acquisition and Processing 163
  Drag Effects of Water and Land Resources 166
  Influence Factors of Water and Land Effects 168
Agricultural Water Use Efficiency Calculation 169
  Agricultural Water Use Efficiency in First Stage 169
  Agricultural Water Use Efficiency in Second Stage 170
  Agricultural Water Use Efficiency in Third Stage 173
  Agricultural Water Use Efficiency Change During 2004–2012 173
Summary 176
References 179

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Abstract

Water and land resources play vital roles in agricultural growth. They not only remarkably support overall economic growth but may also restrict agricultural development. To document the influence of water and land on agriculture, we examined the “drag effects” of these two resources in limiting agricultural production. In this study, data from eight counties collected during 2000–2012 from the Heihe Agricultural Production Area in Gansu Province were used to analyze the drag effects of water and land resources on agricultural growth. These effects varied largely among the eight counties, which were consistent with the availability of these resources. Also we used a three-stage data envelopment analysis for examining agricultural water use efficiency (WUE) and related issues in Heihe River Basin from 2004 to 2012. This method adjusts technology efficiency (TE), pure technology efficiency (PTE), and scale efficiency (SE). Results show that WUE-related efficiency varies according to scale. TE and SE decreased in the study area, while PTE increased. This means the effects of pure technology on improving overall technology are very limited, and scale adjustment is vitally important to the agricultural production area in the Heihe River Basin. The results provide recommendations for decision-makers to plan efficient use of water resources in arid and semiarid areas. This study will give scientific support to coordinating development with the availability of water and land resources in agricultural areas of China.

Keywords

Water and land resources · Agricultural growth · Restriction · Drag effect · Three-stage data envelopment analysis

Introduction

Water and land resources are the lifeblood of agricultural development (Xiangzheng Deng et al. 2010). With the recently accelerated urbanization in China, land use, especially agricultural land use, has become the main limiting factor to the expansion of agriculture that should be considered by academia or even the state (Li et al. 2015). Water resources, as an indispensable element in agricultural production (Zhang and Wang 2014), are increasingly consumed by agriculture, because of China’s accelerating population growth and the related demands for industrial water (Nian et al. 2013). In particular, after the development of an “ecological civilization in China” was proposed (Zhao et al. 2015), decision-makers now face problems related to knowing how to reasonably allocate water resources (Piao et al. 2010) and how to achieve a balance for water resource use among agricultural, industrial, domestic, and environmental needs (Fisher et al. 2014). Because water and land resources play diverse roles in these four areas of need (Haddeland et al. 2014), two concerns have emerged: will a lack of water and land resources restrict local agricultural development? And, will this restriction destabilize agricultural growth? These resources and agricultural growth are related in a complex way with a repeating cycle. Agricultural development depends on the supply and support of resources (Susskind 2013), while resource shortages can modestly inhibit the potential for agricultural growth (Wei et al. 2016).

Water plays an important role in human life, societal development, and environmental sustainability. According to a World Water Development report regarding serious climate change, water supply has become a major challenge, especially in arid and semiarid areas (Tolk et al. 2016). Currently, water shortage is the greatest problem in China, where average per capita water use is 2200 m^3 (El-Mageed and Semida 2015). The distribution of water resources in the country has exacerbated a water crisis in Northwest China (Chen et al. 2015). The central government has set a target such that the entire nation will be poverty-free in 2020, which would severely restrict water (Wu et al. 2015). The acceleration of urbanization and population growth also brings challenges to water utilization (Gadanakis et al. 2015). Increasing water use efficiency (WUE) has become a vital step toward a more sustainable world (Bravo-Ureta et al. 2007). As an important maize seed production area, the Heihe Agricultural Production Area in Gansu Province is one of the most water-stressed parts of the country (Wang et al. 2016). There, agricultural water use accounts for more than 85% of total socioeconomic water consumption (Olivier and Singels 2015). Low water utilization may come from inadequate water infrastructure, and water scarcity has become a major issue.

The effects of water and land resources on agricultural development have been extensively and intensively studied (Xin et al. 2013). Solow and Stiglitz applied the neoclassical growth model to study the possibility that resources could be exhausted (Álvarez and Sánchez-Blanco 2013). Research on the drag effects of resources was started many years ago (Guoju et al. 2013), especially in the field of water and soil resources (Abd El-Wahed and Ali 2012). Nordhaus studied the drag effects of resources and land on economic growth in the US; using the Cobb-Douglas production function, the drag effect was computed to be 0.24% (Du et al. 2013). The drag effects of water and land resources on economic growth in China have been reported to be 0.01397 and 0.013201, respectively (Sangüesa-Barreda et al. 2013). The joint drag effect of water and land resources was found to be 0.14548. Existing research on water and land resources in the Heihe Agricultural Production Area has focused on water use efficiency, water resource productivity, land resource bearing capacity, and land resource potential. In terms of a limitation on growth caused by a lack of water resources in this region, an analysis of agricultural production data during 2000–2010 in Minle and Linze counties shows that because of a restriction caused by a lack of water resources, the average annual rates of increase for total agricultural productions were 0.9979% and 0.6228% lower than the previous year in these two counties, respectively. Various studies have focused on how to calculate and improve water use efficiency. Many studies also calculated per capita or per GDP water use. Water resource supply studies may give a basic description of water consumption.

There are many case studies that include multi-input, multi-output, and multi-decision questions. Using data envelopment analysis (DEA) will be very helpful in dealing with multi-input and multi-output questions. DEA was proposed by Charnes et al. in 1973 and has become an efficient evaluation method. This method is commonly used in water resource management. Many researchers have been concerned with water-related issues. Research on WUE solve water problems on different levels, linking WUE at different level. From previous studies, DEA can be more effective for analysis of water use than other methods. For example, WUE has been calculated for 31 Chinese provinces and Wuhan over 1998–2008. Such research on WUE has strong effects on improving WUE. However, the DEA method assumes that inefficiency comes entirely from management, ignoring the external environment and random error. We calculated WUE in the Heihe River Basin using a three-stage DEA and calculated the Malmquist index. We also describe static and dynamic change of the water situation.

Climate change is one of the most pressing global environmental issues (Liu and Deng 2011). The northwest provinces in China have encountered the dual challenge of ecological production and poverty alleviation (Glomsrod et al. 2016). The deterioration of the ecological environment that carbon emissions as the characterization and poverty alleviation happened at the same time in 2001–2014 (Zhang et al. 2015; Zanin and Marra 2012). The rural poverty slowed down, while the annual growth rate of GDP per million yuan of carbon emissions is 8.58%, and the average annual growth rate of per capita carbon emissions is 13.2% (Wossen and Berger 2015). It shows that the region has the possibility of short-term poverty reduction at the cost of ecological destruction (Wang et al. 2017; Walelign et al. 2016). In order to better set the target of policy choice, it is necessary to determine the relationship between poverty and ecological environment (Suich et al. 2015; Turpie et al. 2008). Poverty, degradation of ecological environment, and the relationship between them have occupied the mainstream research since the 1980s; however, there are different views on the relationship between poverty and ecological environment (Diswandi 2017; Fisher et al. 2013).

Throughout the study of the relationship between poverty and ecological environment, there are two relatively clear theoretical origins and research context: one is the pessimism of the argument, mainly affected by the "poverty trap" (Njuguna and McSharry 2017) and "environmental Kuznets curve" (Apergis and Ozturk 2015), and the other is the view of relative optimism, which emphasized that the progress of technical means is necessary and possible to coordinate poverty alleviation and ecological environment protection (Suich et al. 2015; Sandhu and Sandhu 2014). Poverty is a result of the degradation of the ecological environment or the poor are the victims of ecological degradation and the view has aroused many scholars' resonance (Chen et al. 2015; Pinho et al. 2014). Poor families are more dependent on natural resources and environment relative to the rich families. Obviously, the resource environment as an important livelihood capital and its degradation will lead to the occurrence of poverty or intensify the degree of poverty (Njuguna and McSharry 2017). The main argument focuses on whether poverty leads to ecological environment degradation; the standpoint of the schools of thought is widely divergent.

The poverty in Northwest China mainly refers to income poverty and consumption poverty, income increase is the main driving force for poverty alleviation, and it is along with the path of economic "growth–factor participation–primary allocation–secondary allocation–income increase" to achieve endogenous poverty alleviation (Hertel and Lobell 2014; Hanjra et al. 2009). Secondly, if the economic growth of the northwest region comes up with the path of dependence on natural resources, it will limit the supply of local labor quality (Hannum et al. 2014). The northwest region is generally in an ecologically fragile area, and there is no objective condition for pollution treatment. The northwest region is bound to face the bottom line of environmental destruction in the process of development (Barbier 2015; Friend and Moench 2013). Once the environmental problems hit the bottom line, economic transformation will experience a shock, seeking sustainable ecological environment is the target of economic development, and the industrial structure will not depend anymore on the consumption of natural resources for economic growth, which leads to the mismatch problem to the quality of labor supply and a new mode of economic development (Hanjra et al. 2009). The existing income growth model of the poor is not sustainable, and the ability to resist the ecological risk becomes lesser force. Therefore, the poor people in the northwest region will increase the depth of poverty under the dual role of labor supply and demand mismatch and the ecological environment risk, which will result in the deterioration of ecological quality and the increase of poverty (Fisher et al. 2014). These two mechanisms have potential relevance that can be approximated represented by environment-poverty U-shaped curve (Glomsrod et al. 2016): if the poor revenue increases through natural resources consumed in the northwest region, then the relationship is represented on the left in the U-shaped curve, and if the northwest area is facing the second association mechanism, the quality of the ecological environment decrease will exacerbate poverty; thus, in a U-shaped curve, it is presented on the right. The relationship between the ecological environment and poverty alleviation in Northwest China depends on the current economic growth mode, the supply of labor, and the change of ecological environment quality (Kenter et al. 2015; Hertel and Lobell 2014).

The less developed northwest region is not a major contributor to greenhouse gas emissions; however, it could be the biggest victims of climate change. The ecological system is relatively weak in underdeveloped areas, and the natural environment and social economic support system are relatively sensitive (Chen et al. 2015; Emran and Shilpi 2017). The fact that climate change may not have a big impact in the developed region but could pose a huge risk in less developed regions (Yang et al. 2015). Less developed areas need to pay more attention to the impact of climate change and more thoroughly promote and implement climate change response actions (Ward 2016; Wan and Zhang 2013). Then, this chapter will explore the relationship between the ecological environment and poverty alleviation through empirical analysis of the urban poor and rural poor, analysis whether consumption of natural resources gained a wider range of poverty alleviation and whether the existing mode of economic growth makes the poor arrive the process of initial positive promotion.

Many cities around the world have formed special water management systems for urban green space according to climate, terrain, and green space development plans. For example, in order to alleviate urban flood-waterlogged vulnerability and reduce irrigation water, Boston and Minneapolis in the USA began to explore the water management of urban green space since the early twentieth century. They established an urban park system along with a river system in the cities. This system strengthened runoff regulation and decreased the dependence on groundwater. In London and Tees Valley of Britain, due to the scattered distribution of farmland and garden green spaces, the irrigation efficiency was very low, and large amount of water was wasted. The theory of green infrastructure (GI) was put forward, and the main idea is building a unified management mechanism through the construction of green space network, which can effectively connect the sporadic small garden green spaces and farmland by the greenways. In Melbourne and Sydney of Australia, the theory of water-sensitive urban design (WSUD) has been produced to increase rainfall utilization of green space and reduce groundwater consumption by the establishment of a complete rainwater recovery and reuse system.

Identification of Water and Land Situations in the Heihe River Basin

Following the implementation of the reform and opening-up policy in the 1980s, China's economy has grown rapidly. However, there has been a concurrent increase in gaps and disparities between regions, with the eastern, southern, and northeastern regions more developed than the western region. In the 1990s, most discussions on regional economic differences occurred at the national level and focused on East-West, North-South, and coastal areas-inland differences. Foreign scholars have used state-of-the-art research methods to investigate regional economic differences within China, and their studies provide useful references for domestic scholars. Rozelle's decomposition of the Gini coefficient for the period 1984–1989 indicated that economic disparities between the eastern coastal provinces were rapidly expanding, mainly because of advancing rural industrialization.

In 2002, county economies became national strategies aimed at economic reform, gradually evolving into a key research topic within the disciplines of Economics and Economic Geography. The divisions of the Chinese administrative system were clear. There are numerous counties – 1,470 counties, excluding county-level cities and autonomous counties – comprising one component of the Chinese national economy. The total area of all of the counties exceeds 90% of China's entire territory (excluding the marine area), and more than 70% of the total population resides in counties, contributing more than 50% of the total GDP. Therefore, ensuring healthy economic development of counties is critical for sustaining efficient development of the country as a whole. Development of county economies entails availing of the economic advantages of individual counties and conducting appropriate planning.

The northwest region is consist of Xinjiang, Gansu, Qinghai, Ningxia, and Shaanxi, five provinces with vast land. The region is mostly in dry climate and it has scarce water resources and the ecological system is fragile. How to protect and rebuild the ecological environment in the development of the social economy condition, and get sustainable development, is a great challenge to the northwest. Northwest China has unique natural and geographical conditions and abundant energy resources, and the variety is complete, conventional energy, petroleum, natural gas, coal, oil shale, peat, and hydropower, nuclear power, solar, wind, and geothermal and biomass resources. The resources have the characteristics of relatively concentrated distribution, low development cost, and great development potential. The northwest region is mainly formed by agriculture and coordination of heavy industry including coal, petroleum, electric power, metallurgy, machinery, chemical industry, building materials, food, textile and papermaking forest, ten departments, and production system through making use of abundant resources in recent years. Northwest China has become an important basement for nonferrous metal, petroleum, and chemical industry, petroleum machinery manufacturing, and building materials. At present, Northwest China has initially formed a relatively reasonable institutions and relatively complete categories of industrial systems and built a large number of large backbone enterprises and industrial cities.

The Heihe River Basin (Fig. 1) (38°–42°N, 98°00′–101°30′E) is the second largest inland river basin in the arid region of Northwest China and forms a typical desert-oasis zone. The region extends from the northern base of the Qilian Mountains, through Zhangye Basin in Gansu Province, to Ejina Banner of Inner Mongolia. However, some tributary rivers and main stems have ceased to flow after long-term water resource exploitation. Three independent subsystems, in the east, middle, and west parts, have formed. The east subsystem includes more than 20 rivers, including the main stem of the Heihe and Liyuan Rivers. The middle subsystem consists of the Maying and Fengle Rivers. The west subsystem includes the Taolan and Hongshui Rivers. Zhangye and Jiuquan, which are located in the middle and lower reaches of the Heihe River, respectively, represent typical agricultural oases and are also the sites of

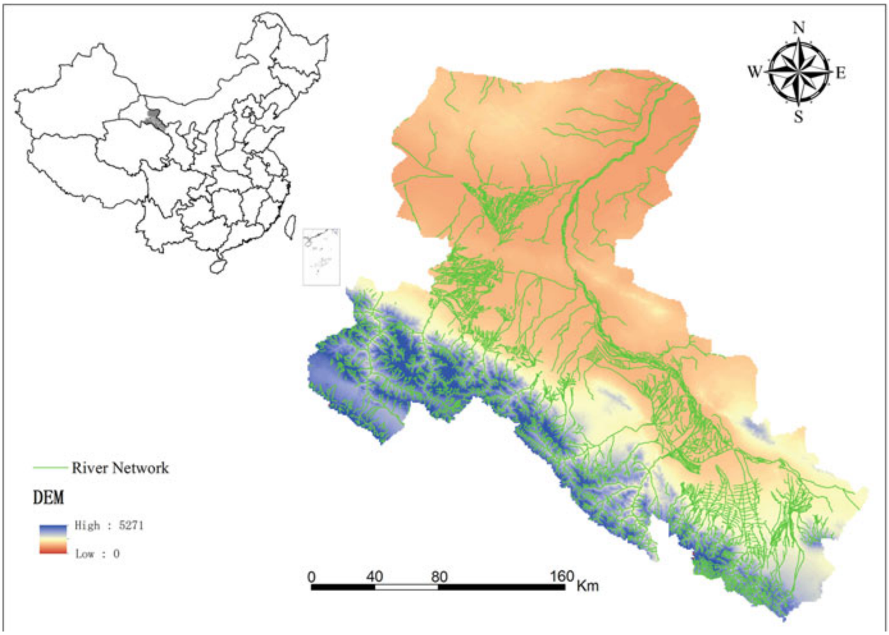

Fig. 1 Agricultural production area in Heihe River region (Reprinted from Guofeng Wang (2018) with permission of Sustainability)

the earliest pilot initiatives to develop water rights and water prices. The water resource management system in these areas has followed a characteristic evolutionary path.

The study area includes oasis agriculture zones in the middle and downstream regions of the Heihe River in Gansu and has been a local major agriculture development zone for many years. It consists of Ganzhou and Suzhou districts, Gaotai, Shandan, Minle, Linze, Jinta counties, and Sunan Yugur Autonomous County. A very important issue in the area is how to improve WUE. Hence, this chapter mainly focuses on WUE using data from Heihe River Basin.

The water in the Heihe Agricultural Production Area is used mainly in four aspects, living, industry, agricultural irrigation, and artificial ecology. Especially, water resources in the region are most consumed in agricultural irrigation (Fig. 2). Taking the water consumption in Ganzhou district as an example, irrigation accounted for 93.95%, artificial ecology 2.92%, and other domestic water and industrial water 1.98% and 1.14%. Therefore, the key to develop the Heihe Agricultural Production Area is to deal with the relationship between water and soil resources and agricultural economic growth in the process of agricultural production.

Water and Land Effects of Agricultural Production in Heihe River Basin

Methods

Based on the Neoclassical Economics Theory, American economist Romer proposed a resource-restrained economic growth model and analyzed the restraints that a lack of natural water and land resources may place on economic growth. We added some water and land resource restraints into the agricultural production model and predicted the drag effects of the limited availability of water and land resources on agricultural growth. The new model was based on the Cobb-Douglas production function and was embedded with the items of water resource and land resources. The concrete expression is showed as Eq. 1:

$$Y(t)=K(t)^{\alpha}W(t)^{\beta}T(t)^{\gamma}[A(t)L(t)]^{1-\alpha-\beta-\gamma}\alpha>0,\ \beta>0,\ \gamma>0,\ \alpha+\beta+\gamma<1 \quad (1)$$

where $Y(t)$, $K(t)$, $W(t)$, $T(t)$, $L(t)$, and $A(t)$ are the actual agricultural output, agricultural stock of capital, water use volume by agriculture, area of agricultural land, and number of people involved in agriculture, respectively. α, β, and γ are technical parameters representing the output elasticities corresponding to capital, water resources, and land resources. To simplify the computation, we set up the model with a constant return to scale. The contribution of technology to agricultural growth was ignored.

Through model transformation, the model was transformed into the form of the growth rate shown in Eq. 2:

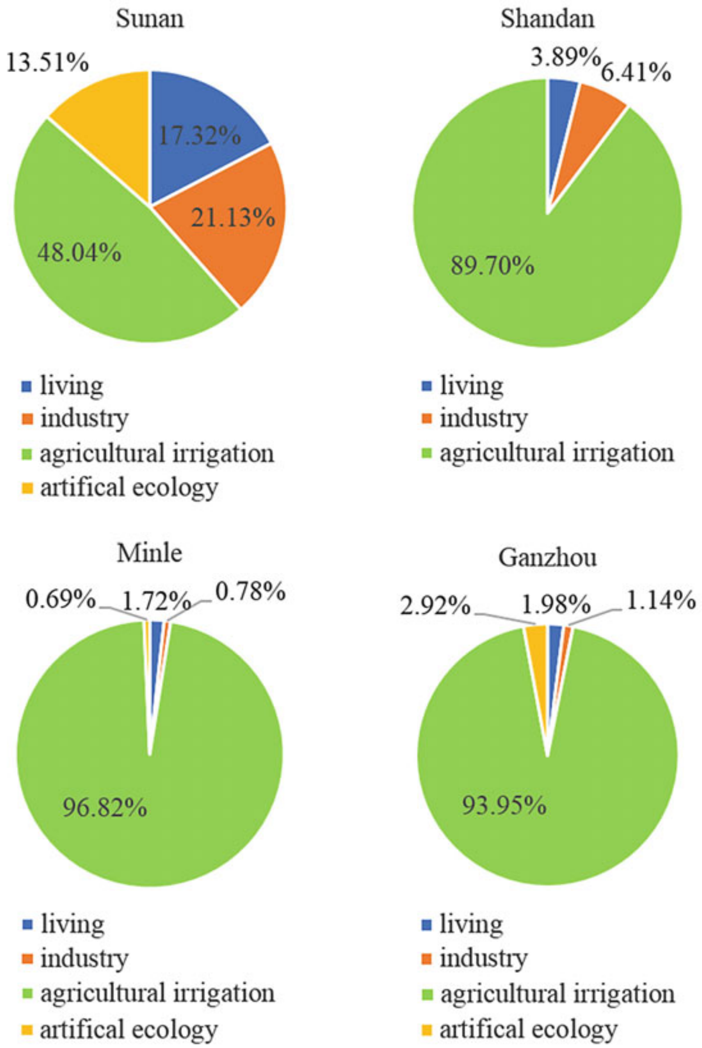

Fig. 2 (continued)

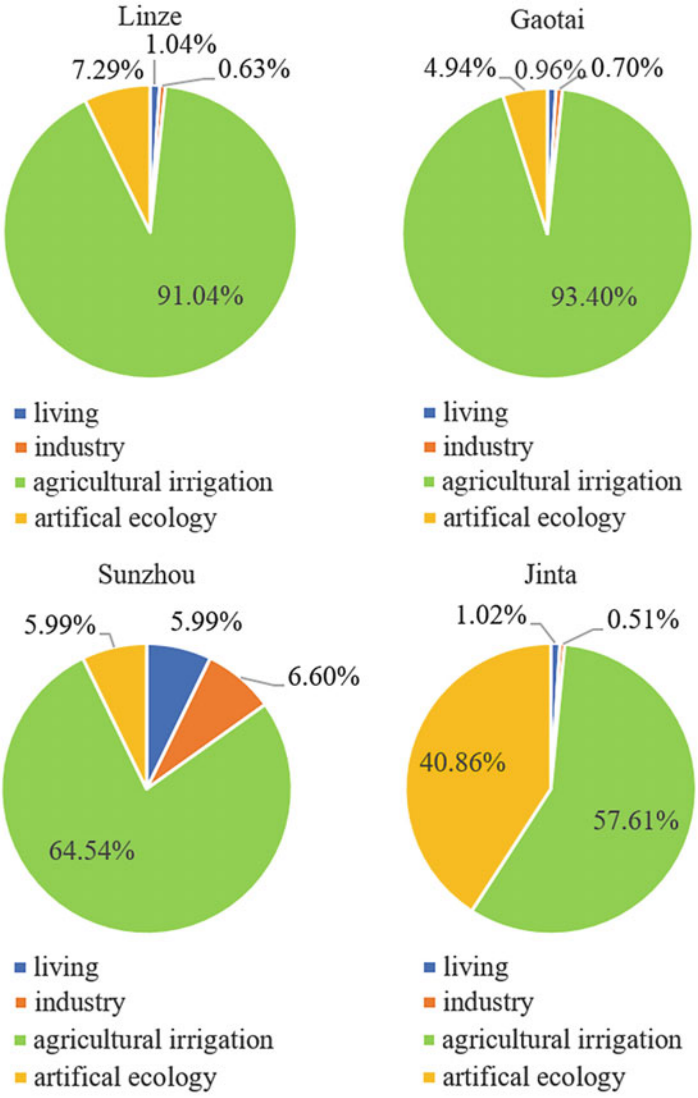

Fig. 2 Water consumption in different sector in the Heihe Agricultural Production Area in 2012 (Reprinted from Guofeng Wang (2018) with permission of Sustainability)

$$g_Y(t) = \alpha * g_K(t) + \beta * g_w(t) + \gamma * g_T(t) + (1 - \alpha - \beta) * [g_A(t) + g_L(t)] \tag{2}$$

It was hypothesized that the dynamic descriptions of capital and labor were consistent (Deng et al. 2010) with the Solow Growth Model as shown in Eq. 3:

$$K(t) = sY(t) - \sigma K(t), \qquad \dot{L}(t) = nL(t) \tag{3}$$

where s is the saving rate, σ is the capital depreciation, and n is the labor growth rate. Similarly, the attenuation rates of water and land resources were both constant. Let the attenuation rates of water and land resources be a and b, respectively. After mathematical transformation, we determined the average rate of production increase per unit labor force with or without restraint by water (or land) resource. Therefore, the drag effect of a resource on agricultural growth can be expressed using Eqs. 4 and 5:

$$\mathrm{Drag}_w = \frac{(n-a)*\beta}{1-\alpha} \tag{4}$$

$$\mathrm{Drag}_T = \frac{(n-b)*\gamma}{1-\alpha} \tag{5}$$

In Eqs. 4 and 5, the direction of the action of a resource on economic growth is decided by the difference in the rates of increase between the labor force and the resource of interest, while the magnitude of the action is modestly correlated with the output elasticity of capital input. Specifically, if the growth rate of the available labor force outweighs that of a resource, the drag effect of this resource is positive, indicating that the occupation of this resource by unit labor force decreases, which leads to the reduced productivity per unit labor force, and thereby the lack of this resource inhibits economic growth. Moreover, if the output elasticity of capital input is constant, the resource element with a larger output elasticity contributes more significantly to economic growth.

The DEA is based on the concept of local efficiency. There may be several units awaiting evaluation, and each unit is a separate decision-making unit (DMU). According to calculation, we can determine whether the unit is efficient. The calculation of DMU is within the interval (0,1), with values closer to 1 indicating greater efficiency. If the efficiency is equal to 1, the DMU is the most efficient compared to other DMUs. Efficiency comparison can be based on the DEA.

In the first stage, aimed at calculating the WUE given a fixed output, we used the BCC input-oriented DEA model. The DEA was used to measure agricultural WUE. With the goal of analyzing how to improve WUE with a fixed water supply amount, we used the input-oriented DEA. When the efficiency value equals 1, the decision unit is on the production frontier, and the actual production value has no difference with the possible maximum value. An efficiency <1 implies that there is still room for improvement for the decision unit. When the value of the efficiency reached 1, the WUE of the decision unit was higher. Supposing that there are N(= 1, 2, 3,. . .0.8) decision units with I (= 1, 2, 3. . .) factors in T(= 1, 2, 3. . .) time periods, then J(= 1, 2, 3. . .) types of outputs are generated. For the input-output index, we used X and Y to represent input and output. Then, the input-output index of N counties (which equaled the decision unit) during various periods was designated $x_{i,n}^t$ and $y_{i,n}^t$. If we set $x_i = (x_{1n}, x_{2n}, \ldots, x_{In})$ and $y_j = (y_{1n}, y_{2n}, \ldots, y_{Jn})$, the model is specified as follows.

$$\begin{cases} \min\theta = V_D \\ \sum_{n=1}^{8} \lambda_j X_i + S^- = \theta X_0 \\ \sum_{n=1}^{8} \lambda_j Y_j + S^+ = Y_0 \\ \lambda_j \geq 0, N = 1, \ldots, 8 \\ S^- \geq 0, S^+ \geq 0 \end{cases} \tag{6}$$

Here, $\theta(0 < \theta < 1)$ is the comprehensive technical scale efficiency, λ_j is the weighting variable, $S^-(S^- \geq 0)$ is the slack variable, $S^+(S^+ \geq 0)$ is the surplus variable, and ε is the Archimedes infinitesimal. The above equation is the DEA model based on constant scale returns; if $\theta = 1$, it means that the county attained the optimal of water use situation on the frontier.

In the second stage, the traditional DEA could not identify whether inefficiency in the first stage of decision-making was caused by management inefficiency or external factors and random errors. Thus, in the second stage, a stochastic frontier analysis (SFA) model was used to eliminate environmental and random error factors, obtaining the input relaxation variable caused by management inefficiency. According to the model concept, the following SFA regression function was constructed.

$$S_{ni} = f(z_i; \beta_n) + \nu_{ni} + \mu_{ni}; i = 1, 2, \ldots, I; n = 1, 2, \ldots, N \tag{7}$$

where S_{ni} is the relaxation value of the nth item of the ith decision-making unit, S_i is the environmental variable and β_n is its coefficient, $\nu_{ni} + \mu_{ni}$ is a mixed error term and ν_{ni} is random interference, and μ_{ni} represents management inefficiency. Among these terms, $\nu \sim N(0, \sigma_\nu^2)$ is the random interference term, symbolizing the influence of that interference on the relaxation variable; μ is management inefficiency, showing the impact of management factors on the relaxation variables. We suppose that μ follows a normal distribution at zero cutoff, which is $\mu \sim N^+\left(0, \sigma_\mu^2\right)$. The equation for separating random error from mixing error is

$$\widehat{E}[\nu_{ni}/\mu_{ni} + \nu_{ni}] = S_{ni} - f(z_i; \beta_n) - \widehat{E}[\mu_{ni}/\mu_{ni} + \nu_{ni}]; i = 1, 2, \ldots, I; \\ n = 1, 2, \ldots, N \tag{8}$$

According to relevant research, the equation is

$$\widehat{E}[\nu_{ni}/\mu_{ni} + \nu_{ni}] = \sigma^* \left[\frac{\phi\left(\lambda \frac{\varepsilon}{\sigma}\right)}{\Phi\left(\lambda \frac{\varepsilon}{\sigma}\right)} + \left(\lambda \frac{\varepsilon}{\sigma}\right) \right] \tag{9}$$

Now,

$$\sigma^{*} = \frac{\sigma_\mu \sigma_\nu}{\sigma}, \sigma = \sqrt{\sigma_\mu^2 + \sigma_\nu^2}, \lambda = \frac{\sigma_\mu}{\sigma_\nu}, \varepsilon = \mu_{ni} + \nu_{ni}; i = 1, 2, \ldots, I; n = 1, 2, \ldots, N \tag{10}$$

The second stage uses SFA methods to eliminate the influence of efficiency from environmental and random factors. To adjust all decision-making units in the same external environment, the equation is adjusted as

$$X_{ni}^{A} = X_{ni} + \left[\max f\left(z_i; \widehat{\beta}_n\right) - f\left(z_i; \widehat{\beta}_n\right)\right] + \left[\max(\nu_{ni}) - \nu_{ni}\right], \quad i = 1, 2, \ldots, I; \quad n = 1, 2, \ldots, N \tag{11}$$

Here, X_{ni}^{A} stands for the adjusted inputs and X_{ni} the unadjusted inputs; $\left[\max f\left(z_i; \widehat{\beta}_n\right) - f\left(z_i; \widehat{\beta}_n\right)\right]$ is used to adjust the external environmental factors; $[\max(\nu_{ni}) - \nu_{ni}]$ is for putting all decision-making units on the same level.

The third stage uses the adjusted input factors to calculate WUE. The exclusion of the external environment and random error factor makes the efficiency value more objective and accurate.

Data Acquisition and Processing

Input-Output Variables

Based on the hypotheses and data availability, we collected 2004–2012 data related to agricultural production from six counties and two districts in the midstream and downstream agriculture zones of Heihe River Basin. Except for data related to agricultural water use, all data were taken from Zhangye and Jiuquan statistical yearbooks. Agricultural water resource quantity data were collected from the Center for Chinese Agricultural Policy, Chinese Academy of Sciences (Table 1).

Environmental Variables

Environmental variables refer to influence factors of WUE, and these variables do not change over short periods. Thus, the variables are also called external variables. From prior research, we used local development, water natural endowment, and industrial structure as environmental variables. Specifically, we used per capita GDP to represent local development, which reflects government finance investment and expense capabilities. Generally, with economic development, there is more investment in infrastructure and WUE increases. We used water possession per person to represent the water natural endowment. Generally, if local people possess more water, their means of water consumption and water conservation consciousness weaken, and WUE declines. We used the proportion of primary industry to GDP to represent industrial structure. If that structure is more rational, the configuration of water consumption is more reasonable and water resource efficiency therefore greater.

Table 1 Basic information of input-output in the Heihe Agricultural Production Area (Reprinted from Guofeng Wang (2018) with permission of Sustainability)

Area	Agricultural production value		Agricultural water use		Agricultural labor force		Investment in fixed assets		Planting area	
	Mean (10,000 RMB)	SD	Mean (10,000 m^3)	SD	Mean (persons)	SD	Mean (10,000 RMB)	SD	Mean (10000mu)	SD
Ganzhou	643,861	325,438	45,922	6207	324,450	7630	283,162	193,488	53.32	3.35
Gaotai	181,451	95,429	20,825	4331	134,339	2468	82,237	56,833	24.58	4.09
Shandan	198,042	81,274	38,181	4251	145,261	11,858	84,225	69,571	35.35	3.1
Minle	169,723	76,394	59,464	6583	210,166	4269	79,446	67,843	58.34	2.26
Linze	183,019	95,153	17,824	3360	125,418	691	89,841	66,615	19.74	2.72
Sunan	90,214	69,316	4436	1737	25,402	559	136,437	121,882	4.82	1.21
Jinta	227,202	157,286	40,030	2667	113,544	2978	136,232	167,775	26.08	4.62
Suzhou	681,796	550,635	69,911	14,718	225,060	8308	518,352	504,639	46.86	1.6

Data Stationarity Test

To test the stationeries of the data, we tested the unit roots of variables for all the counties (districts). Prior to the tests, the data were quantified, which further eliminated the interference caused by heteroscedasticity. The unit root test aimed to eliminate the time-induced nonstationary time series, but regression of nonstationary data would cause spurious regression. Thus, prior to the regression analyses, a variable test was necessary. All tests were conducted using EViews 6.0 software (Table 2). The tests showed that at a significant level of $p < 0.10$, all variables were nonstationary for all counties/districts. After first-order differential analysis, all

Table 2 Results of unit root test

Area	Variable	Y/ΔY	K/ΔK	L/ΔL	T/ΔT	W/ΔW
Ganzhou	ADF statistic	4.49/ −3.43**	4.56/ −2.62**	0.55/ −3.54**	0.9978/ −3.21*	1.39/ −5.42***
	p-value	0.9998/ 0.0361	0.9998/ 0.0185	0.8194/ 0.0281	0.9031/ 0.0886	0.9485/ 0.0022
Gaotai	ADF statistic	12.87/ −2.87*	2.96/ −5.28***	−1.06/ −3.86**	1.40/ −3.54**	2.11/ −4.35***
	p-value	0.9999/ 0.0833	0.9968/ 0.0021	0.2429/ 0.0170	0.9485/ 0.0306	0.9840/ 0.0093
Shandan	ADF statistic	4.94/ −5.81***	4.22/ −4.76***	−0.77/ −3.35**	3.59/ −4.51***	0.47/ −4.92***
	p-value	0.9999/ 0.0010	0.9995/ 0.0064	0.3616/ 0.0437	0.9991/ 0.0063	0.7983/ 0.0042
Minle	ADF statistic	5.99/ −3.72**	3.90/ −6.60***	0.47/ −4.19*	2.92/ −3.46**	0.40/ −4.80***
	p-value	1.0000/ 0.0211	0.9993/ 0.0005	0.4919/ 0.1000	0.9966/ 0.0347	0.7802/ 0.0049
Linze	ADF statistic	13.90/ −3.52**	3.28/ −4.56**	−0.05/ −3.7**	1.69/ −5.48***	2.19/ −4.64***
	p-value	0.9999/ 0.0316	0.9984/ 0.0105	0.6452/ 0.0218	0.9694/ 0.0020	0.9862/ 0.0061
Sunan	ADF statistic	10.05/ −4.57***	1.29/ −3.75**	−0.41/ −3.23*	3.17/ −3.13*	4.17/ −5.39***
	p-value	1.0000/ 0.0067	0.9385/ 0.0224	0.5150/ 0.0566	0.9980/ 0.0537	0.9995/ 0.0023
Jinta	ADF statistic	7.54/ −3.39**	2.06/ −4.51***	−0.17/ −4.58***	0.71/ −11.74***	−1.07/ −4.05**
	p-value	1.0000/ 0.0412	0.9844/ 0.0062	0.6028/ 0.0056	0.8540/ 0.0000	0.2392/ 0.0144
Suzhou	ADF statistic	12.42/ −22.77***	2.17/ −4.17**	2.24/ −3.32**	1.13/ −3.93**	0.04/ −4.01**
	p-value	0.9999/ 0.0001	0.9857/ 0.0120	0.9888/ 0.0399	0.9224/ 0.0171	0.6774/ 0.0135

Note: Δ first-order differential
$^{*}p < 0.05$; $^{**}p < 0.1$; $^{***}p < 0.01$

variables tended to be stable at a significant level of $p < 0.10$. Thus, the least square method was used to further estimate the variables.

Drag Effects of Water and Land Resources

The variables used in the first-order differential were used in the regression modeling. The final results were normalized and then used to determine the production functions for all counties/districts. Then, the increasing rate of labor force was computed from $n = \left({}^{b}/_{a}\right)1/12 - 1$, where a and b are the agricultural labor force numbers in each county or district in 2000 and 2012, respectively, and the time period is 12 years. Similarly, the effects of water or land resources on agricultural growth in the six counties and two districts could be determined. The drag effects of water or land resources on agricultural growth were estimated using Eqs. 4 and 5, respectively. Results show that the drag effects of water and land resources, respectively, were 0.04% and 0.24% in Ganzhou District, 0.01% and 1.72% in Gaotai County, 1.14% and 2.48% in Shandan County, 1.12% and −0.49% in Minle County, 0.69% and −0.24% in Linze County, 0.02% and −2.68% in Sunan County, 0.11% and −1.06% in Suzhou District, and 5.05% and −1.50% in Jinta County (Fig. 3). In summary, during 2000–2012, the changes in the availability of water or land resources per unit labor force affected the economic growth in different regions of the study area to different extents. For instance, in Ganzhou District, the overall drag effect of water and land resources in the study period was 0.28%, indicating that the actual rate of increase in agricultural production fell by 0.28% annually. This occurred because

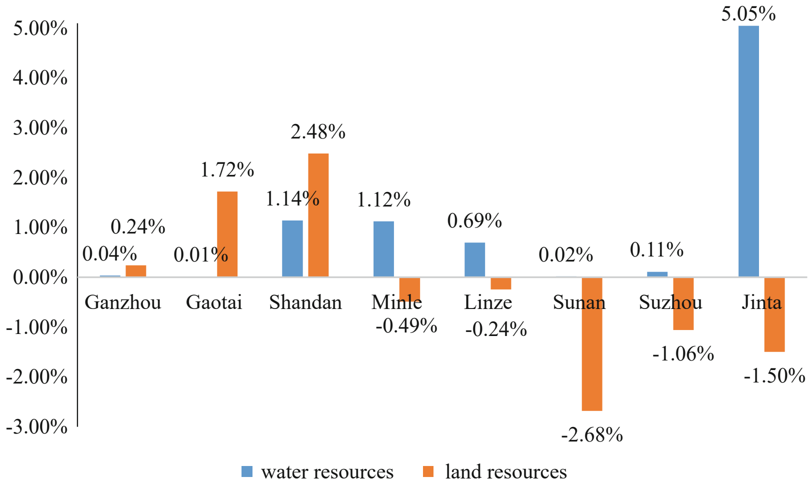

Fig. 3 The intensity and magnitude effects of the availability of water and land resources on agricultural

the increasing rates of water and land resources use during agricultural production were lower than that of labor force. As for Sunan County, the overall drag effect of water and land resources in the study period was −2.66%, indicating the water and land resources occupied by a unit of labor force promoted agricultural growth at an annual growth rate of 2.66%. Similarly, for different counties or districts, the drag effects of water and land resources varied widely. In particular, the difference was 5.01% between Jinta County and Ganzhou District where the drag effects of water resources were the largest and smallest, respectively. Moreover, the difference was 5.16% between Shandan and Sunan counties where the drag effects of land resources were the largest and smallest, respectively. This occurred because of the difference in availability of different resources, so that the overall effects of water and land resources on agricultural growth varied widely.

From the view of space, the hindering force of soil and water resources have made to the growth of agricultural economy presents different roles. From the view of water resources and labor resources grew year on year, while the agricultural economic growth in the Heihe Agricultural Production Area showed a decreasing trend. From the view of county scale, the growth of agricultural economy in Jinta County located in the lower reaches of the agricultural area declined was obviously due to the lack of water resources.

From the view of land resources, the force in some counties is negative, that is to say the land resources occupied by the unit labor force promote agricultural economic growth to a certain extent during the period. The agricultural land development in the region has little influence on land resources during the study period. Specific to the county scale, land resources force is positive in Zhangye City, Shandan County, and Gaotai County while negative in Minle County, Linze County, Jinta County of Sunan Yugur Autonomous County, and Suzhou District. This is closely related to the local industrial structure. Zhangye County, Shandan, and Gaotai County are important industrial areas in Heihe Basin, and agricultural land has preempted large-scale industrial areas in recent years. Thus, land resources become a hindrance to the local agricultural economic growth. For other counties, land resources are an important driving force for agricultural economic growth in recent years. To sum up, in the Heihe Agricultural Production Area, the main threat to the development of agricultural economy comes from water resources and industrial development, especially the second, the tree industry. In the development of these industries, not only the agricultural land or farmland was preempted but also the consumption of water resources accelerated, resulting in more adverse impact on agricultural development.

Resource elements, including water resources and land resources and other important resources, play a role in promoting technological progress in economic development. Due to the constraints of resources, the main body of economic development will gradually adjust the substitution elasticity and coefficient of resources through technological progress, especially the development of new technologies to directly and indirectly adjust the relationship between them so as to promote rapid economic growth.

Influence Factors of Water and Land Effects

In this study, the influencing factors of primary selection are analyzed from three dimensions: social dimension, economic dimension, and natural dimension. The area of corn, wheat planting area, total area, average net income of each rural, effective irrigation area, disaster area, GDP, proportion of primary industry, proportion of secondary industry, proportion of tertiary industry, and change rate of investment in fixed assets are included. According to the relationship between the dependent variable and the independent variable, this chapter carries on the regression analysis to the influence factors of the soil and water resource comprehensive force, water resource force, and land resource force. The results are as follows (Table 3).

Table 3 The influence factors of agricultural water and land effect

Variable	Comprehensive effects		Water effects		Land effects	
	Coefficient	Std. Error	Coefficient	Std. Error	Coefficient	Std. Error
Corn planting area	−6.28	4.24	−46.02	31.13	39.73	26.88
	−1.48		−1.48		1.48	
Wheat planting area	−3.32*	1.88	−24.3*	13.82	20.98*	11.93
	−1.76		−1.76		1.76	
Total planting area	2.95	1.92	21.59	14.12	−18.65	12.19
	1.53		1.53		−1.53	
Average net income of each rural resident	−0.002	0.0019	−0.02	0.01	0.013	0.01
	−1.07		−1.07		1.07	
Effective irrigation area	0.00002	0.00003	0.0002	0.0002	−0.0001	0.0002
	0.69		0.69		−0.69	
Disaster area	−0.13	0.71	−0.94	5.21	0.81	4.5
	−0.18		−0.18		0.18	
GDP	0.00003*	0.00002	0.00003*	0.0001	−0.0002*	0.0001
	1.81		1.81		−1.81	
Proportion of primary industry	−5.48	20.87	−40.14	153.08	34.66	132.21
	−0.26		−0.26		0.26	
Proportion of secondary industry	−53.77	50.64	−392.58	371.39	338.81	320.76
	−1.06		−1.06		1.06	
Proportion of tertiary industry	−155.54*	81.95	−1137.67*	601.05	982.12*	519.09
	−1.9		−1.9		1.9	
Change rate of investment in fixed assets	2.52	6.64	18.54	48.7	−16.02	42.06
	0.38		0.38		−0.38	
Constant	75	40.64	547.87	296.76	−472.87	256.3
	1.85		1.85		−1.85	

Note: t statistics in parentheses
*Significant at 10%

Based on the comprehensive analysis of water and soil resources and the results of single-factor regression of water resources and land resources, the main factors which play a major role are the wheat planting area, the regional GDP, and the proportion of tertiary industry. The wheat planting area was negatively correlated with the agricultural water and soil comprehensive forces and the water resource force. The larger the wheat planting area, the smaller the binding force of water resources on agricultural production. For land resources, the expansion of wheat planting area will be restricted by the planting area; this is mainly related to the water requirement of wheat.

From the perspective of GDP, the increase of GDP in the region will lead to the increase of the water and land resources and water resources to agricultural economic growth but reduce land resources' force to the agricultural growth.

From the proportion of the tertiary industry, the increase of the proportion of the third industry will lead to the reduction of the comprehensive effect of the soil and water resources, and the effect of water resources on overall economic growth will also be reduced. However, due to the development of the third industry, land resource force has enhancement in agricultural production.

Agricultural Water Use Efficiency Calculation

Agricultural Water Use Efficiency in First Stage

The results reveal disparities among different areas with regard to agricultural WUE. On average from 2004 to 2012 (Table 4), the comprehensive efficiency in these areas varied obviously. The comprehensive efficiency of Minle was the greatest, with a mean reaching 0.92. The efficiency of Sunan was the least, with a mean reaching only 0.19. From the standpoint of pure technical efficiency (PTE), the difference between counties was greatly reduced. Suning had the maximum PTE, nearly twice that of Suzhou. From the scale of efficiency, Minle's technology efficiency was nearly five times Sunan's scale efficiency.

Regarding county-scale time difference (Fig. 4), in 2004, the technical efficiency of Shandan and Minle was located on the frontier, whereas that efficiency of Jinta was the lowest. The pure technology efficiencies of Shandan, Minle, Sunan, and Jinta were equal to 1. The point of scale efficiencies of Shandan and Minle were also equal to 1. By 2012, the technology efficiency of Minle was equal to 1, and the pure technology efficiency of Ganzhou, Sunan, and Suzhou was equal to 1. The scale efficiencies of Ganzhou, Shandan, Minle, Sunan, and Suzhou were equal to 1. The main reason for the changes is that the various efficiencies measured by our approach represent a relatively comparative concept. Between 2004 and 2012, the agricultural production area of the Heihe River Basin substantially increased. In particular, agricultural production land reclamation entered a period of rapid development. Thus, the scale efficiency has increased, especially beginning in 2012. In addition to the five counties above, scale efficiency of the other counties was >0.9, indicating that the scale of efficiency to enhance the space was smaller. The technical efficiency of Minle was on the frontier. Since the 12th

Table 4 First stage average agricultural water use efficiency from 2004 to 2012 (Reprinted from Guofeng Wang (2018) with permission of Sustainability)

Location	TE	PTE	Scale
Ganzhou	0.65	0.67	0.98
Gaotai	0.63	0.82	0.78
Shandan	0.75	0.76	0.98
Minle	0.92	0.92	1.00
Linze	0.81	0.88	0.91
Sunan	0.19	0.95	0.20
Jinta	0.29	0.55	0.51
Suzhou	0.38	0.42	0.87

five-year plan, Minle has been committed to transforming traditional to modern agriculture, and its industrial structure improved considerably, leading to an intensive and professional mode of agricultural production and management. Because of improvement in organization and socialization, the agricultural water resource efficiency of Minle also increased.

Agricultural Water Use Efficiency in Second Stage

To establish the SFA equations, we used investment in fixed assets (Eq. 1), planting area (Eq. 2), agricultural labor force (Eq. 3), and agricultural water use (Eq. 4) as dependent variables and local development, water natural endowment, and industrial structure as independent variables. To identify the effects clearly, we constructed 24 equations using progressive panel regression, and the equations for 2012 are listed in Table 3.

Results show that the T-value of the likelihood ratio of unilateral error is larger than the critical value of a mixed χ^2 distribution. Thus, the original hypothesis is rejected, indicating that the model is reasonable and suitable for regression analysis using SFA. Among them, if the value of $\gamma = \frac{\sigma_\mu^2}{\sigma_\mu^2 + \sigma_\nu^2}$ in the variables is close to 1, the effect of inefficiency on the relaxation variable in the mixed error term is dominant, and the effect of random error on the relaxation variable is very small. In constructing the model, it is seen that input redundancy can be regarded as the opportunity cost of each region. A positive regression coefficient shows that the explanatory variable is positively correlated with the relaxation variable, indicating that increase in the explanatory variable is not conducive to a decrease in redundancy variables. When the regression coefficient is negative, increase of the explanatory variables reduces the relaxation variable. Thus, increase of the explanatory variables improves the efficiency of agricultural water resource utilization (Table 5).

The regression coefficient of local development for the four relaxation variables was negative throughout the significance testing. This was mainly because in more developed areas, other industries made up a larger proportion than agriculture, and the proportion of agriculture in industry was small. This caused a weak water resource scale effect.

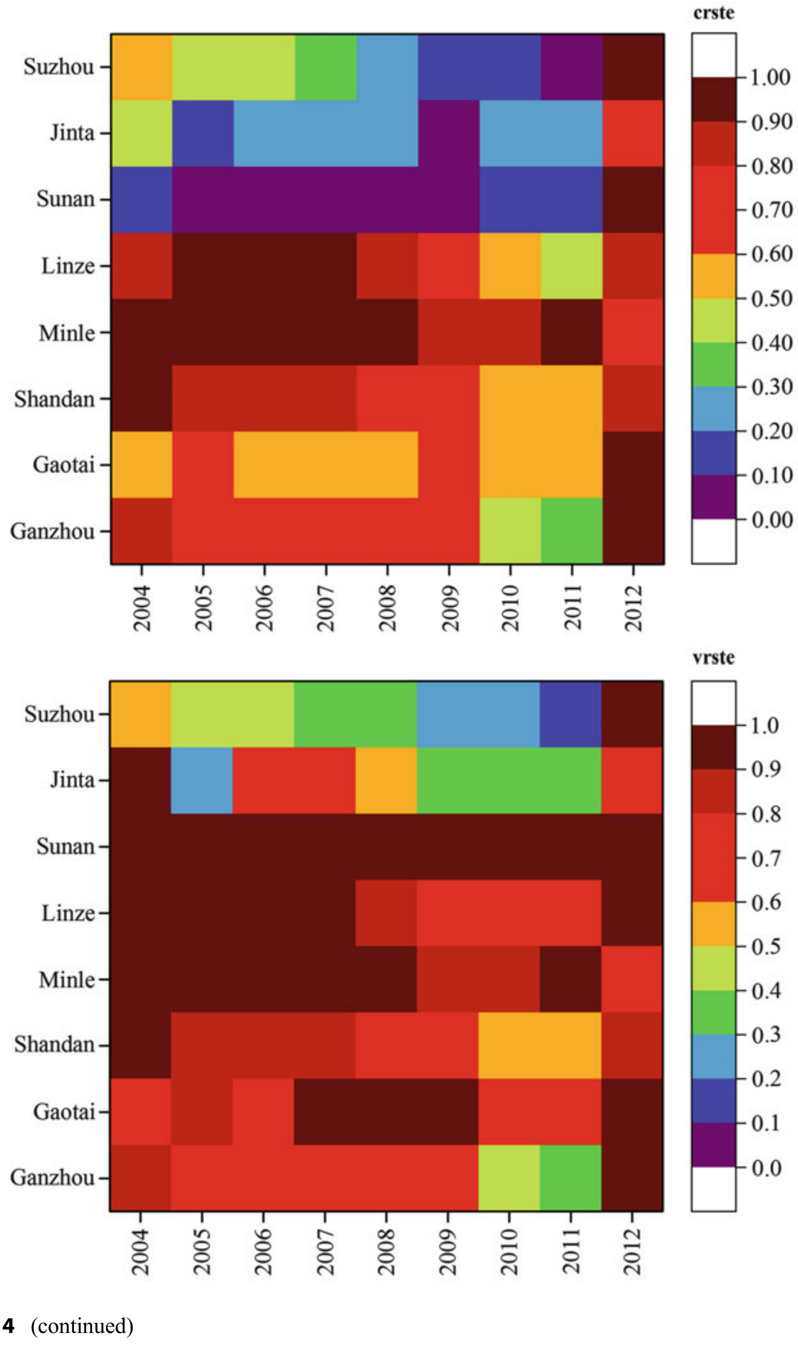

Fig. 4 (continued)

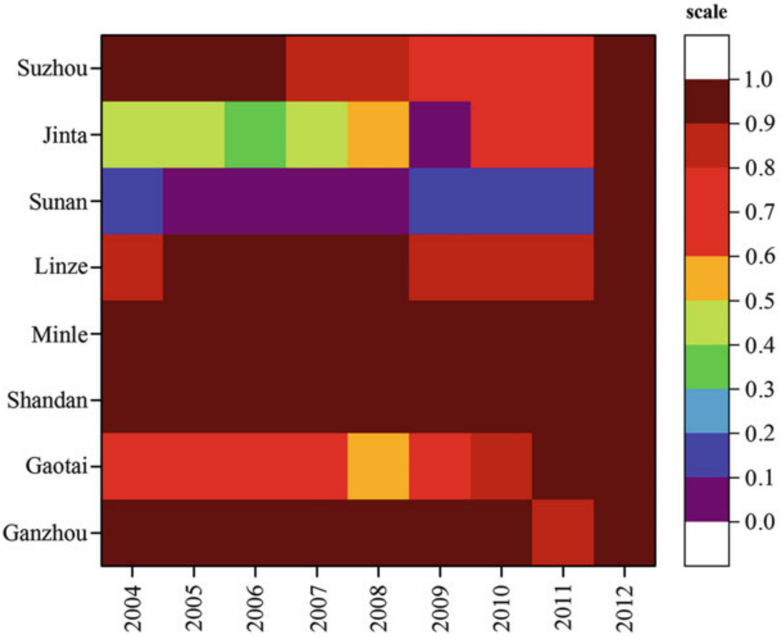

Fig. 4 Technology, pure technology, and scale efficiency in the Heihe Agricultural Production Area (Reprinted from Guofeng Wang (2018) with permission of Sustainability)

Table 5 Second stage: SFA analysis for 2012 in the Heihe Agricultural Production Area (Reprinted from Guofeng Wang (2018) with permission of Sustainability)

Variables	Equation 1	Equation 2	Equation 3	Equation 4
Constant	24490.60* (49900.15)	0.30* (2.63)	2304.71* (14517.76)	−1245.39* (−3501.62)
Local development (per capita GDP)	32.19* (6.2)	0.00*** (0.00)	8.01*** (1.80)	1.15** (0.44)
Water resource endowment (per capita water resources)	−93.49* (110.92)	0.02** (0.01)	57.07* (32.27)	30.41*** (7.78)
Industrial structure (the proportion of the primary industry)	−45167.11* (78599.98)	−2.52* (4.14)	−11931.18* (22867.58)	−4726.67* (5515.56)
σ^2	1011.06	72.63	2216.43	128.94
γ	0.99	0.77	0.68	0.64

Note: Figures in parentheses are standard deviations of corresponding coefficients
***, ** and * represent 1%, 5% and 10% significance levels, respectively

The regression coefficient of water resource endowment for the relaxation variable of fixed asset investment was negative throughout the significance testing. Water resource endowment had a positive effect on the other variables. This means that the increase of water resource endowment had a positive effect on the input to agricultural water resources, consistent with related research. In particular, the "resource curse" of certain scholars was strongly reflected.

The regression coefficient of the proportion of primary industry for the four relaxation variables was negative, meaning that the larger the proportion of primary industry, the stronger the scale effect. The increase in the proportion of primary industry generates more social capital to invest in primary industry, thereby improving water resource infrastructure and water resource efficiency.

Agricultural Water Use Efficiency in Third Stage

After the adjustments, we used the same input-output variables as in the first stage, and the results show some differences. After adjustment (Fig. 3), on average over 2004–2012, there were obvious differences in comprehensive efficiency across the areas. The technology efficiency of Ganzhou was maximum, with mean = 0.45. The adjusted pure technology efficiencies of five counties were all >0.9. The maximum scale efficiency was that of Ganzhou.

Specifically, in 2012, the technology efficiency of Suzhou was the highest, reaching the frontier, i.e., an efficiency value = 1. The smallest technology efficiency value was that of Sunan. Compared with 2004, Sunan did not change much, but its technical efficiency clearly increased. Pure technical efficiency was >0.9, and the scale efficiency difference was obvious. In particular, the scale efficiency of Sunan in 2012 was only 0.296 (Fig. 5).

Agricultural Water Use Efficiency Change During 2004–2012

From a comprehensive view (Fig. 6), technical efficiency of the counties declined significantly after eliminating the effects of environmental and stochastic factors. For technical efficiency, the major change in performance was a declining trend. For the trend of technology efficiency, Minle decreased the most. According to the estimated result, in 2007, Minle's adjusted technical efficiency and the original had an obvious gap. For Ganzhou in 2011 and Suzhou from 2007 to 2012, technical efficiency had an upward trend. In particular, for Suzhou, after elimination of the relevant effects of technical efficiency, there was an upward trend over many years. For scale efficiency, in addition to Suzhou in 2011, the other counties had a downward trend.

To elucidate changes of different counties in detail, we took Ganzhou District as an example (Fig. 7). It is seen that after adjustment of the technical and scale efficiencies of agricultural production, those efficiencies showed a declining trend, while the pure technology efficiency had an upward trend. In 2012, changes of scale efficiency led to all technical efficiency changes, i.e., in the first stage of the estimation, scale efficiency was overestimated. This means that the region's agricultural scale efficiency did not seriously affect agricultural water resource efficiency.

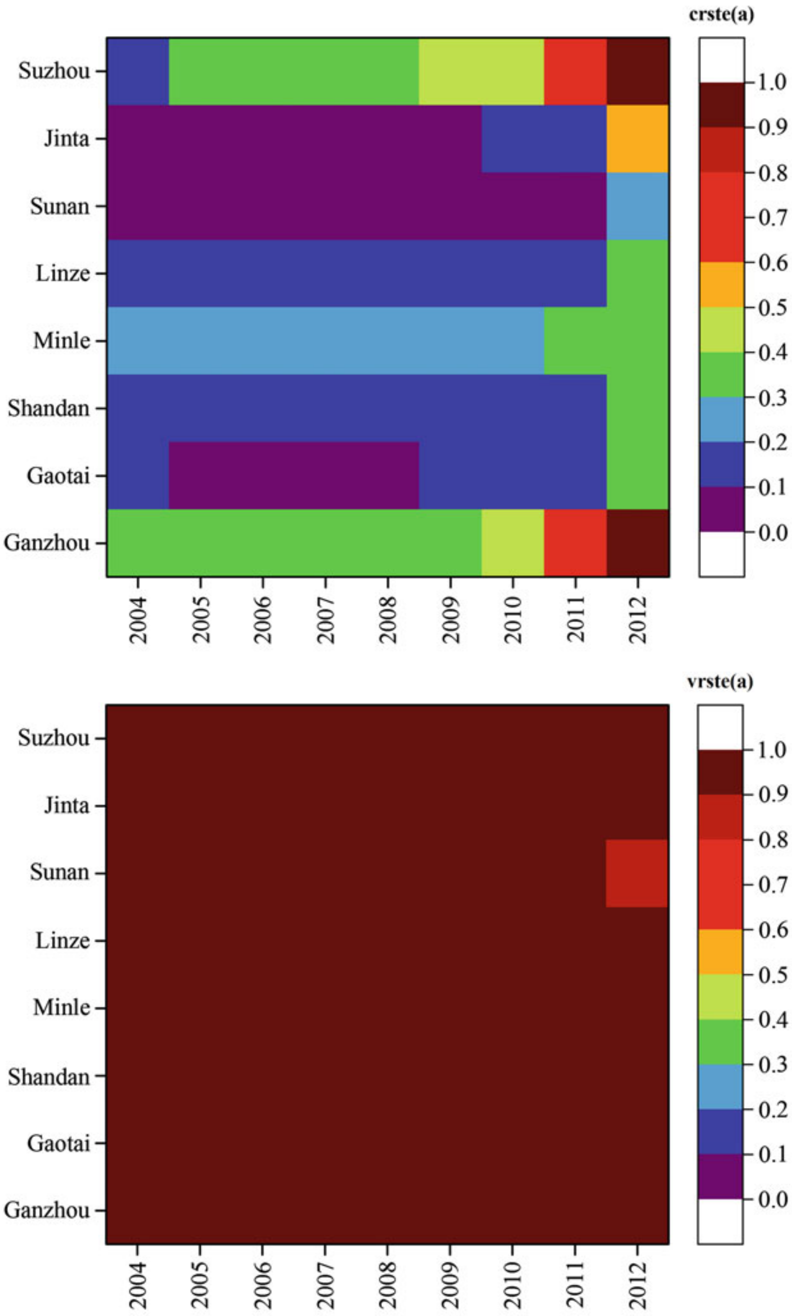

Fig. 5 (continued)

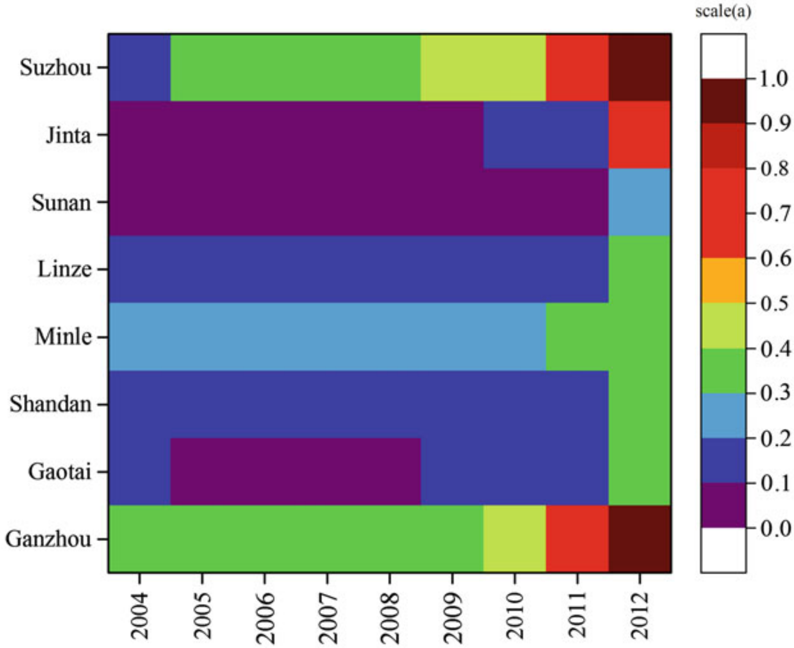

Fig. 5 Adjusted technology, pure technology, and scale efficiency in the Heihe Agricultural Production Area (Reprinted from Guofeng Wang (2018) with permission of Sustainability)

The above analyses suggest that the availability of water resources in all these counties/districts restricted economic growth in the midstream of the Heihe River Basin which experienced water shortages. In other words, during agricultural growth, because the availability of water and land resources did not increase proportionally with the input of the labor force, the growth rate of real agricultural yield was smaller than when the water and land resources per unit labor force were constant. The shortage of land resources was not severe in the study area. In particular, Sunan County supported 25,500 agro-pasture workers using a total area of 24,000 km^2 that was dominated by the stockbreeding industry and was rich in land resources. The calculations show that, when compared with other studies (Table 4), the drag effects of water and land resources were relatively severe in some counties/districts, but the results generally fall within the range from the mainstream trends in China and abroad (Table 6).

The main possible cause for this result is that our study extended from 2000 to 2012. Thus, the effects of water and land resources on agricultural growth acted in a cycle of “inhibition–promotion–inhibition–promotion,” which led to cumulative and additive effects and thereby created relatively larger results.

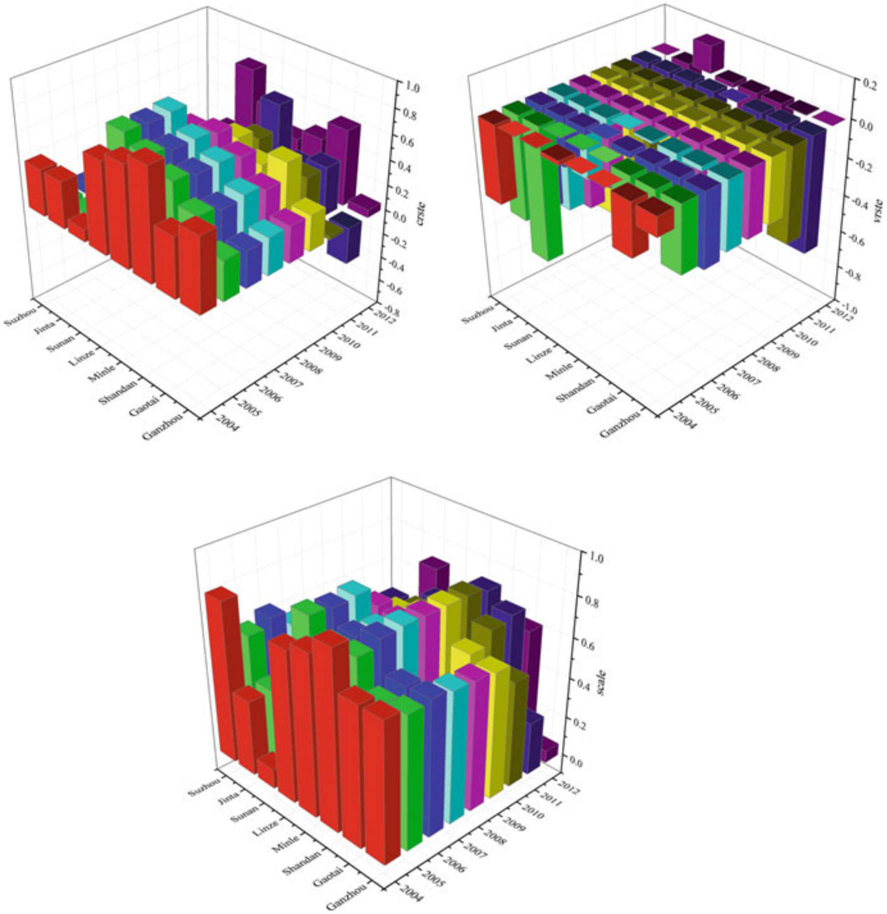

Fig. 6 Differences before and after adjustment (Reprinted from Guofeng Wang (2018) with permission of Sustainability)

Summary

In this study, based on the theory of neoclassic economic growth and the Romer model, we estimated the drag effects of water and land resources on agricultural growth in the midstream of the Heihe River. We found the drag effects of water and land resources on agricultural growth differed largely among counties/districts. In particular, in the arid and semiarid study area, the inhibition of water resources on agricultural development became a major constraint. Our findings will help to promote water use efficiency and substantially relieve the inhibition of water endowment shortages on agricultural development. The implementation of water resource management in the Heihe River Basin dates back to the early 1950s, when

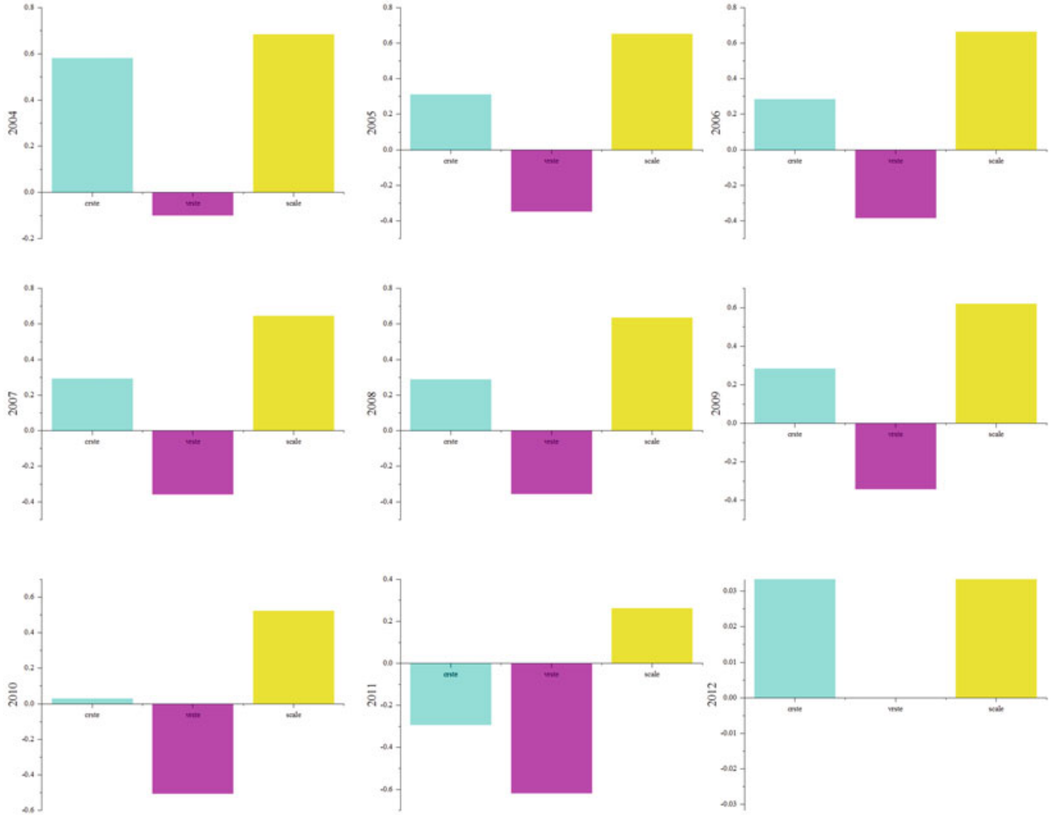

Fig. 7 Difference before and after adjustment in Ganzhou County (Reprinted from Guofeng Wang (2018) with permission of Sustainability)

Table 6 Comparison of the drag effects of water and land resources with findings of other studies

Authors	Year	Studied resource	Conclusion
Nordhaus	1992	Land	The drag effect of land resource is 0.06%
Xie Shuling et al.	2005	Water and land	The drag effect of water and land resources is 1.45% (land, 1.32%; water, 0.13%)
Nie Hualin	2011	Water and land	The drag effect of water and land resources on the growth of agricultural growth in China is 0.11% (water, 0.08%; land, 0.03%)

water resources were studied extensively, but mainly in terms of water resource productivity and water use efficiency. Increasing the unit water use efficiency would effectively relieve water shortages. Increasing water use efficiency through reasonable planning and management together with enhanced water conservation and infrastructure development could gradually relieve the water resource deficiency in the study area. As for land resources in the study area, appropriate exploitation, reasonable use, and accelerated transformation should be combined so as to focus on reforming land use in the Heihe Agricultural Production Area. Agricultural development can be sustained only through the reasonable use of water and land resources.

Our findings will affect agricultural growth in China over the long term. The continued economic development of China depends on agricultural support. In China, agriculture supports the lives of 43% of the population directly because they receive their income by working in agriculture. Meanwhile, the labor force in China, especially the agricultural labor force, seems to be aging. In other words, much of the labor force comprises elderly people, with relative few young people entering the agricultural labor force. After the confirmation of countryside land rights in China, the agricultural labor force in China is expected to continue to decrease in size. Determining the appropriate rates of increase in the labor force as well as in the availability of water or land resources will help China to use and protect resources efficiently.

In this work, three-stage DEA was used to analyze the efficiency of agricultural water resource utilization in the Heihe Agricultural Production Area over 2004–2012. From regional analysis, after exclusion of external environmental and random factors, regional agricultural water efficiency underwent great changes. Comprehensive technical efficiency and scale efficiency mainly manifested as overestimated trends, and pure technical efficiency had an underestimated trend. Therefore, the three-stage DEA could better describe WUE in the Heihe Agricultural Production Area. Based on the above conclusions, technology is not the main factor restricting the improvement of agricultural water resource efficiency in the region. The main restriction on the efficiency of agricultural water resources is the scale factor.

A favorable scale of agriculture has always been a focus of research, especially the resource-saving effect of scale operation. There is serious water waste in irrigation areas of China, and the ecological environment of general irrigation areas is more fragile. A reasonable irrigation scale will greatly improve the efficiency of agricultural water resources. Improvement in water efficiency of traditional agriculture is more focused on technical improvements, and studies have shown that the possibility for agricultural water conservation on the technical level is almost nil. In the present work, owing to limitations of data acquisition, only change of regional agricultural water resource efficiency from 2004 to 2012 was studied. In the future, input/output indicators will be an important component of the DEA model.

Along with the global combat of climate changes, the world is toward a greener revolution. According to the new agreement, the average temperature rise should be limited to 2 °C. This target aims to alleviate potential dangers from natural disasters. The IPCC AR5 indicates that the average temperature on Earth is becoming increasingly warming in the recent decades. From 1880 to 2012, the surface average temperature rise approximately 0.85 °C. In particular, temperature rise is faster on land versus in seas, in high-latitude areas versus low- or middle-latitude areas, and in the winter half year versus the summer half year. Periodicity, the year from 1983 to 2012 is the hottest 30 years in the past 1400 years. The warming trend in China is consistent with global warming. Since 1913, the average land temperature has risen by 0.91 °C. The past 60 years have witnessed extremely significant temperature rise at an average rate of 0.23 °C per 10 years, which is nearly twice the global rate. The contribution from anthropogenic greenhouse gas emissions could be 0.5–1.3 °C. The most severe consequence is the elevation of air CO_2 concentrations, the contribution from natural factors may be −0.1–0.1 °C.

Climate change is closely related to the water use. For example, the primary, secondary, and tertiary sectors will produce different greenhouse gases and thus will induce climate change. While concerning the main reason of global climate change, many social and nature influence factors may contribute to this process. Among which, CO_2 emission is a vital role to climate change.

However, because of the use of different statistical analysis methods in this study, the general results were basically in agreement with those of other researchers, which was more or less consistent with the actual situation. Therefore, the analysis and evaluation results were considered appropriate. Inefficient allocation of resources and a relatively slow pace of economic development of the entire region have led to an unobvious regional economic integration development trend.

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Spatiotemporal Surface of Agricultural Water Requirement for Integrated Water Resources Management

Wei Song, Yaqun Liu, Xiangzheng Deng, Ying Zhang, and Ze Han

Contents

Introduction 185
Methodology for Mapping Spatiotemporal Surface of Agricultural Water Requirement 187
  Multi-Temporal NDVWI and Decision Tree Algorithm for Crop Planting Structure 187
  USDA-SCS Method for Effective Rainfall (ER) 188
  FAO Penman-Monteith Formula for Reference Crop Evapotranspiration (ET_o) 189
  Crop Coefficient Method for Crop Evapotranspiration Under Standard Conditions (ET_c) 190
  Water Balance Theory for Agricultural Water Requirement (AWR) 191

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Spatiotemporal Surface of Agricultural Water Requirement in HRB 191
Materials 191
Spatiotemporal Changes in ER 194
Spatiotemporal Changes in ET_o 194
Spatiotemporal Changes in ET_c 197
Spatiotemporal Changes in AWR 197
Reasons and Policy Implications of AWR Changes 200
Reasons of AWR Changes 200
Policy Implications of AWR Changes 205
Summary 206
References 208

Abstract

Agricultural irrigation consumes about 80% of total worldwide water consumption, and agricultural intensification has led to negative consequences including ecosystem degradation and decreases in biodiversity, especially in arid and semi-arid areas. Thus, it is crucial for sustainable development of economy and ecosystems to effectively manage agricultural water. We model the spatiotemporal surface of agricultural water requirement (AWR) in the Heihe River Basin (HRB) using multiple methods, such as multi-temporal normalized difference vegetation-water index (NDVWI) and the Food and Agriculture Organization of the United Nations (FAO) Penman-Monteith formula. We also discuss the reasons and policy implications for AWR changes. The results show that AWR increases upstream-to-downstream within the HRB from 0 up to 150 mm and between 300 and 450 mm. From 2007 to 2012, annual mean AWR increased from 339.95 to 370.11 mm. Monthly mean AWR initially increased before decreasing in concert with crop growth, and the largest values for this index were recorded during June. Mean AWR for oilseed rape, corn, barley, and other crops all increased by 33.37, 43.75, 21.91, and 26.01 mm, respectively. While the mean AWR of wheat decreased by 14.84 mm. Mainly because of changes in crop planting structure and climate, the total AWR for the HRB in 2012 reached 2692.58×10^6 m^3, an increase of 332.16×10^6 m^3 (14.07%) compared to 2007. Thus, to maintain both the sustainable development and ecological security, the cultivation of water-demanding crops and the further expansion of agricultural land should also be avoided.

Keywords

Agricultural water requirement · Evapotranspiration · Agricultural irrigation · Crop planting structure · Spatiotemporal surface · TM/ETM+ RS images · Multi-temporal NDVWI · FAO Penman-Monteith formula · Crop coefficient · Integrated water resources management · Sustainable development · Heihe River Basin

Introduction

Water is one of the most important substance on Earth, intimately involved in the formation and evolution of all facets of the environment, including biogeochemical cycles, climate change, and the configuration of the planet (Li et al. 2015; Liu et al. 2017a). Water is critical to the survival of biological organisms and ecosystems, and thus to sustainable development, especially food security (Bekchanov et al. 2010). In light of the comprehensive effects of various factors, including the natural environment, social economy, and technology, more than 40 countries worldwide (about 40% of the global population) currently face severe water shortages, directly restricting their sustainable social and ecological development (Vorosmarty et al. 2000; Xu et al. 2016). Imbalances in water supply and demand lead to shortages; specifically, global climate change, population growth, urbanization, and agricultural intensification have all caused the water demands of different sectors to increase rapidly (Deng et al. 2015a; Song and Pijanowski 2014; Song et al. 2015; Yu et al. 2017). Global warming leads to increased evapotranspiration, which aggravates water cycling processes and causes increased rainfall (Fan et al. 2012; Ning et al. 2017). However, in most arid areas where water is scarce, rainfall is decreasing, leading to an increasing imbalance between global water supply and demand (Deng et al. 2006; De Wit and Stankiewicz 2006). At the same time, water waste and pollution exacerbate water shortages and cause a number of negative effects including ecosystem degradation and decreases in biodiversity (Qi and Luo 2005; Song and Deng 2017; Tao et al. 2005; Yang and Lu 2015). It is therefore critical to understand the water supply available to, and the demand of, the main water-using sectors as well as to explore reasonable and sustainable ways to utilize this resource to ensure regional sustainable development and ecological security.

Research on the supply of water has mainly focused on total and available volumes. A range of climate and hydrological models, including the Soil and Water Assessment Tool (SWAT), the Global Hydrologic Evaluation Model (GHEM), the Regional Hydro-climate Model (Reg-HCM), the Rainfall-Runoff Modeling System (PRMS), and the Water Balance/Transport Model (WBM/WTM), have all been used to quantitatively estimate rainfall and runoff at different scales, including globally, nationally, and at the level of individual basins (Kavvas et al. 1998; Uniyal et al. 2015; Van Beusekom and Viger 2016; Vorosmarty et al. 1996). In contrast, research on water demand has mainly focused on the usage of different sectors such as agricultural, urban domestic and ecological. In this context, water demand is usually estimated based on factors such as population size, cultivated and natural land area, and water use efficiency (Ge et al. 2016; Zhou et al. 2015). Among the different water-using sectors, agriculture consumes the highest volumes of water globally; irrigation water, for example, accounts for about 80% of total worldwide water consumption. Thus, research to date has estimated agricultural water requirement (AWR) based mainly on models such as CROPWAT, AquaCrop, and PolyCrop (Bocchiola 2015; Luo et al. 2015; Rotich and Mulungu 2017; Shrestha and Shrestha 2017; Ye et al. 2015). These models, however, are unable to evaluate spatiotemporal patterns in AWR at high spatial resolution and thus cannot be used to determine differences over time and space and due to crop types. This lack of spatiotemporal data on AWR for different crop types has hampered the scientific research that underlies integrated water resources management.

Compared with developed countries, water shortages in developing regions globally are more acute and less well-studied, especially in arid and semi-arid areas. China is one of the largest developing countries and one of the most arid; 20% of the global population live in this country yet it boasts between just 5% and 7% of global freshwater resources. The available water per capita in China is just a quarter of the global mean (Shen et al. 2013; Yang et al. 2016). Arid and semi-arid areas in Northwest China make up 30% of the national land area, but have less than 20% of total national available water resources because rainfall is low and evapotranspiration is high; thus, water shortages in this region are of particular concern (Deng et al. 2015a; Xu et al. 2016). This issue is even more critical because much of the irrigated cultivated land in China is also distributed in these arid and semi-arid areas; natural rainfall cannot meet the water requirements of crops in this region and so supplementary irrigation is essential to increase yields and to guarantee food security in these areas (Jin et al. 2016; Lu and Fan 2013). Agricultural irrigation water nationally accounts for 60% of total water use, but more than 80% of total consumption in the arid and semi-arid areas of Northwest China (Li et al. 2015; Uniyal et al. 2015). Thus, accurate AWR calculations are crucial to the regional social-economic and ecological sustainable development of these areas where water is scarce (Lang et al. 2017).

The rapid expansion of agricultural oases combined with population growth and urbanization have further exacerbated the imbalance between urban and agricultural water use in China (Zhou et al. 2015). Thus, to meet escalating water demands for crop irrigation, agricultural producers have utilized increasing volumes of runoff and groundwater which leads to ecosystem degradation including the seasonal cutoff of rivers, groundwater overdraft, and decreasing ecological land area (Deng et al. 2015b, 2016). To mitigate these issues, the Chinese government has implemented a range of water management measures concerning water yield, water rights, and water prices and has also promoted the application of new technologies including drip and sprinkler irrigation (Deng and Zhao 2015). However, managers and producers are still unable to effectively allocate agricultural water according to actual demand because of the absence of high-precision, fine-scale spatiotemporal AWR data. This situation has led to inefficient water use including irrigation waste and deficits (Zhou et al. 2015). It is therefore critically important to provide comprehensive data on water usage as it relates to the spatiotemporal distribution of crops, climate, and evapotranspiration in order to precisely estimate AWR. Such data will support decision making, enable the formulation of efficient irrigation schemes, and allow the implementation of integrated water resources management measures to alleviate the negative economic and ecological effects caused by shortages.

Water shortages are restricting the sustainable development of society, the economy, and ecosystems within the Heihe River Basin (HRB), a continental system that encompasses both arid and semi-arid areas of China. The rapid expansion of agricultural oases in recent decades, as well as expansion and changes to crop planting structures, have led to rapidly increasing demands for agricultural water in the HRB (Liu et al. 2016, 2017b; Song and Zhang 2015). At the same time, however, the water supply of this region has not kept pace with demand, even though it has increased slowly and intermittently as climate has become warmer and wetter. Rapid population growth and urbanization has further exacerbated the water supply and demand imbalance between agriculture, cities, and ecology and has led to negative effects, including ecosystem degradation. Understanding changes in spatiotemporal AWR patterns because of changes in crop planting structure and climate is therefore critical to the integrated management of water resources. Thus, using the HRB as our study area, we extracted spatiotemporal distributional information on crop planting structure using multi-temporal normalized difference vegetation-water index (NDVWI) from Thematic Mapper and Enhanced Thematic Mapper Plus (TM/ETM+) remote sensing (RS) images, and we calculated spatiotemporal AWR using the Food and Agriculture Organization of the United Nations (FAO) Penman-Monteith formula. The objectives of this study are: (1) To reveal the spatiotemporal characteristics of variation in effective rainfall (ER), crop evapotranspiration, and AWR between 2007 and 2012 in the HRB; (2) To analyze the influences of crop planting structure and climate changes on AWR; and (3) To discuss the implementation of policies that could contribute to alleviating the imbalance between agricultural water supply and demand.

Methodology for Mapping Spatiotemporal Surface of Agricultural Water Requirement

AWR is determined jointly by evapotranspiration and rainfall, and varies with crop types. Therefore, based on the mapping of crop planting structure, the spatiotemporal surfaces of crop evapotranspiration and rainfall should be carried out. In this study, we developed a methodology to map spatiotemporal surface of agricultural water requirement based on the synthesis of multiple methods. Specifically, we applied multi-temporal normalized difference vegetation-water index (NDVWI) and decision tree algorithm for crop planting structure, the United States Department of Agriculture and Soil Conservation Service (USDA-SCS) method for effective rainfall (ER), the FAO Penman-Monteith formula for reference crop evapotranspiration (ET_o), crop coefficient method for crop evapotranspiration under standard conditions (ET_c), and water balance theory for AWR.

Multi-Temporal NDVWI and Decision Tree Algorithm for Crop Planting Structure

(1) NDVWI. We identified crop types in this study using the multi-temporal NDVWI, a new spectrum index that we developed based on the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI) (Liu et al. 2016). Because the NDVI can effectively, empirically, and simply characterize vegetation growth status, it is one of the most widely used indexes in vegetation

classification (Huete et al. 2002). At the same time, the NDWI is sensitive to moisture in the vegetation canopy and is therefore also helpful for classification (Gao 1996). Our index, the NDVWI, combines the merits of both the NDVI and the NDWI and can achieve higher crop classification accuracy than either, especially in arid and semi-arid areas. Values for the *NDVWI* range between −2 and 2 and are dimensionless. The formula used to calculate this index is as follows:

$$\mathrm{NDVWI} = \frac{\rho(nir) - \rho(red)}{\rho(nir) + \rho(red)} + \frac{\rho(nir) - \rho(swir)}{\rho(nir) + \rho(swir)} \tag{1}$$

where $\rho(red)$, $\rho(nir)$, and $\rho(swir)$ denote the surface reflectance of red, near-infrared, and short-wave infrared bands, the third, fourth, and fifth bands in TM/ETM+ images, respectively.

(2) Decision Tree Algorithm. A decision tree algorithm is a top-down classification approach which is used to organize complex data sets step-by-step by effectively combining their characteristics with professional knowledge (Liu et al. 2017b). A decision tree comprises root, internal, and leaf nodes; of these, parent nodes (i.e., root or internal nodes) are further classified as child nodes (i.e., internal or leaf nodes) based on classification rules. A series of crop classification rules were developed by integrating the key time-windows and their thresholds of different crops.

The main crops in HRB were corn, wheat, barley, and oilseed rape. The phenological information of corn and oilseed rape is significantly different from that of wheat and barley, since the first two are autumn crops while the latter two are summer crops. Based on the response of multi-temporal NDVWI to variations and differences in crop phenological information over time, the key time-windows of different crops were determined (Liu et al. 2016). Specifically, the key time-window in August was selected to classify summer crops and autumn crops, since summer crops in HRB have been harvested but autumn crops are still growing. In addition, based on the differences of growth stages between corn and oilseed rape, relevant key time-window in September was selected to classify those two. Similarly, the key time-windows in June and August were selected to classify corn and oilseed rape.

Furthermore, comprehensively analyzing the maximum, minimum and average values of different crops in the multi-temporal NDVWI, the NDVWI thresholds of key time-windows were determined using mathematical statistics. Thus, based on crop sample training, the key time-windows and their thresholds were integrated to develop classification rules for different crops in this study. Finally, use of crop classification decision trees enabled us to extract HRB crop planting structures for 2007 and 2012.

USDA-SCS Method for Effective Rainfall (ER)

In agricultural production, ER is the portion of rainfall that can be effectively used by crops. This concept is important; not all rainfall is available to agriculture as a component is always lost through runoff and infiltration. It is difficult to obtain accurate runoff and infiltration other than field observation, since the two depend on multiple factors, such as soil type, slope, crop canopy, storm intensity and the initial soils water content. However, the implement of field observation in large areas is time-consuming and costly. Fortunately, simulation methods, e.g., the FAO/AGLW formula, the empirical formula and the USDA-SCS method provide the effective and accurate estimation of ER (Allan et al. 2005). Among those methods, the USDA-SCS method proved to be a more effective way (Allan et al. 2005; Nagarajan and Poongothai 2012). Thus, applying the USDA-SCS method, we calculated *ER* in monthly steps as follows:

$$\mathrm{ER}_{month} = \begin{cases} \mathrm{AR}_{month} \times (125 - 0.2 \times \mathrm{AR}_{month})/125 & for\ \mathrm{AR}_{month} \leq 250\ \mathrm{mm} \\ 125 + 0.1 \times \mathrm{AR}_{month} & for\ \mathrm{AR}_{month} > 250\ \mathrm{mm} \end{cases} \tag{2}$$

where ER_{month} and AR_{month} refer to the effective and actual rainfall in each month, respectively.

FAO Penman-Monteith Formula for Reference Crop Evapotranspiration ($\mathrm{ET_o}$)

Reference crop refers to a hypothetical crop growing actively with a sufficient water supply with an assumed height of 0.12 m having a surface resistance of 70 s/m and an albedo of 0.23. The $\mathrm{ET_o}$ refers to the evapotranspiration that would be recorded if the whole surface of the Earth was covered with reference crop (Allan et al. 2005; Penman 1948). In 1990, the FAO convened a large group of experts and researchers to collaborate with the International Commission for Irrigation and Drainage and the World Meteorological Organization to jointly improve the AWR calculation methodology. This process resulted in the development of the FAO Penman-Monteith formula for the calculation of $\mathrm{ET_o}$ (Allan et al. 2005; Luo et al. 2015). The FAO Penman-Monteith equation is a close, simple representation of the physical and physiological factors governing the evapotranspiration process. The simplification in formulation and errors in data measurement lead to the use of any weather-based method can not achieve the perfect prediction of evapotranspiration. The FAO Penman-Monteith formula is expected to overcome the numerous shortcomings of earlier methods; $\mathrm{ET_o}$ values calculated using this approach are more consistent with global actual crop water consumption data. We computed ET_o (mm/d) as follows:

$$\mathrm{ET_o} = \frac{0.408 \times \Delta \times (R_n - G) + \gamma \times \dfrac{900}{T_{\mathrm{mean}} + 273} \times u_2 \times (e_s - e_a)}{\Delta + \gamma \times (1 + 0.34 u_2)} \tag{3}$$

$$\Delta = \frac{4098 \times e(T_{\mathrm{mean}})}{(T_{\mathrm{mean}} + 237.3)^2} \tag{4}$$

$$e(T) = 0.6108 \times e^{\frac{17.27T}{T+237.3}} \tag{5}$$

$$e_s = \frac{e(T_{\max}) + e(T_{\min})}{2} \tag{6}$$

$$e_a = RH \times e_s \tag{7}$$

$$\gamma = 0.665 \times 10^{-3} P \tag{8}$$

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)} \tag{9}$$

where R_n is crop surface net radiation ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$); G is soil heat flux ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$); Δ is the slope of the saturated water vapor pressure curve (kPa/°C); γ is the psychrometric constant (kPa/°C); u_2 is wind speed at a height of 2 m (m/s); T_{mean}, $T_{\max}$, and $T_{\min}$ refer to mean temperature, mean maximum temperature, and mean minimum temperature, respectively (°C); e_s denotes the saturated water vapor pressure (kPa); e_a is the actual water vapor pressure (kPa); $e(T_{\text{mean}})$, $e(T_{\max})$, and $e(T_{\min})$ are water vapor pressures at temperatures of T_{mean}, $T_{\max}$, and $T_{\min}$, respectively; RH is relative humidity (%); P is atmospheric pressure (kPa); and z is the elevation from the surface of the Earth when measuring wind speed.

Crop Coefficient Method for Crop Evapotranspiration Under Standard Conditions ($\mathrm{ET_c}$)

In this context, $\mathrm{ET_c}$ is defined as crop evapotranspiration when a disease-free, well-fertilised crop is growing actively in an given optimum climatic condition with sufficient water supply, and achieving full production. The $\mathrm{ET_o}$ can be estimated by the FAO Penman-Monteith formula, but there is still a considerable lack of information for different crops. Thus, an experimental definition called crop coefficient (K_c) was determined as the ratios of ET_c to ET_o. The $\mathrm{K_c}$ integrates the effect of characteristics that can effectively distinguish a specific crop from the reference (Allan et al. 2005; Luo et al. 2015). According to the crop coefficient method, we calculated ET_c (mm) for the major crops grown in the HRB for the period between March and September as follows:

$$ET_{\mathrm{c}} = ET_{\mathrm{o}} \times K_{\mathrm{c}} \tag{10}$$

However, $\mathrm{K_c}$ is influenced mostly by crop type. Moreover, $\mathrm{K_c}$ for a given crop varies over time in the crop growth stages. Thus, for more accurate estimation of $\mathrm{ET_c}$, $\mathrm{K_c}$ values for the initial stage, development stage, mid-season stage and end-season stage of different crops are all required. In this study, we corrected and determined those values for different crop stages using a survey based on FAO Irrigation and Drainage Paper No. 56 (Allan et al. 2005) and crop phenological information (Table 1). Oilseed rape and corn are autumn crops, so their growth

Table 1 K_c values for different crop growth stages within the HRB in 2007 and 2012

Crop	Sowing date	Initial stage		Development stage		Mid-Season stage		End-Season stage	
		Duration (d)	$K_{c\ ini}$	Duration (d)	$K_{c\ dev}$	Duration (d)	$K_{c\ mid}$	Duration (d)	$K_{c\ end}$
Oilseed rape	10 April	30	0.35	36	0.73	35	1.10	32	0.73
Corn	15 April	30	0.10	56	0.56	57	1.02	21	0.79
Barley	20 March	30	0.30	43	0.78	26	1.25	22	0.75
Wheat	20 March	30	0.30	50	0.77	26	1.24	22	0.77
Other crops	1 April	30	0.26	46	0.71	36	1.15	24	0.75

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stages are longer than those of summer crops such as barley and wheat; the growth phase of oilseed rape is between April and August, while that of corn is between April and September, those of barley and wheat are between March and July, and those of other crops are between April and August.

Water Balance Theory for Agricultural Water Requirement (AWR)

In some areas, especially in arid and semi-arid areas, natural rainfall is not sufficient to meet the water demand for crop growth. AWR represents the fraction of the crop water requirements that needs to be satisfied through irrigation contributions in order to guarantee to the crop optimal growing conditions. Thus, based on water balance theory, *AWR* is required to replenish the deficit between evapotranspiration loss and rainfall supplement (Allan et al. 2005). The value is the difference between *ER* and ET_c, calculated as follows:

$$\mathrm{AWR} = \begin{cases} ET_c - ER & \text{for } \mathrm{ET_c} > ER \\ 0 & \text{for } \mathrm{ET_c} < ER \end{cases} \tag{11}$$

Spatiotemporal Surface of Agricultural Water Requirement in HRB

Materials

Basic Information of HRB

The HRB is the second largest continental river basin within the arid and semi-arid areas of Northwest China, located in the center of the “One Belt and One Road” and “Silk Roads” economic belts (97°30′ E–101°43′ E, 37°55′ N–40°00′ N) (Fig. 1). The HRB borders the Qinghai-Tibet Plateau in the southwest, the Shule River Basin in the west, the Shiyang River Basin in the east, and Mongolia in the north. The entire basin encompasses an area of 12.80×10^6 ha and consists of 11 administrative

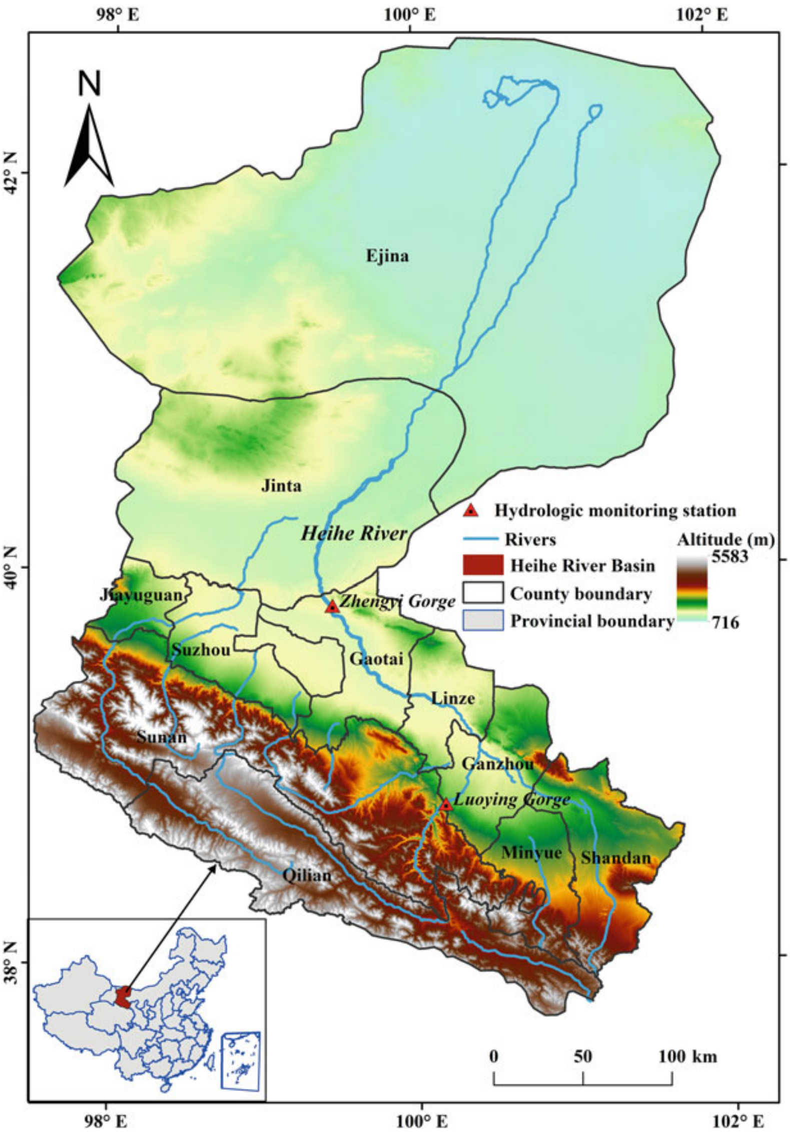

Fig. 1 Map to show the geographical location and administrative divisions of the HRB (Reprinted from Liu et al. (2017a) with permission of Water)

counties. The upper, middle, and lower reaches of the HRB are demarcated by the Yingluo and Zhengyi gorges; the upper reaches of this system mainly comprise the Qilian Mountain (Qilian and Sunan counties) water conservation area, while the middle reaches encompass agricultural oases in the center of the Hexi Corridor (i.e., Shandan, Minle, Ganzhou, Linze, Gaotai, Suzhou, and Jiayuguan counties), and the lower reaches extend into the Gobi Desert (Jinta and Egina counties). The HRB is located in the central part of the Eurasian plate, and is characterized by a temperate continental climate. This region is typically dry and water is scarce; the small amount of rainfall seen within the HRB tends to have a non-uniform spatiotemporal distribution. Mean annual rainfall in the upper, middle, and lower reaches of the HRB decreases gradually, from 250–500 mm, 100–250 mm, and less than 50 mm, respectively; 70% of the rainfall are concentrated in June, July, and August, with an annual potential evapotranspiration of 2400–3000 mm.

Water resources are the most important factor for ecosystem maintenance and the social and economic development of the HRB. The mean annual available amount of water within this basin is 28.0×10^8 m^3, of which surface water comprises 24.7×10^8 m^3 and groundwater comprises 3.3×10^8 m^3. In addition, the HRB is one of the ten largest commodity grain bases nationally; the main crops grown between March and September in this region include corn, wheat, barley, and oilseed rape. Agriculture is also the sector that consumes the most water in the HRB; irrigation water alone accounts for more than 85% of total water consumption in the basin. However, because of the lack of rainfall and runoff water, groundwater is used excessively in this area for irrigation. Because of the expansion of cultivated land area, rapid population growth, and urbanization in recent years, competition for water in the HRB among different sectors has become more-and-more intense, while the use of flood irrigation-oriented methods also waste a substantial volume, reducing agricultural water use efficiency to between 20% and 30%. In the face of these issues, a number of aspects of current water management within the HRB are unreasonable; the irrigation quota, for example, is far higher than the actual AWR. It is therefore critical to develop management strategies for the use of agricultural water according to the spatiotemporal water requirements of crops in order to avoid water waste, yield losses, and environmental degradation.

Data Sources

We utilized TM/ETM+ RS images at a spatial resolution of 30 m and a temporal resolution of 16 d in this study to extract crop planting structures for 2007 and 2012 in the HRB. Eleven images comprised the entire image of HRB, and their corresponding path/row numbers were 133/31, 133/32, 133/33, 133/34, 134/30, 134/31, 134/32, 134/33, 135/31, 135/32 and 135/33. The images we selected were then subjected to a series of systematic radiometric, geometric, and atmospheric corrections, as well as radiometric calibration and de-striping to obtain the mosaic images of HRB that included seven time phases for 2007 and ten time phases for 2012. The numbers of useable mosaic images differed between the 2 years because of cloud cover; for both years, the number of effective mosaic images was far less than the total number of time phases.

We used ground monitoring data collected at 20 meteorological sites in the HRB and adjacent areas to calculate reference crop evapotranspiration (including under standard conditions), ER, and IWRc. Meteorological data included mean monthly rainfall, temperature, maximum and minimum temperature, relative humidity, wind speed, and pressure for 2007 and 2012. We applied the thin plate spline (TPS) method using the software ANUSPLIN to interpolate meteorological data. This method enables the spatial interpolation of multivariate data via comprehensive statistical analysis, data diagnosis, and the use of spatial distribution standard errors to allow the introduction of related covariates and increase interpolation precision (Hutchinson 1998).

We then utilized the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) Version 2 elevation data with a spatial resolution of 30 m and an elevation resolution of 7 m to calculate net surface crop radiation (Fu and Rich 2002). Besides, phenological data from corn, wheat, barley, and oilseed rape were used to determine crop planting structures and coefficients at different growing stages.

Spatiotemporal Changes in ER

Results show that between 2007 and 2012, ER values in the HRB were non-uniform in their spatiotemporal distribution (Fig. 2). Specifically, annual ER values gradually fell along an upstream-to-downstream transect; in the upper reaches of the HRB, annual ER was higher than 250 mm, while values were between 100 mm and 200 mm in the middle reaches, falling to below 100 mm in the lower reaches. Data show that the annual mean ER of the HRB decreased from 139.49 mm in 2007 to 106.29 mm in 2012 (Fig. 2a, b). Thus, given the same evapotranspiration, decreasing ER means that the AWR in 2012 was greater than that of the same crop in 2007. Monthly ER also significantly differed within the same year, exhibiting a tendency to initially increase before decreasing (Fig. 2c, d). In both years, mean and minimum ER values were highest in July; highest monthly maximum values were recorded in June 2007 and in July 2012, while within each year, 70% of ER was concentrated between June and August. Results show that mean ER values in June 2007, July 2007, and August 2007 were 17.99, 41.68, and 19.29 mm, respectively, while in June 2012, July 2012, and August 2012 they were 26.82, 34.56, and 16.65 mm, respectively. Interestingly, mean ER values in April 2007 (16.79 mm) and September 2007 (20.97 mm) were significantly higher than those in April 2012 (4.42 mm) and September 2012 (5.74 mm). Some growth phases of dominant crops were also characterized by lowered ER values, including the seeding period between March and April, and the late growing period in September. In contrast, some fast growth periods, including between May and June and the intermediate phase between July and August were characterized by higher ER values. In other months, ER values were lower that those seen during crop growth periods (i.e., in January, February, October, November, and December).

Spatiotemporal Changes in ET_o

Data show that annual ET_o values for the HRB tend to increase along an upstream-to-downstream transect. Thus, in water conservation areas in the upper reaches, values were as low as 750 mm, increasing to between 750 and 1250 mm in

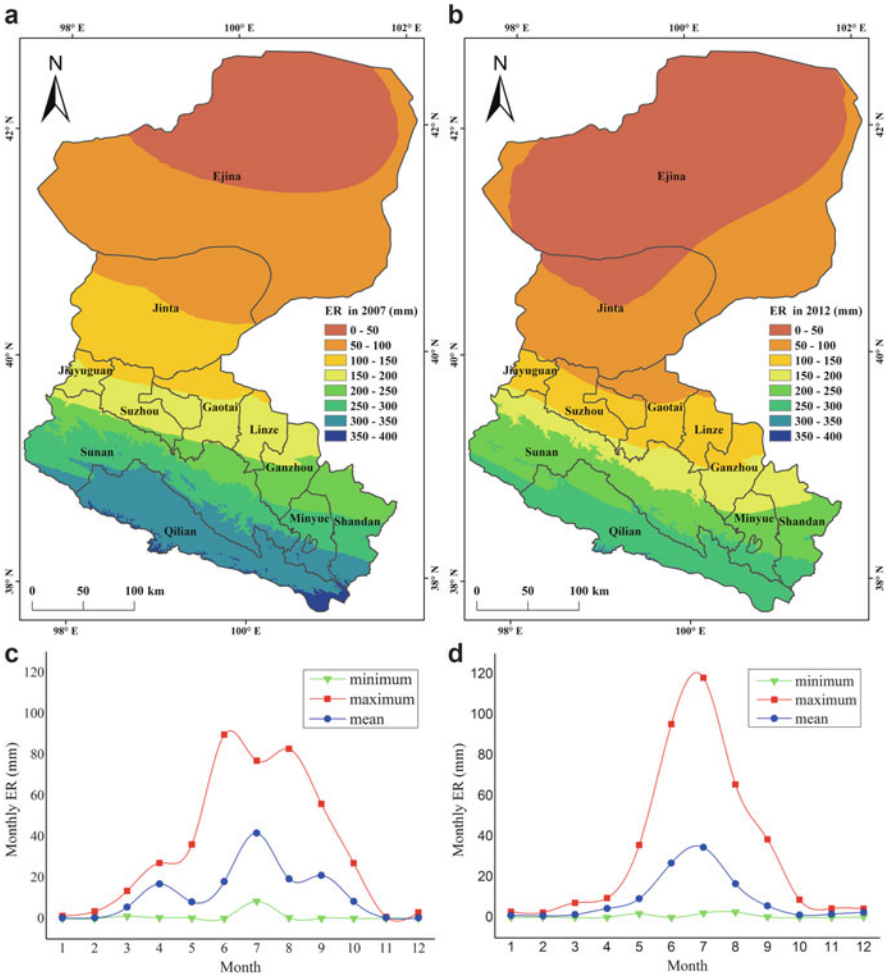

Fig. 2 ER within the HRB in 2007 and 2012: (**a**) Spatial distribution of ER in 2007; (**b**) Spatial distribution of ER in 2012; (**c**) Monthly mean, maximum, and minimum ER in 2007; (**d**) Monthly mean, maximum, and minimum ER in 2012 (Reprinted from Liu et al. (2017a) with permission of Water)

agricultural oases regions in the middle reaches, and were higher, between 1250 and 2500 mm, in the lower reaches. Annual ET_o exceeded 1750 mm in the northeastern ecological conservation area in the lower reaches of the HRB (Fig. 3a, b). Results show that between 2007 and 2012, mean annual ET_o decreased from 1406.04 to 1392.44 mm; monthly mean ET_o values in 2007 and 2012 were between 0.67 and 8.42 mm/d (mean: 3.84 mm/d) and between 0.54 and 7.52 mm/d (mean: 3.80 mm/d), respectively. Mean ET_o in June was highest (Fig. 3c, d), while monthly minimum ET_o values in 2007 and 2012 were 1.34 and 1.46 mm/d, respectively. The lowest

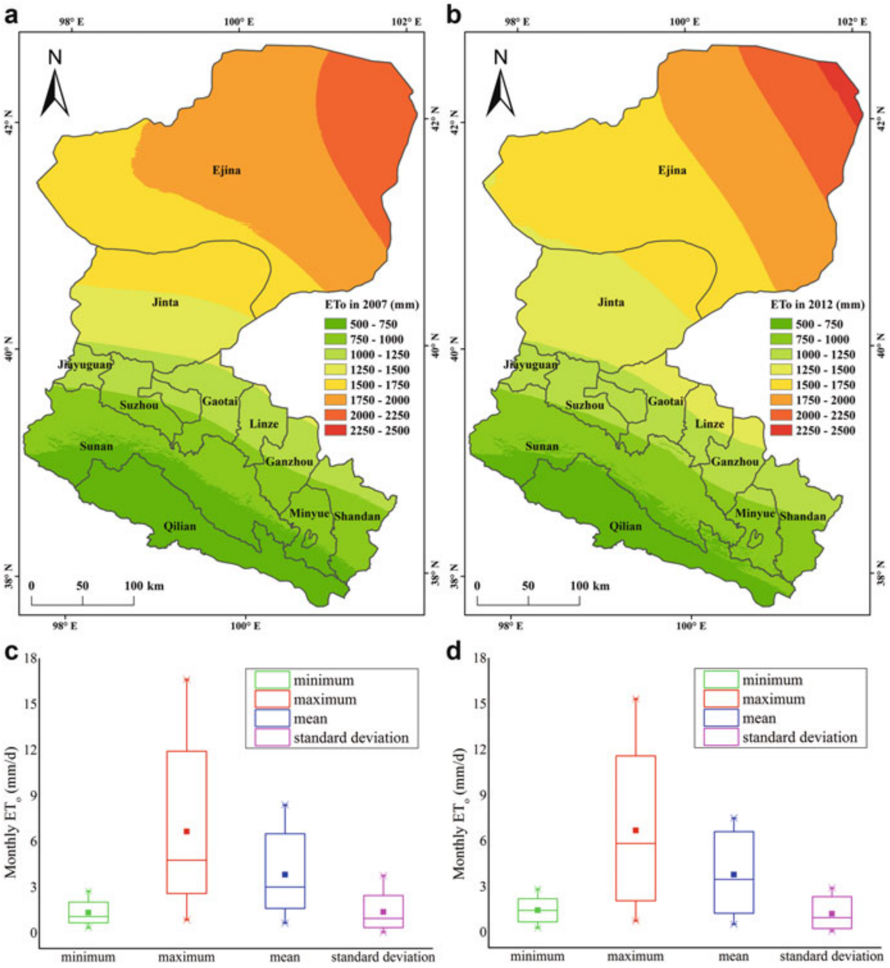

Fig. 3 HRB ET$_o$ values for 2007 and 2012: (**a**) Spatial distribution of ET$_o$ in 2007; (**b**) Spatial distribution of ET$_o$ in 2012; (**c**) Monthly mean, maximum, and minimum ET$_o$, as well as monthly standard deviation for 2007; (**d**) Monthly mean, maximum, and minimum ET$_o$, as well as monthly SD for 2012 (Reprinted from Liu et al. (2017a) with permission of Water)

recorded monthly minimum ET$_o$ values in 2007 (0.36 mm/d) and 2012 (0.30 mm/d) were both in January, while mean values of monthly maximum ET$_o$ in 2007 and 2012 were 6.66 and 6.70 mm/d, respectively. Highest monthly maximum ET$_o$ values were recorded in June 2007 (16.63 mm/d) and July 2012 (15.34 mm/d); results show that standard variations in mean monthly ET$_o$ were 1.40 and 1.23 mm/d in the 2 years, respectively, and that monthly ET$_o$ values were greater in 2007 than they were in 2012. During the main growth phases of dominant crops, mean ET$_o$ values were higher during fast and medium growing stages in the months between June and

August; values of 7.77, 8.42, 6.60, and 6.43 mm/d, respectively, were recorded in 2007, compared to 6.56, 7.52, 6.90, and 6.65 mm/d, respectively, in 2012.

Spatiotemporal Changes in ET_c

Results show that annual ET_c values within the HRB exhibit similar spatial variation to annual ET_o; increasing along an upstream-to-downstream transect (Fig. 4a, b). As a small proportion of cultivated land within the upper reaches of the HRB is located in the river valley, annual ET_c was as low as 375 mm in this area. In contrast, 85% of cultivated land is within oases in the middle reaches where annual ET_c values fall between 375 and 625 mm. In the lower reaches, the annual ET_c of cultivated land in the Gobi Desert was between 625 and 1125 mm, while values for this land use type in the northeast exceeded 1000 mm. Results show that mean ET_c was 483.87 mm in 2007 and that it increased to 500.38 mm in 2012; during crop growth phases, mean, maximum, and minimum ET_c values for May, June, and July (middle growth stage) were relatively elevated, while those for early and late growth stages were relatively lower (Fig. 4c, d). Mean HRB ET_c values for May 2007, June 2007, and July 2007 were 100.28, 144.53, and 141.32 mm, respectively, while they were 101.69, 143.95, and 142.24 mm, respectively, in 2012.

Data show that mean ET_c values for oilseed rape, corn, barley, and other crops increased from 394.26, 495.11, 377.89, and 495.32 mm, respectively, in 2007 to 417.03, 521.50, 393.53, and 506.58 mm in 2012. Interestingly, the mean ET_c of wheat decreased from 418.94 mm in 2007 to 411.39 mm in 2012 (Fig. 4e, f); mean values for barley and wheat were at their highest in June 2007, 161.40 and 160.98 mm, respectively, but increased in 2012 to 178.77 and 165.48 mm, respectively. Mean ET_c values for barley and wheat in May 2007 were relatively higher, 113.66 and 117.39 mm, respectively, but fell to 101.65 and 101.83 mm, respectively, in 2012. Oilseed rape was characterized by higher mean ET_c values in June and July of each year; mean values in 2007 were 116.59 and 122.68 mm, respectively, and 133.19 and 120.65 mm in 2012. Similarly, corn was characterized by relatively higher mean ET_c values, 133.57 and 136.13 mm, in July 2007 and August 2007, respectively, and these values rose to 130.62 mm and 155.98 mm, respectively, in 2012. Other crops also had higher mean ET_c values in May 2007, June 2007, and July 2007, 122.20, 154.06, and 151.90 mm, respectively, corresponding to 115.50, 156.52, and 152.51 mm, respectively, in 2012.

Spatiotemporal Changes in AWR

Results show that annual AWR values within the HRB tend to increase along an upstream-to-downstream transect (Fig. 5a, b). Thus, in 2012, the number of regions with AWR values between zero and 150 mm in the upper reaches decreased compared to 2007; a similar trend was seen in the number of regions with AWR values between 150 and 300 mm in the middle reaches, while the values of some

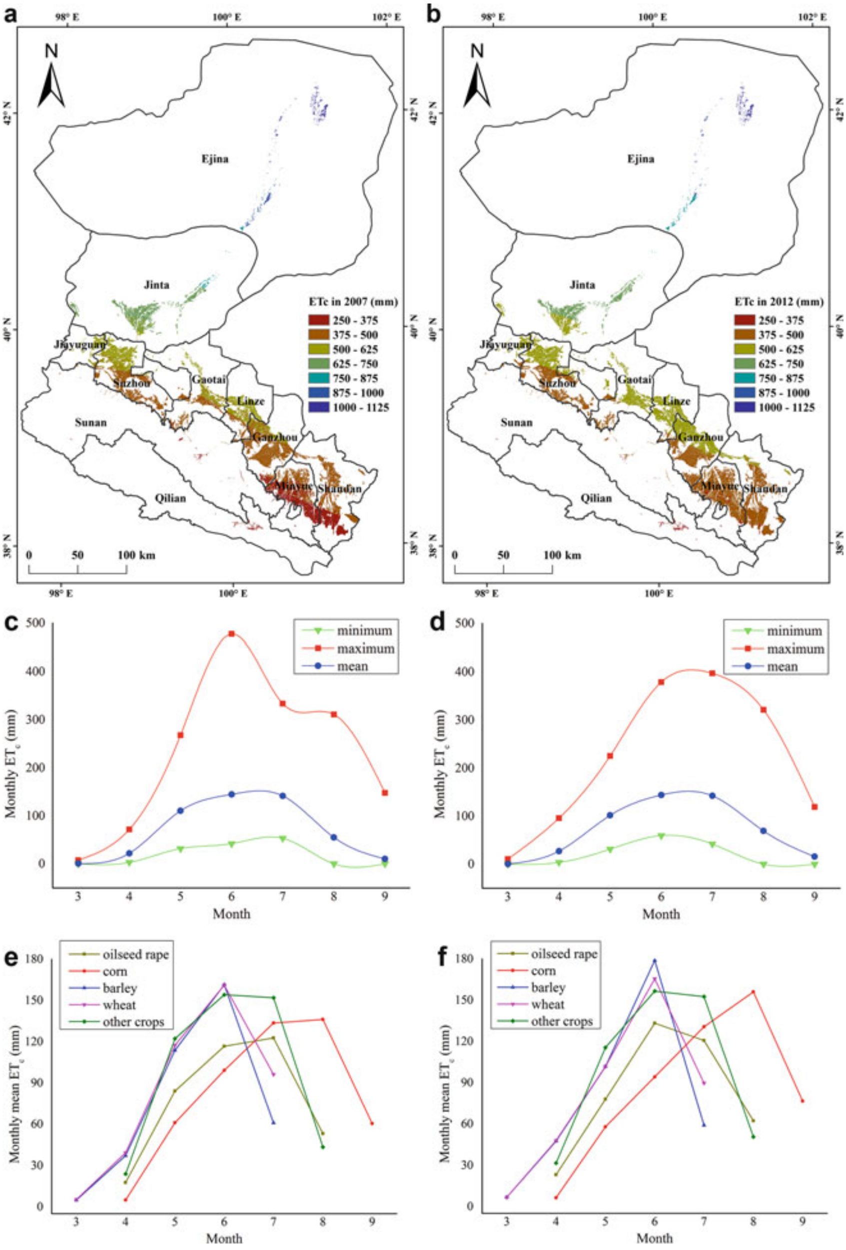

Fig. 4 HRB ET$_c$ values for 2007 and 2012: (**a**) Spatial distribution of ET$_c$ in 2007; (**b**) Spatial distribution of ET$_c$ in 2012; (**c**) Monthly mean, maximum, and minimum ET$_c$ for 2007; (**d**) Monthly mean, maximum, and minimum ET$_c$ for 2012; (**e**) Monthly mean ET$_c$ of different crops in 2007; (**f**) Monthly mean ET$_c$ of different crops in 2012 (Reprinted from Liu et al. (2017a) with permission of Water)

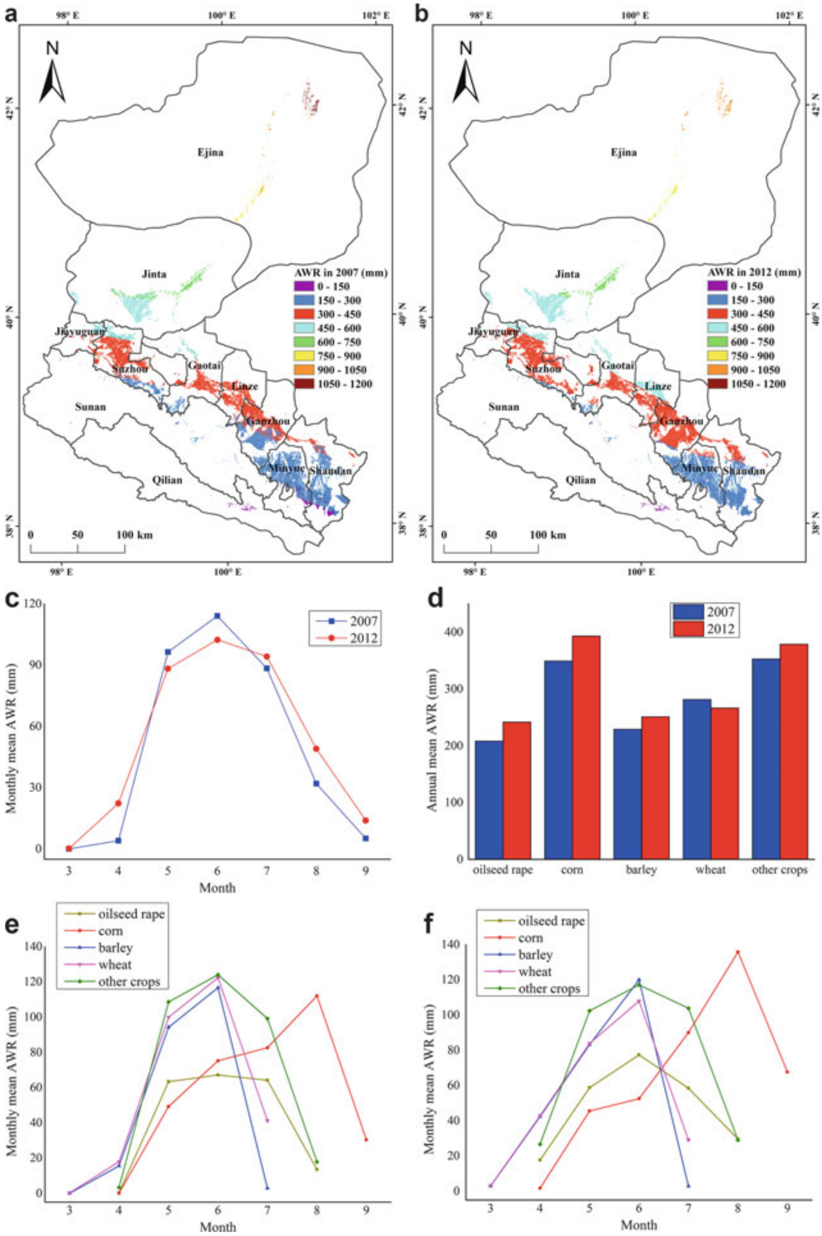

Fig. 5 HRB AWR values for 2007 and 2012: (**a**) Spatial distribution of AWR in 2007; (**b**) Spatial distribution of AWR in 2012; (**c**) Monthly mean AWR for 2007 and 2012; (**d**) Annual mean AWR of different crops in 2007 and 2012; (**e**) Monthly mean AWR of different crops in 2007; (**f**) Monthly mean AWR of different crops in 2012 (Reprinted from Liu et al. (2017a) with permission of Water)

regions increased to between 300 and 450 mm over the time period of this study. At the same time, some regions with initial (2007) AWR values between 300 and 450 mm increased to between 450 and 600 mm, while the number of regions with values greater than 1050 mm in the lower reaches also fell. These changes resulted in an overall increase in annual mean AWR, from 339.95 mm in 2007 to 370.11 mm in 2012. Data also show that in both years, 2007 and 2012, mean AWR values in May, June, and July were all higher (Fig. 5c); values were 96.36, 114.01, and 88.39 mm in 2007, and 88.22, 102.34, and 94.14 mm in 2012, respectively. Considering these 2012 values (Fig. 2c, d), variation in mean AWR between the three major water-consuming months might help to ease the imbalance between irrigation water supply and demand. Data show that the mean AWR values for March 2007, April 2007, August 2007, and September 2007 also increased, from 0.01, 4.05, 31.96, and 4.05 mm, respectively, to 0.20, 22.32, 48.99, and 13.91 mm in 2012.

The results of this study show that mean AWR values for oilseed rape, corn, barley, and other crops also increased, from 208.43, 349.35, 229.26, and 352.85 mm, respectively, in 2007 to 241.81, 393.10, 251.17, and 378.86 mm, respectively, in 2012. In contrast, mean AWR values for wheat decreased from 281.53 mm in 2007 to 266.69 mm in 2012 (Fig. 5d). These results suggest that barley and wheat should mostly be irrigated in May and June, oilseed rape and other crops should mostly be irrigated in May, June, and July, and corn should mostly be irrigated in July and August (Fig. 5e, f). Highest mean AWR values for oilseed rape, barley, wheat, and other crops were recorded in June; mean values for 2007 were 67.20, 116.60, 122.32, and 124.03 mm, respectively, while the corresponding values for 2012 were 77.32, 119.95, 107.87, and 117.08 mm, respectively. The highest mean AWR for corn was recorded in August; 112.04 mm in 2007 and 135.76 mm in 2012, while in 2007 and 2012, the mean AWR of barley and wheat increased in March. Mean AWR values of all crops increased in April and decreased in May, while the mean values for crops still growing tended to increase between August and September.

Reasons and Policy Implications of AWR Changes

Reasons of AWR Changes

Crop Planting Structure Changes

Corn is planted over the largest area within the HRB, followed by wheat, oilseed rape, and barley (Fig. 6a, b). The most crop is planted mainly in Ganzhou, Linze, Gaotai, Suzhou, and Jinta counties, while oilseed rape, barley, and wheat are mainly planted in Minle and Shandan counties. Corn cultivation extends from northwestern high-latitude regions to southeastern high-elevations and planting is usually concentrated. In contrast, oilseed rape, barley, and wheat tend to be planted in a more scattered fashion within the HRB. Nevertheless, between 2007 and 2012, areas planted with oilseed rape and corn increased by 3.65×10^3 and 31.31×10^3 ha, respectively (Table 2), while those planted with barley, wheat, and other crops decreased by 8.08×10^3, 12.24×10^3, and 18.51×10^3 ha, respectively. In 2012,

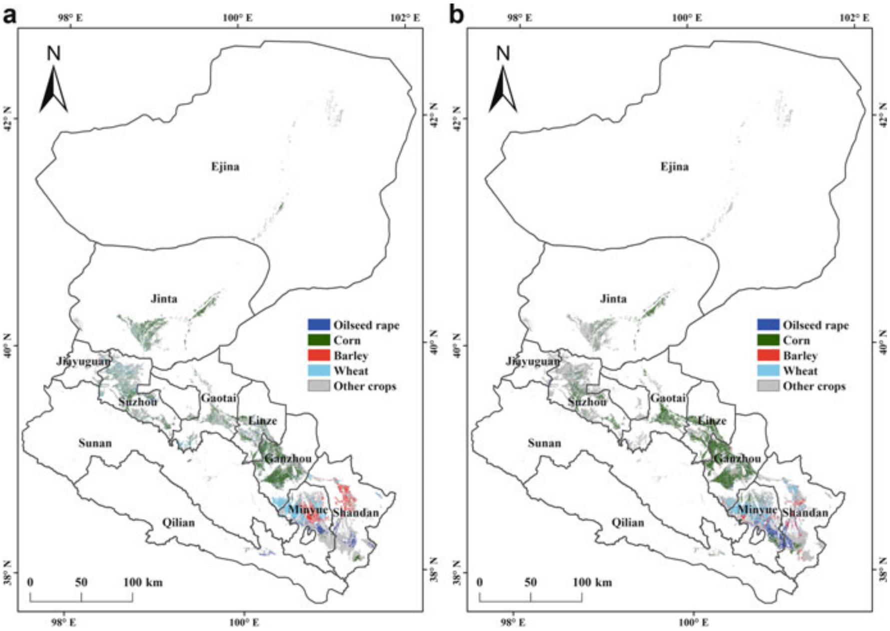

Fig. 6 Spatiotemporal distribution of crop planting within the HRB in (**a**) 2007 and (**b**) 2012 (Reprinted from Liu et al. (2017a) with permission of Water)

the cultivated land area in the HRB was 727.50 × 10^3 ha, an increase of 33.15 × 10^3 ha (4.77%) compared to 2007.

These changes in planting structure resulted in a AWR increase within the HRB. Data show that in 2012, the AWR of the HRB was 2692.58 × 10^6 m^3, 14.07% higher than in 2007 (Table 2). At the same time, between 2007 and 2012, AWR values for oilseed rape, corn, and other crops increased by 14.29 × 10^6 m^3 (41.88%), 174.80 × 10^6 m^3 (42.33%), and 197.67 × 10^6 m^3 (11.43%), respectively, while those for barley and wheat decreased by 15.14 × 10^6 m^3 (28.10%) and 39.46 × 10^6 m^3 (30.52%).

Data reveal a relatively large increase in the area of planted corn between 2007 and 2012 in Ganzhou, Linze, and Gaotai counties; 12,180.06, 11,941.02, and 11,941.02 ha, respectively. Over the same period, the corresponding area of planted corn in Jinta County decreased by 8135.37 ha (Table 3), while the area of planted wheat increased in just Minle and Shandan counties; 915.30 and 5092.83 ha, respectively. The areas of wheat cultivation in Ganzhou and Suzhou counties decreased significantly, by 4219.29 and 6805.26 ha, respectively, while planted areas of barley decreased by 6340.59 and 3591.54 ha, respectively, in Minle and Shandan counties and increased by 1418.31 ha in Ganzhou County. The planted area of oilseed rape in Minle County increased by as much as 5086.26 ha, but decreased significantly by 1157.58 and 1211.58 ha in Ganzhou and Qilian counties, respectively. The planted areas of other crops increased by 10,312.63 and 10,678.99 ha in

Table 2 Changes in HRB crop planting area and AWR between 2007 and 2012

Crop type	Planting area (10^3 ha)			AWR per unit area (m^3/ha)			Total AWR (10^6 m^3)		
	2007	2012	Change	2007	2012	Change	2007	2012	Change
Oilseed rape	16.37	20.02	3.65	2084.35	2418.08	333.74	34.12	48.41	14.29
Corn	118.21	149.52	31.31	3493.53	3931.04	437.51	412.97	587.77	174.80
Barley	23.51	15.43	−8.08	2292.60	2511.72	219.12	53.90	38.76	−15.14
Wheat	45.92	33.68	−12.24	2815.27	2666.86	−148.41	129.28	89.82	−39.46
Other crops	490.34	508.85	18.51	3528.48	3788.59	260.11	1730.15	1927.83	197.67
Cropland	694.35	727.50	33.15	3399.45	3701.12	301.67	2360.42	2692.58	332.16

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Table 3 HRB county-level changes in crop planting area and AWR values between 2007 and 2012

County	Changes in crop planting area (ha)					Changes of total AWR (10^6 m^3)		
	Oilseed rape	Corn	Barley	Wheat	Other crops	2007	2012	Change
Ganzhou	−1157.58	12,180.06	1418.31	−4219.29	155.09	366.24	465.25	99.01
Minle	5086.26	5924.07	−6340.59	915.30	1644.33	225.74	291.33	65.59
Shandan	405.36	2257.65	−3591.54	5092.83	−2829.03	228.86	268.39	39.53
Linze	−469.62	11,941.02	8.64	−2069.64	−7115.14	207.61	247.08	39.47
Gaotai	−98.82	8488.89	0.81	−2062.71	−4298.19	191.43	225.80	34.37
Sunan	126.54	−1125.54	52.20	−511.56	10,312.63	36.51	76.73	40.22
Suzhou	374.13	1097.46	276.75	−6805.26	6231.75	459.84	476.00	16.16
Jinta	334.71	−8135.37	53.91	−1747.80	10,678.99	418.61	424.02	5.41
Jiayuguang	286.20	−782.73	36.18	−728.10	1663.32	70.93	69.43	−1.51
Egina	−17.28	−715.32	0.00	−82.26	917.89	150.41	143.61	−6.80
Qilian	−1211.58	175.50	8.64	−24.39	1151.96	3.49	4.82	1.33

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Sunan and Jinta counties, respectively, but decreased by 7115.14 and 4298.19 ha in Linze and Gaotai counties, respectively. Changes to crop planting structures resulted in increased AWR values in Ganzhou, Minle, Shandan, Linze, Gaotai, Sunan, Suzhou, Jinta, and Qilian counties; increases of 99.01 × 10^6, 65.59 × 10^6, 39.53 × 10^6, 34.37 × 10^6, 40.22 × 10^6, 16.16 × 10^6, 5.41 × 10^6, and 1.33 × 10^6 m^3, respectively. Over the same time period, however, AWR values decreased in Jiayuguan and Egina counties; reductions of 1.51 × 10^6 and 6.80 × 10^6 m^3, respectively.

Changes in crop planting between 2007 and 2012 in the HRB resulted in an AWR increase of 76.77 × 10^6 m^3, 23.11% of the total (Table 4). The area of corn transferred from other crop types was the largest, up to 72.58 × 10^3 ha, accounting for 29.22 × 10^6 m^3 (8.80%) of the total AWR increment. The areas of other crops transferred from oilseed rape, corn, barley, and wheat were also relatively large,

Table 4 Crop conversion contributions to AWR changes within the HRB between 2007 and 2012

Conversion type	Converted area (10^3 ha)	Contribution value (10^6 m^3)	Contribution rate (%)	Conversion type	Converted area (10^3 ha)	Contribution value (10^6 m^3)	Contribution rate (%)
OR to C	3.70	6.83	2.06	B to W	7.58	2.84	0.85
OR to B	1.03	0.44	0.13	B to OC	11.27	16.86	5.08
OR to W	1.17	0.68	0.21	W to OR	1.37	−0.54	−0.16
OR to OC	8.16	13.91	4.19	W to C	3.07	3.43	1.03
C to OR	2.08	−2.24	−0.67	W to B	2.43	−0.74	−0.22
C to B	0.44	−0.43	−0.13	W to OC	26.41	25.71	7.74
C to W	0.59	−0.49	−0.15	OC to OR	13.48	−14.97	−4.51
C to OC	46.25	13.65	4.11	OC to C	72.58	29.22	8.80
B to OR	0.85	0.11	0.03	OC to B	8.11	−8.25	−2.48
B to C	0.51	0.84	0.25	OC to W	11.69	−10.07	−3.03
Total						76.77	23.11

Abbreviations: *OR* oilseed rape, *C* corn, *B* barley, *W* wheat, *OC* other crops
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8.16×10^3, 46.25×10^3, 11.27×10^3, and 26.41×10^3 ha, respectively; these equate to contributions of 13.91×10^6 m^3 (4.19%), 13.65×10^6 m^3 (4.11%), 16.86×10^6 m^3 (5.08%), and 25.71×10^6 m^3 (7.74%) of the total AWR increment, respectively. In contrast, transfer of other crops to oilseed rape, barley, and wheat were largely negative in their contributions, decreasing the total AWR increment within the HRB by 14.97×10^6 m^3 (4.51%), 8.25×10^6 m^3 (2.48%), and 10.07×10^6 m^3 (3.03%), respectively. The remaining change in total AWR, 76.89% (255.39×10^6 m^3), was the direct result of the cultivated land expansion (i.e., the transfer of other land use types to agriculture).

Our results show that changes in crop planting structure are the main explanation for increasing AWR values within the HRB; specifically, the expansion of cultivated land has made the largest contribution to this increase. This result is important because in order to generate additional economic benefits, farmers often choose to either reclaim cultivated land or adjust the types of crops grown on existing land (Liu et al. 2016). Our results show that a rapid expansion in cultivated land leads directly to increased crop irrigation requirements. The dominant crop in the HRB is seed corn, an agricultural product with higher economic benefits than oilseed rape, barley, or wheat. This crop, however, also consumes far more water than others; thus, increasing the planted area of corn (high water consumption) while decreasing the planted areas of barley and wheat (low water consumption) will only serve to further increase the AWR in the HRB.

Climate Changes

Variation in AWR of the same crop over time due of climate change is another factor that underlies the overall increase in these values within the HRB. Climatic factors, such as monthly mean temperature, relative humidity, wind speed, and atmospheric pressure all directly influence ET_o and indirectly AWR (Allan et al. 2005). The data presented in this study show that temporal changes in monthly mean temperature and atmospheric pressure were more regular in the HRB than the other two factors in both 2007 and 2012 (Fig. 7). Temperature exerts a positive controlling influence on ET_o; both ETo loss and AWR are enhanced in warm compared to cold weather (Fig. 7a). Besides, both relative humidity and wind speed influence vapor removal; water vapor is stored in humid air, while wind promotes the transport of water allowing more water vapour to be taken up (Fig. 7b, c). Although tending to fluctuate in the same place very little over time, atmospheric pressure nevertheless determines the psychrometric constant, which is negatively correlated with both ET_o and AWR (Fig. 7d).

Due to changes in rainfall of HRB from 2007 to 2012, the annual mean ER decreased from 139.49 mm to 106.29 mm during this time period. Moreover, under the comprehensive influences of climatic factors, e.g., temperature, relative humidity, wind speed, and atmospheric pressure, that mean ET_c values for oilseed rape, corn, barley, and other crops all increased in different amplitudes from 2007 to 2012. Certainly, as a result of the decreased ER and the increased ET_c, the mean AWR values for oilseed rape, corn, barley, and other crops also increased from 208.43, 349.35, 229.26, and 352.85 mm in 2007 to 241.81, 393.10, 251.17, and 378.86 mm in 2012, respectively. Consequently, the annual mean AWR of the whole HRB increased from 339.95 mm in 2007 to 370.11 mm in 2012. Thus, as a result of the

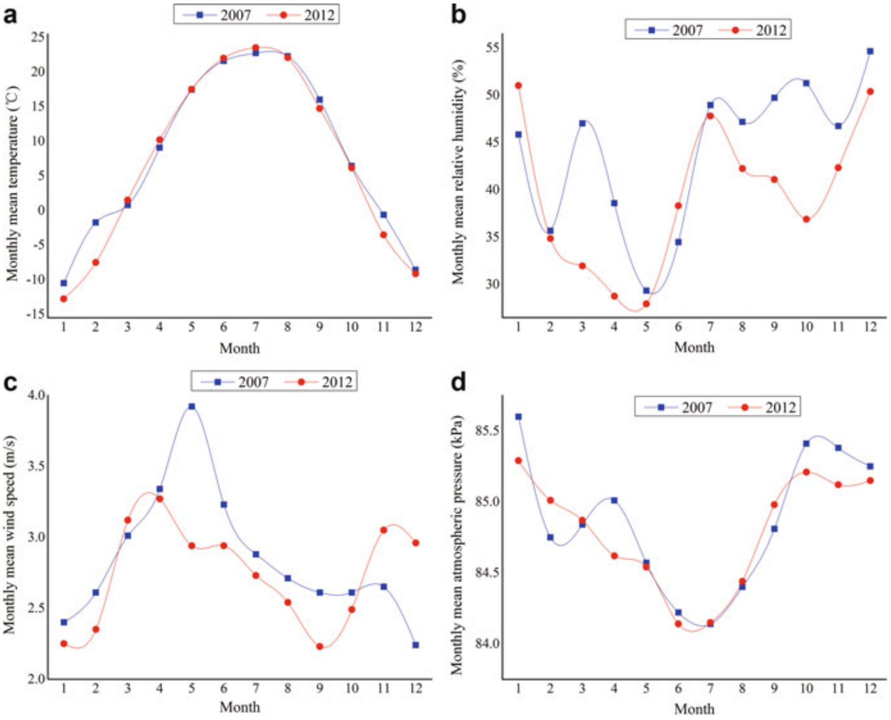

Fig. 7 Changes in monthly mean values for climatic factors between 2007 and 2012 in the HRB: (**a**) Temperature; (**b**) Relative humidity; (**c**) Wind speed; (**d**) Atmospheric pressure (Reprinted from Liu et al. (2017a) with permission of Water)

joint impacts of crop planting structure and climate changes, AWR values per unit area of oilseed rape, corn, barley, and other crops all increased between 2007 and 2012, and caused a concomitant overall increase across the whole HRB.

Policy Implications of AWR Changes

From the Perspective of Time

Agriculture is the sector that consumes the most water in the HRB. Thus, the management of agricultural water based on sequential variation and spatial differences in AWR, as well as differences due to crop types, will be conduce to the sustainable development of both the social economy and ecological system. Data show that AWR values for the same crop vary depending on growth stage; in other words, crop water requirements are highest during the middle growth stage but are lower during early and late stages. According to our field survey results, most farmers currently do not take sequential variation in AWR into account when irrigating their crops. This means that both irrigation time and water supply do not correspond with the actual water requirements of crops and result in the inefficient use of irrigation water. This can lead to waste or deficit in agricultural water resources, resulting in the reduce in crop yields and farmers' income. Thus, in order to efficiently allocate and utilize available agricultural water, it will be necessary to adjust both irrigation times and volumes based on sequential variations in AWR.

From the Perspective of Space

The results of this study show that AWR values gradually increased between 2007 and 2012 along an upstream-to-downstream transect; this means that, especially in arid areas where water is extremely scarce, AWR values exceeded 1000 mm. Obviously, the agricultural production in downstream of HRB is unreasonable with a lot of water consumption and a low water use efficiency. Moreover, the downstream of HRB is an important ecological conservation area, and adequate water resources are needed to ensure that it is not degraded. Agricultural water consumption is bound to contradict the ecological water consumption, which may lead to degradation of ecosystems in this area. We therefore recommend that agricultural production in the lower reaches of the HRB should at least be reduced to preserve water and enhance ecological conservation. Unfortunately, however, the area of cultivated land in the lower reaches of the HRB expanded unreasonably between 2007 and 2012. It is therefore critical to establish a more effective mechanism of ecological compensation (Han et al. 2017; Jiang et al. 2011a) that enables farmers to abandon crop cultivation in the lower reaches of the HRB.

The increasing intensification of agricultural production in the upstream and downstream of HRB will lead to a sharp decline in the available ecological water in downstream. Furthermore, the increased agricultural water consumption can also lead to ecological degradation in upstream and middle reaches. Therefore, the agricultural production intensity in upstream and middle reaches must also be controlled in a reasonable range. Irrigation schemes and technologies that can improve agricultural water use efficiency are urgently needed.

From the Perspective of Crop Type

Our results show that over the time period of this study and driven by economic interests, cultivated areas of autumn crops (e.g., oilseed rape and corn) increased, while those of summer crops (e.g., barley and wheat) decreased; these changes led to a decrease in AWR during May and June within the HRB and a concomitant increase in July. As the volumes of rainfall and runoff water within the HRB are largest and concentrated in June, July, and August, such a change to crop planting structures would help to ease the imbalance between water supply and demand. At the same time, however, results show that AWR values for corn were significantly higher than those for the other major crops; thus, a rapid expansion in the area of cultivated corn would only serve to intensify the water supply imbalance (Liu et al. 2017b). We argue that a continuous increase in the area of cultivated corn is not feasible; rather, it is crucial to minimize the cultivation of water-intensive crops and the expansion of cultivated land, emphasizing instead the husbandry of plants that require less water (Jiang et al. 2011b; Liu et al. 2016).

Summary

Water resources are intimately related to regional sustainable development and ecological security. Water wastage and inefficient use in regions subject to shortages results in serious negative economic, social, and ecological impacts. Typical for an inland river basin in an arid or semi-arid area, water consumption for crop irrigation in the HRB accounts for more than 80% of total regional consumption. It is therefore critical to understand the differences and variation in AWR temporally, spatially, and in terms of different crop types. We used the spatiotemporal distribution of crop planting structures to estimate spatiotemporal AWR values for 2007 and 2012 in the HRB. To do this, we used the FAO Penman-Monteith formula, revealed the characteristics of spatiotemporal variation in AWR, and analyzed the resultant impacts of crop planting structure and climate changes.

Compared with previous research, we not only calculated AWR for a variety of crops in this study, but also evaluated the month-by-month spatiotemporal distribution of these values. Thus, the spatiotemporal AWR patterns obtained in this research, (based on crop planting structures and at a spatial resolution of 30 m) are likely to aid both managers and producers to reasonably and efficiently allocate and use agricultural water in temporal and spatial sequences that coincide with differences between crop types.

However, as this study classified all crops other than oilseed rape, corn, barley, and wheat as ‘other crops’, it was not possible to obtain accurate growing stage and crop coefficients. We therefore estimated AWR values for other crops based on the growing stages and mean Kc values of the main crops. This is a drawback of our study as this grouping will have involved some plants with relatively low water consumption as well as fallow cultivated land; this means that our processing method, use of mean Kc values, may have consequently overestimated the duration of each growing stage and Kc values for other crops. This would therefore have resulted in overestimates of AWR for 2007 and 2012 as well as for the whole HRB. It is also clear that, in addition to changes in crop planting structures, crop AWR per unit area will also vary with time; these two factors will both affect spatiotemporal AWR patterns. We did not exclude the influence of variation in crop AWR per unit area in this study when analyzing the influences of crop planting structure changes, a feature of this research that will require further attention. Finally, this research is also limited by the time period we considered, just between 2007 and 2012. Our aim in future studies is to estimate the AWR of the HRB over a longer time period. Furthermore, predicting future AWR changes associated with crop conversion potentials (Liu et al. 2016) will also be critical for the integrated water resource management of river basins, especially in arid and semi-arid areas.

The results of this study show that the AWR within the HRB varied between zero and 1250 mm and that the amplitude of variation increased along an upstream-to-downstream transect. Values for AWR in the lower reaches of the HRB were as high as 1000 mm, which suggests that agricultural production in this region should be minimized in order to save water for ecological conservation. Data show that the annual mean AWR of the HRB increased from 339.95 mm in 2007 to 370.11 mm in 2012; at the same time, monthly mean AWR initially increased before gradually decreasing with the highest values each year seen in June. Between 2007 and 2012, AWR values in May and June decreased by 8.14 and 11.67 mm, respectively, while those for July increased by 5.75 mm. As the ER in May and June is less than that in July, this change in AWR might be useful to help alleviate the imbalance between water supply and demand for irrigation. In terms of crop types, AWR values for corn were significantly higher than those for oilseed rape, barley, and wheat; nevertheless, mean AWR values of oilseed rape, corn, barley, and other crops increased, respectively, from 208.43, 349.35, 229.26, and 352.85 mm in 2007 to 241.81, 393.10, 251.17, and 378.86 mm in 2012. At the same time, the mean AWR for wheat decreased from 281.53 mm in 2007 to 266.69 mm in 2012. Therefore, in order to efficiently manage and utilize agricultural water, we argue that it is necessary to adjust both irrigation times and amounts in different areas depending on the differences and characteristics of AWR variation temporally, spatially, and by crop types.

To increase their economic benefits, farmers have tended to adjust planting structures to favor more profitable crops that also need more water (e.g., corn) or reclaim more cropland. Our data show that planting structure changes took place within the HRB between 2007 and 2012 to increase areas of corn and oilseed rape, while simultaneously decreasing areas of planted barley and wheat and expanding the cultivated land area. These changes resulted in an AWR increase from $2360.42 \times 10^6\ \text{m}^3$ in 2007 to $2692.58 \times 10^6\ \text{m}^3$ in 2012, corresponding to an increase by $332.16 \times 10^6\ \text{m}^3$ (14.07%). Data show that 23.11% ($76.77 \times 10^6\ \text{m}^3$) of this change can be explained by crop type transfers, and that the remaining 76.89% ($255.39 \times 10^6\ \text{m}^3$) was caused by the rapid expansion of cultivated land. Although farmers obtained economic benefits in the short term, this approach was not conducive to maintaining the sustainable development and ecological security of the HRB. We recommend that, in future, the cultivation of water-demanding crops and the expansion of cultivated land should be kept to a minimum.

The analysis of spatiotemporal changes in AWR presented in this paper will enable both managers and producers to develop more efficient irrigation strategies that those presently available in the absence of these data. Future research is nevertheless essential for the integrated management of water resources in river basins. Studies should include estimating large scale spatial (e.g., at the national or global scale) AWR over longer time periods, predicting future AWR changes associated with crop conversion potential, and the multi-objective optimization of water resources between agriculture and other sectors in light of different scenarios for development. All of these directions are essential if we are to guarantee regional and global sustainability.

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Oasis Agriculture: Improving Water Usage Efficiency Within River Basin

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Contents

Introduction 213
Water-Use Efficiency and Oasis Farmer Income 214
  Uneven Water Use in China 214
  Empirical Study Between Water Use and Farmer Income 217

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Heihe River Basin (HRB) Land Use Change and Agricultural Expansion 224
  Heihe River Basin (HRB) 224
  Land Use Patterns and Changes in HRB 224
  Expansion of Agricultural Oasis in HRB 227
Methods of Measuring Water-Use Efficiency 228
  Measurement of the Water-Use Efficiency for Soil Conservation 228
  Measurement of the Water-Use Efficiency for Agriculture 230
  Driving Forces of Agricultural Water-Use Efficiency Using Tobit Model 231
Results of Water-Use Efficiency 231
  Spatiotemporal Variation of the Soil Conservation Amount 231
  Spatiotemporal Variation of Evapotranspiration 234
  Spatiotemporal Variation of the Water-Use Efficiency for Soil Conservation 235
  Changes of the Agricultural Water-Use Efficiency and TFP Rate 237
  Impacts of Driving Factors on the Agricultural Water-Use Efficiency 237
Summary 240
References 242

Abstract

The Heihe River Basin (HRB) in Gansu Province is the second largest inland river basin in the arid region of Northwest China. An agricultural oasis is a typical landscape in arid regions providing precious fertile soil, living space, and ecological services. The agricultural oasis change has been one of the key issues in sustainable development in recent decades. In this chapter, we examined the changes in the agricultural oasis in HRB and analyzed the socioeconomic and climatic driving forces behind them. It was found that the agricultural oasis in HRB expanded by 25.11% and 14.82% during the periods of 1986–2000 and 2000–2011, respectively. Most of the newly added agricultural oases in HRB were converted from grassland (40.94%) and unused land (40.22%). The expansion in the agricultural oasis mainly occurred in the middle reaches of HRB, particularly in the counties of Shandan, Minle, Jinta, and Jiuquan. There has been very limited research on the water-use efficiency for soil conservation in the lower Heihe River Basin, a typical water-scarce area where the soil conservation service plays a key role in guaranteeing the ecological safety of the northern part of China. The soil conservation service based on soil conservation amount was estimated with an experiment-based model in this study. The water-use efficiency has direct impacts on the water consumption of agriculture production and is vital for water conservation at both local and regional extent. Taking the HRB as the case study area, this study also explores the changing trajectories of agricultural water use based on the input-output data of 2003–2012 and estimates the water-use efficiency using data envelopment analysis, Malmquist total productivity index, and the decomposition of total factor productivity. Further, the influence of driving factors on the water-use efficiency is analyzed with the Tobit model. The research results indicate that the average agricultural water-use efficiency in different counties is all lower than 1 during 2003–2012, indicating that there is still improvement space in the agricultural water-use efficiency. In addition, there is obvious heterogeneity in the agricultural water-use efficiency among different counties, especially prior to 2009. The research results from the Tobit model indicate that agricultural investment and production, economic growth, industrial restructuring, and agricultural plant structural adjustment have significant influence on the agricultural water-use efficiency. The research results can provide significant references for agricultural water-use management in the middle reaches of the HRB and other similar regions in Northwest China.

Keywords
Water-use efficiency · Oasis · Soil · Agriculture

Introduction

Water resource is one of the most basic and critical elements for the living and production of human beings. The stable supply and efficient use of water resources play an important role in guaranteeing the sustainable socioeconomic development (Deng and Zhao 2014). Water is usually the single most limiting factor for provision of ecosystem services, and water scarcity is impacting human welfare worldwide, especially in arid and semiarid regions that are very sensitive to climate change and land use and land cover change. UN World Water Development Report reveals that 66 countries with 21% of the world population would turn from moderate water shortage to severe situation by 2050, indicating great differences occur in global water distribution with severe water disequilibrium, which brings great challenge to the regional water supply. Although an oasis covers less than 5% of the total area in arid and semiarid regions in China, it holds more than 90% of the population and 95% of social wealth in these regions (Wang et al. 2008).

An oasis not only provides precious fertile soil and living space for human beings in the barren desert but also regulates the regional climate by the vegetation and water resources within it. Therefore, the oasis ecosystem directly influences the environmental and social security in arid and semiarid regions. As a country with large population, China has been evaluated as one of the major countries with apparent unbalanced water supply and demand in the Millennium Ecosystem Assessment report (Duraiappah et al. 2005). The utilization of water resource, especially agricultural water resource, plays an important role in the economic development. Agricultural water consumption accounts for the largest proportion in China. According to the Statistics in the Ministry of Water Resources of the People's Republic of China, 51.5% of the cropland production depends on irrigation in 2014 (Deng et al. 2014). Arid and semiarid regions cover more than 30% of the land on the earth's surface and 22% of the land area in China. However, coincident with rapid growth in water demand is the potential for substantial reduction in water supplies in arid regions. Runoff of many rivers in arid regions showed a declining trend under the influence of the climatic and land use change during the past decades. Besides, rapid socioeconomic development that drives land use change, which is altering the hydrologic system and increasing water needs for industrial, domestic, and environmental uses, has potentially large impacts on water resources (Zhang et al. 2011). As a result, the traditional water utilization approach in these arid and semiarid regions is now facing a big challenge, which appeals to people to develop water-saving irrigation and enhance water-use efficiency for sustainable water use.

An agricultural oasis is defined as cultivated land that can be irrigated by human activities (Bai et al. 2014). Since an agricultural oasis can provide the necessary grain for population growth, it plays a vital role in sustainable social development. Enhancing water-use efficiency is a critical response to growing water scarcity, and it is necessary to carry out in-depth research on water-use efficiency, which can provide valuable reference information for scientific water resource allocation to make more efficient use of limited water resources.

There have been extensive researches on water resources, including water protection, effective utilization of water resources (Huang et al. 2013), and evaluation of water security (Chen et al. 2013); particularly, the water-use efficiency has always been the core issue in different countries (Abu-Allaban et al. 2015). The research on the agricultural water-use efficiency started in the middle of the twentieth century. Departments within UN specially established research institutions for water resource issues (Chen et al. 2015a). There have also been many scholars attempting to find out ways to improve the agricultural water-use efficiency. For example, Li et al. (2015a, b) reveal that water-use efficiency was uneven in the 31 provinces of China, with the irrigation efficiency in Hunan and Jiangsu Province (irrigation land) reaching only 60% during 2005–2012. In addition, the average water-use efficiency was 30% in Northwest China in 2006, where only 3% of the water was effectively used and the rest water was wasted (Zhang et al. 2014), while the water-use efficiency has improved significantly in some regions of Northwest China. For example, Minqin County, a typical agricultural area of Northwest China, has experienced three stages to achieve the comprehensive agricultural water use during 2000–2003, and the water-use efficiency proliferated from 22% to 42% during 2004–2008, while the water-use efficiency increased with 6% annually; and from 2009 to 2012, the efficiency finally reached 76%.

Water-Use Efficiency and Oasis Farmer Income

Uneven Water Use in China

According to the National Agricultural Water-Saving Outlines for 2012–2020 published by the Ministry of Water Resources of the P.R. China in year 2012, water-saving programs efficiently retarded the consumption of water stock. Water-use efficiency had increased about 20% from year 2000 to 2013. However, irrigated water use per ha decreased from 15 cubic meter in year 2000 to 24 cubic meter in year 2013. Further, with the increasing demand of water in urban area, the proportion of water use has changed in both agricultural and nonagricultural sectors which fluctuated under 3% over time, and the growth rate of the total amount of water use continually increased about 1% per year (Fig. 1).

Water-saving programs have pushed the industries toward transformation. Through advanced drought-enduring seeds along with their fostering and widely sown, the average yield of crops had arisen from 1.33 kg in year 2000 to 1.75 kg in

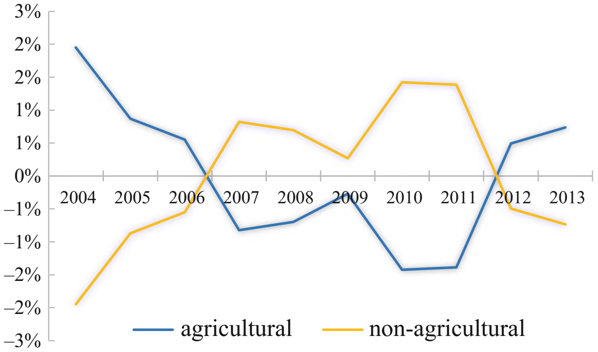

Fig. 1 Water-use proportional changes of agricultural and nonagricultural sectors in the years 2004–2012 (Reprinted from Zhan Wang et al. (2015) with permission of Physics and Chemistry of the Earth) (Data source: National Bureau of Statistics of China (NBSC) in years 2004–2013)

year 2013 from per cubic meter water input. The efficiency of fertilizer and pesticide use with respect to yield was improved around 15%. Over 2000 firms had invested on research and development of water-saving technique and equipment, which successfully supported annual increase of irrigation facilities covering over 200 million ha per year. Until year 2013, irrigated area was 63.47 million ha, about 43% of them covered by irrigation facilities. Moreover, regulations of regional water quota, implementation of forced water-saving technique, installation of water-saving equipment for industrial water consumption, and retreatment including some state subsidies collectively had impacted positively on related industries to save water consumption cost to some extent (Deng et al. 2014).

Impacts of sparing use of water on farmer income of China are rarely researched. Blanke et al. (2007) tended to study household behaviors to irrigated water-saving against drought resistant of cultivation and discussed water-saving technology development and its acceptance in China. Gilg and Barr (2006) did survey research to find evidence that motivation of household behaviors for water-saving through the purchase investment decision of water-saving facilities and their water-use actions. These ideational research designs probe into perception of respondents on water-saving facilities that were practically used in daily living or agricultural production. Wang et al. (2015) analyzed economic welfare of rural and urban residents can benefit from water projects at regional scale that supposed to be achieved by either regional or national government investments to irrigation facilities. However, we do not know yet how much farmer income benefit from sparing use of water at the national level.

Spatial distribution of the total amount of water use is uneven in China. According to regional division of China in geographical categories, there were three large regions: Eastern China, Central China, and Western China. Overall, the consumption of water in China was 556 billion ton in year 2012. Eastern China consumed 218 billion ton of water which accounts for 40% of the total amount of water use in year 2012. Jiangsu (55 bt), Guangdong (45 bt), and Shandong (22 bt) were the top three highest provinces in water use in Eastern China, as shown in Table 1. In Central China, the consumption of water amounted to 196 billion ton in

Table 1 Total amount of water use in each province of China in year 2012

Eastern China		Central China		Western China	
Beijing	3588	Shanxi	7339	Inner Mongolia	18,435
Tianjing	2313	Jilin	12,982	Guangxi	30,301
Hebei	19,531	Heilongjiang	35,890	Chongqing	8294
Liaoning	14,223	Anhui	29,264	Sichuan	24,592
Shanghai	11,598	Jiangxi	24,254	Guizhou	10,082
Jiangsu	55,223	Henan	23,861	Yunnan	15,183
Zhejiang	19,812	Hubei	29,929	Tibet	2981
Fujian	20,008	Hunan	32,880	Shaanxi	8804
Shandong	22,179			Gansu	12,305
Guangdong	45,102			Qinghai	2740
Hainan	4533			Ningxia	6935
				Xinjiang	590
Total	**218,110**		**196,399**		**141,242**

Note: Amount of water used is measured in million ton

Data source: NBSC in year 2012 (Reprinted from Zhan Wang et al. (2015) with permission of Physics and Chemistry of the Earth)

year 2012. Heilongjiang (36 bt), Hunan (33 bt), and Hubei (29 bt) were found to be the top three highest provinces in water use in this region. Similarly, Western China consumed 141 billion ton of water, and the provinces of Guangxi (30 bt), Sichuan (24 bt), and Inner Mongolia (18 bt) were ranked as top three in water use.

Spatial distribution of per capita water use is uneven in China. The per capita water use is the amount of total water use per person, which is the total amount of water use in year 2012 divided by the total population of each province in China. Population of China was 1347.89 million by the end of year 2012.The highest average per capita water use was in Central China (462 t) as shown in Table 2. That was quite close in Eastern China (390 t) and Western China (388 t) in year 2012. Per capita water uses of Shanxi (203 t), Henan (254 t), and Jilin (472 t) were the three lowest in Central China; Tianjing (164 t), Beijing (173 t), and Shandong (229 t) were the three lowest in Eastern China; and Xinjiang (26 t), Shaanxi (235 t), and Chongqing (282 t) were the three lowest in Western China in year 2012.

The relationship between water use and farmer income is ambiguous. According to the statistics of NBSC year 2004–2013, the average farmer income in each province of Eastern China was about 1871 in 2012 USD, which was the highest among three large regions, and that of Central and Western China was sequentially about 1215 and 952 in 2012 USD as shown in Table 3.

Obviously, Eastern China has the highest water use and the highest average farmer income. It seems that there is a linear positive relationship between the total amount of annual water use and the average of contemporaneous farmer income during years 2004–2012. However, this relationship is uncertain with population distribution and may vary over time, as shown in scatter plot in Fig. 2, indicating there is no any observable relationship from year 2002 to 2012.

Table 2 Amount of per capita water use in each province of China in year 2012

Eastern China		Central China		Western China	
Beijing	173.4	Shanxi	203.2	Inner Mongolia	740.4
Tianjing	163.7	Jilin	472.1	Guangxi	647.2
Hebei	268.0	Heilongjiang	936.1	Chongqing	281.6
Liaoning	324.1	Anhui	488.7	Sichuan	304.5
Shanghai	487.3	Jiangxi	538.5	Guizhou	289.4
Jiangsu	697.3	Henan	253.7	Yunnan	325.9
Zhejiang	361.7	Hubei	517.9	Tibet	967.9
Fujian	533.8	Hunan	495.3	Shaanxi	234.6
Shandong	229.0			Gansu	477.3
Guangdong	425.7			Qinghai	478.2
Hainan	511.1			Ningxia	1071.9
				Xinjiang	26.4
Average	**390.5**		**462.0**		**387.7**

Note: Amount of water used is measured in million ton

Data source: NBSC in year 2012 (Reprinted from Zhan Wang et al. (2015) with permission of Physics and Chemistry of the Earth)

Table 3 Average farmer income in each province of China in 2012 (USD)

Eastern China		Central China		Western China	
Beijing	2610.0	Shanxi	1007.0	Inner Mongolia	1205.8
Tianjing	2221.9	Jilin	1362.1	Guangxi	951.7
Hebei	1280.2	Heilongjiang	1363.0	Chongqing	1169.6
Liaoning	1486.5	Anhui	1134.3	Sichuan	1109.1
Shanghai	2820.4	Jiangxi	1240.3	Guizhou	753.0
Jiangsu	1933.0	Henan	1192.1	Yunnan	858.1
Zhejiang	2305.3	Hubei	1243.8	Tibet	906.0
Fujian	1579.0	Hunan	1178.6	Shaanxi	912.9
Shandong	1496.5			Gansu	713.9
Guangdong	1670.1			Qinghai	849.8
Hainan	1173.5			Ningxia	979.1
				Xinjiang	1012.9
Average	**1870.6**		**1215.2**		**951.8**

Data source: NBSC in year 2012 (Reprinted from Zhan Wang et al. (2015) with permission of Physics and Chemistry of the Earth)

Empirical Study Between Water Use and Farmer Income

Key Variables

Farmer income is mainly from selling agricultural production. Water usually is considered as a kind of special goods either as common-pool goods with low price or as free public goods attributed to water rights in an agricultural production process (Perry et al. 1997). Classic economic theory addresses that total consumption demand drives the

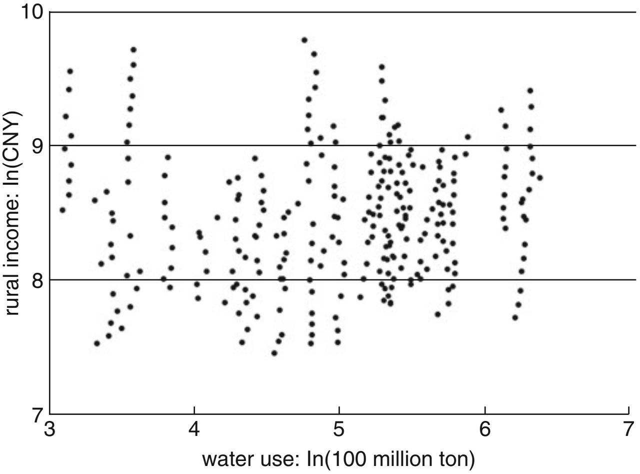

Fig. 2 Scatter plot of unobserved relationships between water use and farmer income in China in Napierian logarithmic numbers for the years 2004 through 2012 (Reprinted from Zhan Wang et al. (2015) with permission of Physics and Chemistry of the Earth)

market equilibrium points back to the optimum path. Under the assumption of unlimited natural resource with unlimited technology improvements, higher demand of resource consumption kicks the critical point at the higher price, driving the bigger gap between demand and supply that leads to market failures when faced with limited resource supply in reality. Water is a kind of special goods, which carries the capacity of both goods and bads. The more water intake, the more discharge with pollution are generated over spatiotemporal distribution. Kelman (1978) reinforced an ideology in Coase theorem by introducing a case study of externality of upstream water pollution in a maximum production process influencing to downstream residential water consumption and bringing about potential agricultural loss of environmental deterioration. These unpredictable losses are caused by overconsumption and disordered exploration of natural resource in the transaction process of economic development with consumption demand increases. Furthermore, it is quite difficult to evaluate social welfare benefited from industrial transformation but lose from environmental deterioration in the past two centuries, although residential quality of life in some regions has been improved. However, that overuse of water and exploration of other resources are still a hard-core strategy for world development. Indeed, China's water shortage has been harming farmer income and threatening worldwide agricultural production due to huge demand of food security. Therefore, the debates between theoretical detection and empirical study have arisen to discuss utilization of water resource in sustainability.

In this research, we aim to study farmer income (*lnfinc*) changes caused by water consumption and seek the impact of sparing water use (*lnwater*) on farmer income changes. We started from a Pool-OLS regression as the following Eq. 1 shows, which will give a brief picture of the relationships between dependent and independent variables:

$$\ln finc = \alpha + \beta_1 \ln pop + \beta_2 \ln water + \beta_3 \ln ele + e \tag{1}$$

where β_1 is the elasticity of how many percent changes in farmer income (*lnfinc*) in 1% changes in population (*lnpop*), β_2 presents how many percent changes in farmer income (*lnfinc*) in 1% changes in water use (*lnwater*) changes, and β_3 is the elasticity of how many percent changes in farmer income (*lnfinc*) in 1% changes in electric power (*lnele*). α is the unknown intercept, and e is the error term.

Viewed from the macroperspective on water allocation, electric power usually is used for representing the capability of water achievement in a region, which is assumed economic assessment of a level of regional development inclines to the level of electric power consumption, and presents the difference of regional characteristics of regional economies in China. For this reason, we set a fixed effect model to further look over both structural changes and variation changes at the provincial level from year 2004 to 2012 in the following constructed Eq. 2:

$$\ln finc_{it} = \alpha_{it} + \beta_1 \ln pop_{it} + \beta_2 \ln water_{it} + \beta_3 \ln ele_{it} + \mu_i + \sigma_{it} \tag{2}$$

where μ_i catches the individual-level effect in each region $i = 1,2,\ldots 31$ in China and captures the cross-sectional effect of panels over variant time t = year 2004, 2005,. . ., 2012.

To examine temporal impacts of regional characteristics of independent variables on farmer income, all variables in a panel dataset have to be tested in a stationary series. Intuitively, economic indices including farmer income, population, and electric power consumption would be in a stationary increasing trend. While water use depends on the fluctuated supply of natural resource over time, it may not be in stationary. If the unit root test for panel-data models proves the above assumptions by using Stata software, the results reported by fixed effect model may distort temporal impacts of water use on farmer income. In order to stick out those defects, a dynamic panel-data model would be considered to suit for this issue. In other words, the results of fixed effect model will prove that the impacts of water-use changes on farmer income cannot be ignored even if this model not suitable for this case study.

Data Description

Data are derived from the NBSC (year 2004–2012). Specified variables include dependent variable, farmer income (*lnfinc*), and independent variables, population (*lnpop*), water use (*lnwater*), and electric power (*lnele*) of 31 provinces of China. All variables are transformed into Napierian logarithmic format for estimating relationships in elasticity. The following Table 4 presents the summary statistics of all the variables of 31 provinces of China.

Empirical Analysis Results

The results from Pool-OLS report biased estimation of the increase of water use having negative impacts on farmer income in China. See Table 5. The arguments here are that coefficient of water use with a negative sign is not statistically

Table 4 Data description of specified variables of 31 provinces of China during years 2004–2012

Variable		Mean	Std. dev.	Min	Max	Observations
Farmer income	Overall	8.41	0.56	7.29	9.88	$N = 372$
[lnfinc]	Between	0.37		7.88	9.29	n = 31
	Within	0.42		7.68	9.19	T = 12
Population	Overall	8.06	0.87	5.55	9.27	$N = 434$
[lnpop]	Between	0.88		5.65	9.17	n = 31
	Within	0.05		7.84	8.31	T = 14
Water use	Overall	4.94	0.84	3.09	6.38	N = 279
[lnwater]	Between	0.85		3.13	6.30	n = 31
	Within	0.06		4.73	5.14	T = 9
Electric power	Overall	6.18	1.00	2.56	8.44	$N = 603$
[lnele]	Between	0.91		2.92	7.44	n = 31
	Within	0.63		4.63	7.66	T = 19

Note: N is the observations in n provinces in T time periods. Data within the missing years did not participate analysis (Reprinted from Zhan Wang et al. (2015) with permission of Physics and Chemistry of the Earth)

significant. Then, the fixed effect model is designed for specifying stability of the regression with regional characteristics of water use for farmer income in each province. Exactly as our assumptions, the estimation results show that water use is one of the key elements to farmer income. Comparing to individual effect, within-panel serial correlation in the idiosyncratic error term is much lower. It indicates that heterogeneity in fixed effect model inclines to regional identification with less heteroscedasticity, so that the regional characteristics are significantly distinguished (Table 5). However, the unit root test with Fisher option of either Dickey-Fuller test or Phillips-Parron test proves our previous assumptions that the fixed effect model may distort stochastic error term in temporal variation because all test results fail to reject the null hypothesis that unit root exits in the variables of farmer income, population, and electric power, but not in water use.

To study further variation of impacts over time and to identify the possibility of distortion due to autocorrelation, the dynamic panel-data model with systematic GMM (DPD-SYS) is introduced to specify time lags caused by autocorrelation in error term. Empirical results of DPD-SYS show statistical significance of population size in China to farmer income. Slightly negative impact of population size at 1% showed on farmer income which increased to 0.15%. However, exactly as our assumptions, the Sargan test for validation of overidentifying restrictions rejected the null hypothesis, and the intercept is statistical significant. Both of that represent some unknown time lags that are still needed to be identified.

After taken into consideration of time lags of farmer income and water use as instrumental variables within GMM estimators, the empirical results of the Blundell-Bond dynamic panel-data model prove that the level of contemporaneous farmer income has relationship with the previous farmer income and water use. Previous farmer income affects the variation of population, water use, and electricity at the different levels in each province of China. The robust empirical results show slightly

Table 5 Estimation results on the impact of water use on farmer income in provincial level of China during years 2004–2012

Variables	Pool-OLS	Fixed effect	DPD-SYS robust	Blundell-Bond robust DPD	BB robust DPD GMM of lag farmer income
Population	−0.356	0.776	−0.150	−0.355	−1.479
[lnpop]	(0.0587)***	(0.1578)***	(0.0237)***	(0.2688)	(0.5919)**
Water use	**−0.027**	**0.641**	**0.077**	**0.118**	**0.190**
[lnwater]	**(0.0436)**	**(0.1028)***	**(0.0222)***	**(0.0495)**	**(0.1108)**
Electric power	0.484	1.000	0.096	0.259	0.415
[lnele]	(0.0411)***	(0.0246)***	(0.0152)***	(0.0710)***	(0.1145)***
Intercept	8.234	−7.698	0.5819	0.280	4.703
[_cons]	(0.2373)***	(1.3483)***	(0.1341)***	(0.2363)	(1.841)**
L1.lnfinc	–	–	0.965	1.083	0.768
	–	–	(0.0125)***	(0.0678)***	(0.1035)***
L2.lnfinc	–	–	–	−0.077	0.028
	–	–	–	(0.0764)	(0.1085)
L1.lnpop	–	–	–	0.257	0.912
	–	–	–	(0.2537)	(0.4960)*
L1. lnwater	–	–	–	**−0.085**	**−0.351**
	–	–	–	**(0.0485)***	**(0.1398)*****
L1.lnele	–	–	–	−0.201	−0.041
	–	–	–	(0.0622)***	(0.1318)
sigma_u	–	1.968	–	–	–
sigma_e	–	0.089	–	–	–
rho	–	0.998	–	–	–
R-squared	0.348	0.934	–	–	–
Sample size[N]	277	277 $(n = 31)$	277 $(n = 31)$	246$(n = 31)$	246$(n = 31)$

Arellano-Bond DPD: GMM type for differenced equation, L(2/.).lnfinc L(1/.).lnwater; standard, LD.lnfinc D.lnpop D.lnwater D.lnele

DPD-SYS and Blundell-Bond DPD: GMM type for level equation, LD.lnfinc D.lnwater; standard: _cons

Arellano-Bond test for H0: no autocorrelation in first-differenced errors, Fail to reject, Fail to reject

Note: N is the observations in n provinces in T time periods. Data within the missing years did not participate analysis

* stands for $0.05 \leq p \leq 0.1$, ** stands for $0.01 \leq p \leq 0.5$, and *** represents statistical significance in values of $p \leq 0.01$ (Reprinted from Zhan Wang et al. (2015) with permission of Physics and Chemistry of the Earth)

positive impact of water use and electric power consumption which are statistically significant to increase contemporaneous farmer income. It seems to match classical consumption theory in that the total consumption brings flourishing. However, it is statistically significant that 1% changes in the first difference time lag of water use has 0.085% of negative impacts on farmer income. It demonstrates that water-saving has positive 0.085% of impacts on an increase of farmer income in the following year. Moreover, the coefficient of first difference time lag of farmer income is over one. It further interprets that overconsuming water harms farmer income in the following year. Comparing the results of Pool-OLS, the causality of the negative sign of water use on farmer income can be explained by two parts in the results of the Blundell-Bond dynamic panel-data model with GMM estimators: water use has positive relationship with contemporaneous farmer income and has negative relationship with future farmer income.

To address robust results of this causality, we assume all future regional development depending on the technology improvement at the last level of farmer income. Then, the GMM estimator of just farmer income is set in the Blundell-Bond dynamic panel-data model. The analysis results indicate the causality is statistically significant in which water use has positive relationship with contemporaneous farmer income and has negative relationship with future farmer income. One percent changes in water use will cause 0.19% increases in contemporaneous farmer income but 0.35% decreases to farmer income in the following year.

Regional diversification can be presented in three sub-models for Eastern, Central, and Western China separately. Table 6 shows the first difference of farmer income which predetermine to the following year in all three parts of China. Especially, in Western China, the farmer income is highly dependent on the previous level of farmer income. Moreover, population has negative relationships with farmer income in China. In Central China, it is statistically significant that 1% increase in population will induce 0.276% decrease in farmer income. In Western China, 1% increase in population will induce 0.063% decrease in farmer income. Water use has positive relationship with contemporaneous farmer income in both Central and Western China. In Central China, the average per capita water use was 462 ton which was the highest in three large regions of China in year 2012. The coefficients of water use to farmer income are over 0.124, but it is not significant, although it is much higher than that in Western (0.03) and Eastern (−0.04) China. It indicates that increase in farmer income is much dependent on current water consumption because the quotient between water use and population (average water use) in Central China is much higher than that in Western and Eastern China.

Eastern China is more developed than the Central and Western China. The total population in three large regions of China was, respectively, 558.5 million in Eastern, 425.1 million in Central, and 364.3 million in Western. The average farmer income in Eastern China was 1870.6 in 2012 USD, which was higher than 1215.2 in 2012 USD in Central China, and 951.8 in 2012 USD in Western China, while per capita water use in Eastern was 390.53 ton in year 2012, which was lower than 462 ton in Central China. Urban expansion has forced land use changes in cultivated land in China; resulting water demand has been increasing

Table 6 Empirical analysis results of impact of sparing use of water on farmer income in three large regions of China during years 2004–2012

	Eastern	Central	Western	China in total
Variables	DPD-SYS			Blundell-Bond DPD
Population	−0.025	−0.276	−0.063	−0.355
[lnpop]	(0.0426)	(0.0906)***	(0.0333)*	(0.2688)
Water use	**−0.040**	**0.124**	**0.033**	**0.118**
[lnwater]	**(0.0199)****	**(0.0570)****	**(0.0256)**	**(0.0495)****
Electric power	0.085	0.222	0.029	0.259
[lnele]	(0.0320)***	(0.0275)***	(0.0230)	(0.0710)***
Intercept	−1.122	1.642	0.061	0.280
[_cons]	(0.5036)**	(0.6197)***	(0.2264)	(0.2363)
L1.lnfinc	0.973	0.840	1.027	1.083
	(0.0222)***	(0.0255)***	(0.0204)***	(0.0678)***
L2.lnfinc	–	–	–	−0.077
	–	–	–	(0.0764)
L1.lnpop	–	–	–	0.257
	–	–	–	(0.2537)
L1.lnwater	–	–	–	**−0.085**
	–	–	–	**(0.0485)***
L1.lnele	–	–	–	−0.201
	–	–	–	(0.0622)***
Sample size[N]	99	72	106	277
Group number[n]	11	8	12	31
DPD-SYS and Blundell-Bond DPD				
Instruments for differenced equation: GMM type, L(2/.).lnfinc L(1/.).lnwater; standard, D.lnpop D.lnwater D.lnele				
Instruments for level equation: GMM type, LD.lnfinc D.lnwater; standard, _cons				
Arellano-Bond test for H0: Fail to reject, Fail to reject, Fail to reject, Fail to reject				

Note: N is the observations in n provinces in T time periods. Data within the missing years did not participate analysis

* stands for $0.05 \le p \le 0.1$, ** stands for $0.01 \le p \le 0.5$, and *** represents statistical significance in values of $p \le 0.01$. Because the availability of sample size is limited, dynamic panel-data model with systematic GMM estimator is used for regional diversification (Reprinted from Zhan Wang et al. (2015) with permission of Physics and Chemistry of the Earth)

for residential living and eco-environmental protection (Zhao et al. 2010). In Eastern China, having a higher rate of urbanization than other regions in China, the empirical results of DPD-SYS model reported statistically significant negative impacts of overconsumption of water on farmer income. It demonstrates the potential trade-offs between rural water loss and urban water use. Numerically, with increase in 1% of total amount of water use, the contemporaneous farmer income will lose 0.04% in Eastern China.

The impact of electric power on farmer income has been attained statistically significant in Eastern and Central China. We discuss the autocorrelation in error term due to correlation of water use and electric power consumption. The Sargan test gives some hints to further identify autocorrelation between water use and electric power in error term. First-time lag differencing autoregression strokes systematic variance-covariance of autocorrelation. Although the chi-square results of the Sargan test are still not in well satisfaction because of its theoretically inefficient structure, the robust results of the Blundell-Bond dynamic panel-data model with GMM estimators of farmer income reported that electric power consumption has inconstant impacts on contemporaneous rural income in the following year. Therefore, water use as a kernel variable is statistically significant. It illustrates that 1% of water-saving will result positive impacts of 0.085~0.35% on farmer income in the following statistical year.

Heihe River Basin (HRB) Land Use Change and Agricultural Expansion

Heihe River Basin (HRB)

HRB is located in Northwest China (38°N–42°N, 98°E–101°E), covering an area over 143.29 thousand kilometers (Fig. 3). HRB is a typical arid region in China. The annual average precipitation is about 37 mm, 45 mm, and 55 mm according to the monitoring result of local meteorological stations of Ejin, Guaizihu, and Dingxin in HRB, while the annual average evaporation exceeded 3000 mm (Xiao et al. 2015).

The Heihe River is the second longest inland river in the arid region of Northwestern China. The total length of the Heihe River reaches 821 km (Huai et al. 2014). According to the location of hydrometric stations of Yingluoxia and Zhengyixia, the Heihe River is divided into upper, middle, and lower reaches. The upper reaches of HRB are runoff formation areas where cold desert accounted for 22% of the total area. The middle reaches of HRB are runoff-using areas where most of the agricultural oasis, population, and GDP (gross domestic product) are concentrated. The lower reaches of HRB are a runoff-fade area with a huge evaporation capacity. The oasis strip in HRB plays a vital ecological role in Northwest China. In past decades, with the continuous expansion of the agricultural oasis, the demand for irrigation water has significantly increased, which has triggered a great deal of ecological and environmental problems.

Land Use Patterns and Changes in HRB

Unused land comprised the largest proportion (67.99%) of HRB in 1986. The proportion of grassland was also high, reaching 23.08% (Fig. 3). However, the proportions of the agricultural oasis, forestry areas, water areas, and built-up areas are as low as 3.45%, 4.11%, 1.06%, and 0.31%, respectively. Gobi is the primary land use type within unused land, contributing to 50.32% of the total. The bare rock and sandy land also take up 23.77% and 13.76% of unused land.

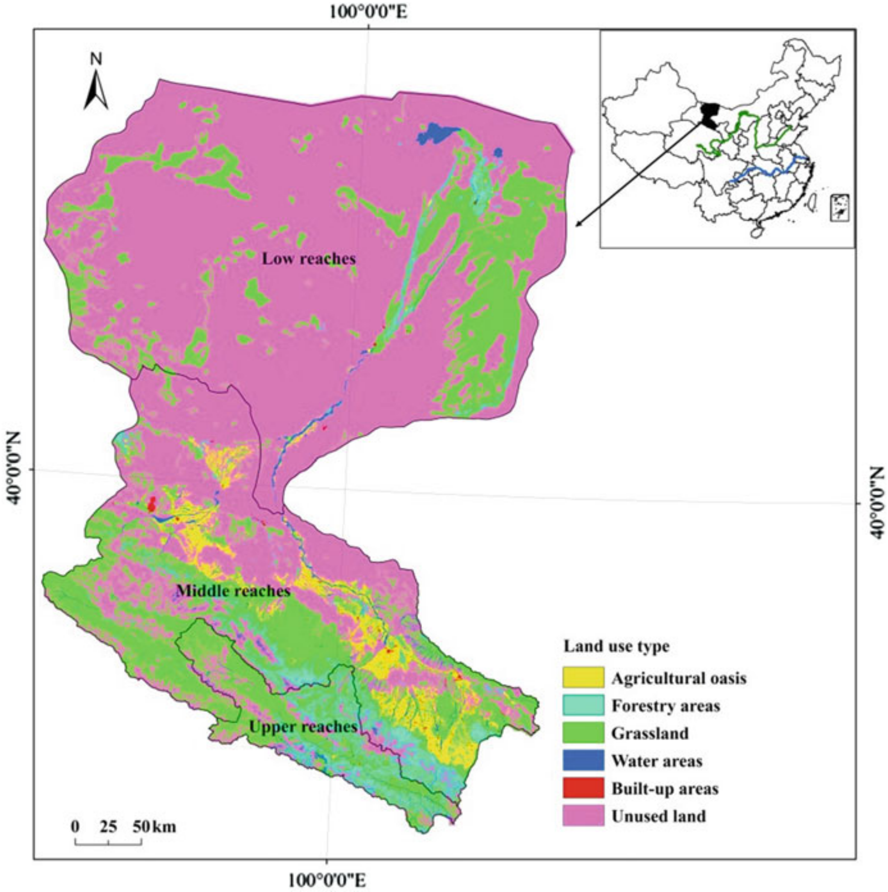

Fig. 3 The location and land use patterns of the Heihe River Basin in 1986 (Reprinted from Wei Song and Deng (2015) with permission of Physics and Chemistry of the Earth)

The distribution of the six land use types showed obvious reaches in variation. The area proportions of upper, middle, and lower reaches in HRB are 7.01%, 59.64%, and 33.35%, respectively. However, 96.58% of the agricultural oasis and 92.73% of built-up areas concentrated in middle reaches, while 72.44% of unused land distributed in the lower reaches. The proportions of forestry areas, grassland, and water areas in middle reaches are also as high as 48.25%, 44.36%, and 49.50%, respectively. Nevertheless, the proportions of the three land use types are all lower than the area proportions of middle reaches (59.64%).

The most significant land use changes from 1986 to 2000 in HRB were the expansion of agricultural oases (25.11%) and water areas (206.06%) and the shrinkage of forestry areas (78.00%) and grassland (27.30%) (Fig. 4). In addition, built-up areas in HRB significantly decreased by 19.02% from 1986 to 2000 in spite of the

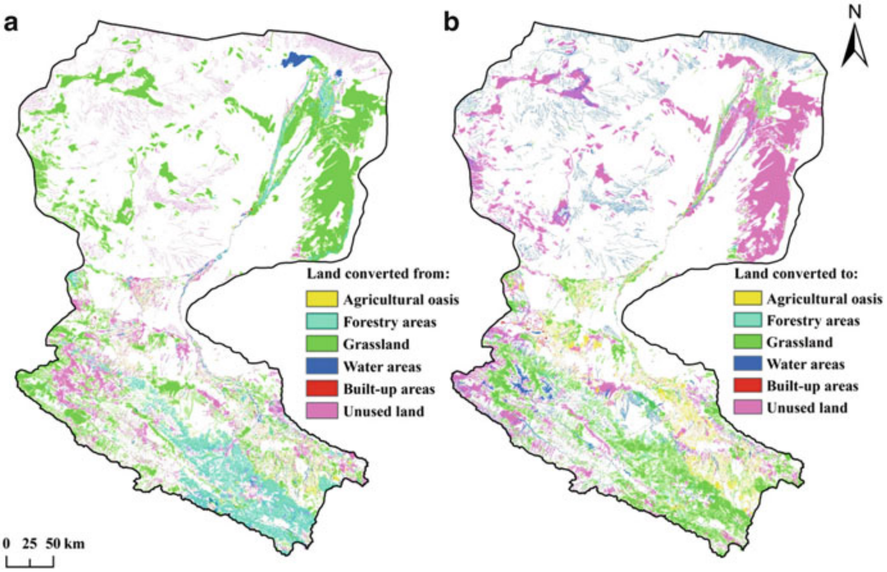

Fig. 4 Land use changes in the Heihe River Basin, 1986–2000 (Reprinted from Wei Song and Deng (2015) with permission of Physics and Chemistry of the Earth)

rapid growth of the population and economy. Unused land also rapidly expanded by 9.60% during this period. In the upper reaches of HRB, the most significant land use changes are the expansion of the agricultural oasis (98.73%) and the shrinkage of forestry areas (−87.17%). In the middle reaches of HRB, water areas significantly expanded by 162.02%, while forestry areas decreased by −78.80%. In the lower reaches of HRB, water areas and built-up areas expanded by 359.72% and 56.01%, respectively, while grassland decreased by 84.29%.

The agricultural oasis continued with positive changes in area, with an increase rate of 14.82% from 2000 to 2011, while the five other land use types all presented opposite trends (Fig. 5) compared to the previous period. Forestry area, grassland, and built-up areas changed from negative trends from 1986 to 2000 to positive trends from 2000 to 2011, with increase rates of 11.57%, 0.95%, and 47.54%, respectively. Water areas and unused land ceased the positive changes in the previous period and decreased by 0.86% and 1.99% from 2000 to 2011, respectively. Although the agricultural oasis increased at the whole HRB, it decreased by 17.37% in the upper reaches of HRB. In middle reaches of HRB, built-up areas significantly increased by 45.63%, while water areas and unused land decreased by 3.08% and 4.28%, respectively. In the low reaches of HRB, the agricultural oasis and built-up areas expanded by 14.83% and 47.69%, respectively, while unused land decreased by 1.49%. As a whole, the predominant land use changes during this period were the expansion of the agricultural oasis and built-up areas.

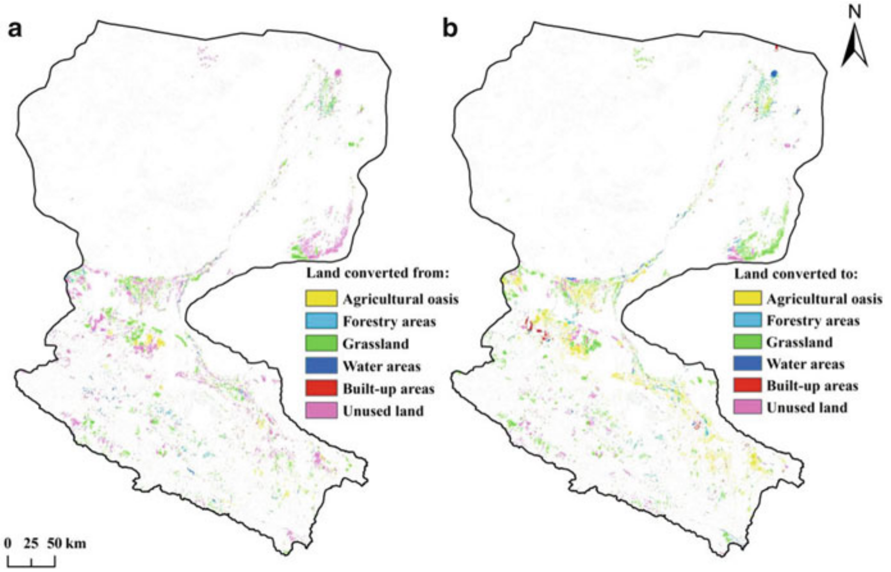

Fig. 5 Land use changes in the Heihe River Basin, 2000–2011 (Reprinted from Wei Song and Deng (2015) with permission of Physics and Chemistry of the Earth)

Expansion of Agricultural Oasis in HRB

The agricultural oasis in HRB changed from 4942.59 km^2 in 1986 to 6183.67 km^2 in 2000, with an expansion rate of 25.11% (annual rate of 1.79%). In the subsequent period (2000–2011), the agricultural oasis increased from 6183.67 km^2 in 2000 to 7100.14 km^2 in 2011, with an increase rate of 14.82% (annual rate of 1.35%). The agricultural oasis expanded continuously during the two periods, while the annual expansion speed decreased over time.

Drastic conversions existed in the agricultural oasis in HRB. A total of 1845.81 km^2 of other land use types was converted into an agricultural oasis from 1986 to 2000 (Table 4), among which grassland contributed to 45.93%, unused land 26.97%, built-up areas 11.57%, forestry areas 8.27%, and water areas 7.26%. The reclamation of grassland was the primary approach to generate new agricultural oases. The agricultural oasis loss was more moderate compared to the expansion of agricultural oases. A total of 604.75 km^2 of agricultural oases was converted into other land use types during the period 1986–2000 (Table 7). Most of the lost agricultural oases were converted into grassland (41.60%), followed by unused land (28.18%), built-up areas (17.42%), water areas (8.94%), and forestry areas (3.87%). The conversions from agricultural oasis to grassland were the leading conversions in agricultural oasis change.

Similar conversions occurred in the latter period (2000–2011). A total of 1283.57 km^2 of other land use types was converted into agricultural oases, while only 366.88 km^2 of agricultural oases was converted into other land use types (Table 4).

Table 7 Land use conversions in agricultural oasis, 1986–2000 and 2000–2011

	Gained agricultural oasis (km^2)		Lost agricultural oasis (km^2)	
	1986–2000	2000–2011	1986–2000	2000–2011
Forestry areas	152.73	34.55	23.38	32.1
Grassland	847.77	433.42	251.57	166.61
Water areas	134.01	37.15	54.05	13.28
Built-up areas	213.53	17.54	105.33	85.86
Unused land	497.78	760.91	170.42	69.02
Total	1845.81	1283.57	604.75	366.88

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Unused land became the main contributor (59.28%) of newly added agricultural oases. Grassland changed to the second contributor (33.77%), followed by forestry areas (2.69%), water areas (2.89%), and built-up areas (1.37%). However, grassland was still the primary destination (45.41%) of the lost agricultural oases, followed by built-up areas (23.40%), unused land (18.81%), forestry areas (8.75%), and water areas (3.62%).

The expansion and shrinkage of agricultural oases mainly occurred in the counties of the middle reaches (Fig. 6). The expansion of the agricultural oasis in the Zhangye municipal district, Minle county, Jiuquan county, and Shandan county accounted for 17.60%, 14.02%, 13.88%, and 12.05% of total expansion, respectively. The counties of Shandan, Minle, Jinta, and Jiuquan city experienced severe agricultural oasis loss, accounting for 26.99%, 15.93%, 11.95%, and 10.45% of total loss, respectively.

In the latter period, agricultural oasis expansion was still concentrated in the same four counties with the former period. However, the orders of the four counties in agricultural oasis expansion slightly changed. Jinta instead of Zhangye municipal district changed to be the first contributor of agricultural oasis expansion, accounting for 18.04% of total, followed by Jiuquan (15.74%), Shandan (11.75%), and Zhangye (9.79%). The agricultural oasis loss at the county level during the period 2000–2011 was a little different from that of 1986–2000. Sunan Yugu changed to the primary region of agricultural oasis loss, accounting for 29.21% of the total. The agricultural oasis losses were also severe in Jiuquan city (12.95%), Zhangye municipal district (11.08%), Minle county (10.08%), and Shandan county (10.10%).

Methods of Measuring Water-Use Efficiency

Measurement of the Water-Use Efficiency for Soil Conservation

In its broadest sense, the water-use efficiency is the net return for a unit of water used, and in previous research the crop water-use efficiency is the amount of grain yield (e.g., kilograms of grain) obtained per unit of water consumption (e.g., cubic meters of water). Besides, depending on the type of water sources considered, crop water-use efficiency is generally expressed as grain yield per unit water

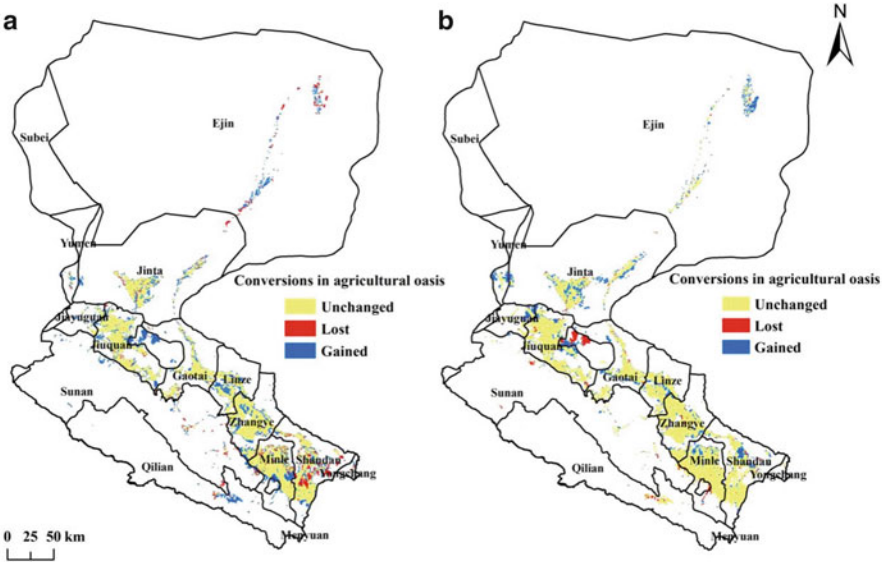

Fig. 6 Expansion and shrinkage of agricultural oasis in the Heihe River Basin, 1986–2000 (**a**) and 2000–2011 (**b**) (Reprinted from Wei Song and Deng (2015) with permission of Physics and Chemistry of the Earth)

evapotranspired or grain yield per unit total water input (irrigation plus rainfall). For example, there are three major definitions of water-use efficiency that are widely used, i.e., (1) gross primary production (GPP)-based water-use efficiency, GPP/ET; (2) net primary productivity (NPP)-based water-use efficiency, NPP/ET; and (3) net ecosystem carbon production (NEP)-based water-use efficiency, NEP/ET. All these definitions only reflect the water-use efficiency for primary production, but all involve ET, which the most active process in the hydrological cycle and is also a major component of energy and water balance in agriculture ecosystems, and therefore the water consumption is also represented with ET in this study. In addition, this study primarily focuses on the soil conservation service, which is the most important ecosystem services provided in the lower Heihe River Basin, and the water-use efficiency for the soil conservation is therefore calculated as the soil conservation amount divided by ET as follows:

$$WUE - SC = SC/ET \tag{3}$$

where WUE-SC is the water-use efficiency for soil conservation (unit: t•mm-1), SC is the soil conservation amount (unit: t), and ET is the evapotranspiration (unit: mm), which is assumed to be the consumptive water used by vegetation to provide the ecosystem services such as soil conservation. In this study, the average WUE-SC over a region was calculated as the area-weighted average value of all grid cells. It is noteworthy that the WUE-SC of water bodies was also calculated in the same way as other land cover types in this study.

Measurement of the Water-Use Efficiency for Agriculture

Agricultural water-use efficiency refers to the ratio of the minimum water consumption which can be realized theoretically to the actual water consumption with the predefined input and output level. There are a number of methods to analyze the agricultural water-use efficiency, and the most widely used ones were the parametric method, the stochastic frontier analysis (SFA), and the nonparametric method, DEA (Lin and Tseng, 2005). DEA analysis aims to establish a nonparametric frontier by using the data. The DEA was chosen to measure the agricultural water-use efficiency in this study. Aiming to analyze how to improve the water-use efficiency with the fixed water supply amount, we utilized input-oriented DEA. When the value of efficiency equals to 1, it means the decision unit is on the production frontier and the actual production value has no difference with the possible maximum value. When the efficiency is lower than 1, it implies that there is still improvement potential for the decision unit. In this research, when the value of the efficiency reaches 1, the water-use efficiency of this decision unit would be higher (Branda 2015). Suppose there are $N(=1, 2, 3, \ldots 0.8)$ decision units putting in $I\,(=1, 2, 3\ldots)$ factors at $T\,(=1, 2, 3\ldots.)$ time periods, then $J\,(=1, 2, 3\ldots..)$ kinds of outputs will be generated. When referring to the input-output index, we used X and Y to represent the input and output, and then the input-output index of N counties (which equal to the decision unit) during different periods can be marked as $x^t_{i,n}$ and $y^t_{i,n}$. If we set $x_i = (x_{1n}, x_{2n}, \ldots, x_{In})$ and $y_j = (y_{1n}, y_{2n}, \ldots, y_{Jn})$, the model is specified as follows:

$$\begin{cases} \min\theta = V_D \\ \sum_{n=1}^{8} \lambda_j X_i + S^- = \theta X_0 \\ \sum_{n=1}^{8} \lambda_j Y_j + S^+ = Y_0 \\ \lambda_j \geq 0, N = 1, \ldots, 8 \\ S^- \geq 0, S^+ \geq 0 \end{cases} \tag{4}$$

where $\theta(0 < \theta < 1)$ is the comprehensive technical scale efficiency. λ_j is the weighting variable, $S^-(S^- \geq 0)$ is the slack variable, $S^+(S^+ \geq 0)$ is the surplus variable, and ε is the Archimedes infinitesimal. The equation above is the DEA model based on constant scale returns; if $\theta = 1$, it means the county reaches the optimal situation of water use on the frontier.

The Malmquist total factor productivity index was utilized to compute the TFP growth rate and to analyze the improvement in technical efficiency and technical change (Afsharian and Ahn 2015). Supposing $D^t_c(x_t, y_t)$ are the distance functions, calculation of the Malmquist total factor productivity index based on the period t and $t + 1$ and calculation of comprehensive technical efficiency change are as follows:

$$M(x_t, y_t, x_{t+1}, y_{t+1}) = EC \times TC = \left[\frac{D^c_t(x_{t+1}, y_{t+1})}{D_t(x_t, y_t)} \times \frac{D^{t+1}_c(x_{t+1}, y_{t+1})}{D^{t+1}_c(x_t, y_t)}\right]^{\frac{1}{2}} \tag{5}$$

$$EC = M_t\left(x^t, y^t, x^{t+1}, y^{t+1}\right) = \frac{D_t^c\left(x_{t+1}, y_{t+1}\right)}{D_t(x_t, y_t)} \tag{6}$$

$$TC = M_{t+1}\left(x^t, y^t, x^{t+1}, y^{t+1}\right) = \frac{D_c^{t+1}\left(x_{t+1}, y_{t+1}\right)}{D_c^{t+1}(x_t, y_t)} \tag{7}$$

The Malmquist total factor productivity index is widely used to divide the rate of TFP change into technical efficiency change (EC) and technical change (TC). The technological development will bring about changes in the production frontier, and EC is the changes of TFP growth caused by the changes of production frontier within a certain time period. Technical efficiency refers to the changes in TFP caused by efficiency change of technology itself.

Driving Forces of Agricultural Water-Use Efficiency Using Tobit Model

The Tobit model shows superiority to the ordinary least squares regression when there are both continuous variables and discrete variables. In this study, the agricultural water-use efficiency ranges from 0 to 1; therefore the Tobit model is applied to analyze the effects of driving factors on agricultural water-use efficiency, which is as follows:

$$y_i^* = \beta_0 + \sum_{j=1}^{k} \beta_j x_{ij} + \varepsilon_i \tag{8}$$

$$y_i = \begin{cases} 0\,, & if \quad y_i^* \in (-\infty, 0] \\ y_i^*\,, & if \quad y_i^* \in (0, 1] \\ 1\,, & if \quad y_i^* \in (1, +\infty] \end{cases} \tag{9}$$

where y_i represents the agricultural water-use efficiency in the i^{th} county and x_{ij} includes various factors influencing the agricultural water-use efficiency.

Results of Water-Use Efficiency

Spatiotemporal Variation of the Soil Conservation Amount

The results suggested that there was significant spatiotemporal variation of potential wind erosion amount, soil conservation amount, and soil conservation rate in the study area (Figs. 7 and 8). The annual soil conservation modulus in the study area ranged from 0 to 8822 $\mathrm{t \cdot km^{-2} \cdot a^{-1}}$, with an average of 75.47, 71.38, and 137.18 $\mathrm{t \cdot km^{-2} \cdot a^{-1}}$ in 2000, 2005, and 2008, respectively. Besides, the annual total soil conservation amount of the study area showed a first decreasing and then increasing trend during 2000–2008, reaching approximately 5.80 million ton, 5.48 million ton, and 10.55 million ton in 2000, 2005, and 2008, respectively. In addition to the spatiotemporal variation at the annual scale, the soil conservation amount also varied significantly at the monthly scale (Fig. 7). The climax of the soil conservation amount occurred during March and May in 2000 and 2008 and during April and June in 2005, while there is very limited soil conservation amount in other months, indicating the soil conservation mainly occurred in the spring during 2000–2008 (Fig. 7). There is frequently strong wind in the spring in the lower Heihe River Basin, which leads to the rapid increase of the potential wind erosion amount; what's worse, the vegetation coverage rate is still very low during the spring when most vegetation just begins to grow, making the study area extremely susceptible to the wind erosion.

Although the soil conservation amount in the study area varied substantially across the years, the overall spatial pattern of soil conservation kept consistent during 2000–2008, only with significant change in some part of the study area (Fig. 8). The soil conservation amount was generally very low in most part of the study area, and the high soil conservation amount only occurred in a few regions such as the northeast border region and the area near Gurinai Lake in the southeast border region. The soil conservation amount showed an obvious decreasing trend from the northeast to the southwest in the northeast border region during 2000–2008, and there was also an obvious decreasing trend of the soil conservation amount in the southeast border region in 2008. It is not surprising that the spatial pattern of the soil conservation amount is similar to that of the potential wind erosion amount, since the latter is the maximum of the former, but the soil conservation amount is also influenced by the vegetation coverage. What's more, the soil conservation amount

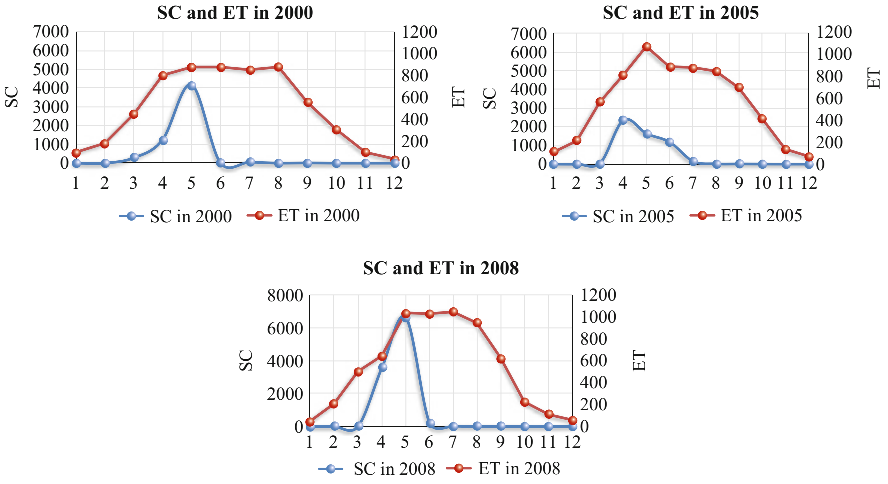

Fig. 7 The monthly soil conservation amount (SC) (unit: thousand ton) and ET (unit: thousand mm) in 2000, 2005, and 2008 (Reprinted from Haiming Yan (2015) with permission of Sustainability)

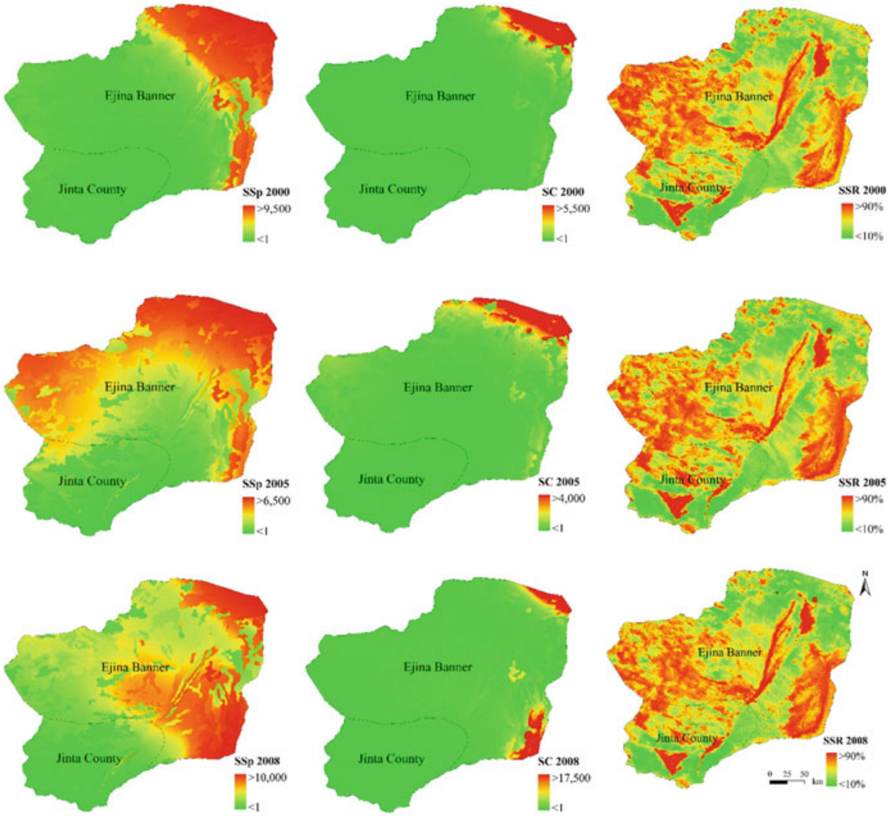

Fig. 8 The annual potential soil loss (SSp), annual soil conservation amount (SC) (unit: t), and soil conservation rate (SCR) in 2000, 2005, and 2008 (Reprinted from Haiming Yan (2015) with permission of Sustainability)

varied greatly among different land cover types. For example, the high soil conservation amount in 2008 occurred in the Gobi Desert in the northeast border region, the water body over East Juyanhai, the low-coverage grassland, shrub forest, and the sandy land in the southeast border region, where the vegetation coverage rate was generally low. The lowest soil conservation amount occurred in the Gobi Desert near the southwest border, where both the vegetation coverage rate and potential wind erosion amount were very low.

The soil conservation rate also showed obvious spatial heterogeneity (Fig. 8). The regions with the high soil conservation rate concentrated in the oases and irrigated area along the Heihe River, where the vegetation coverage was in good conditions and the major land cover types were cultivated land, shrub forests, closed forest land, and medium-coverage grassland or water bodies. Besides, the soil conservation rate ranged from 2.62% to 100% during 2000–2008, with the average of 55.32%, 57.36%, and 55.98% in 2000, 2005, and 2008, respectively, showing a first slight increasing and then slight decreasing trend, which is contrary to the changing trend of the soil conservation amount. Although the average soil conservation rate was the highest in 2005, the soil conservation amount in 2005 was the lowest, indicating there were still some other factors that influenced the soil conservation amount, e.g., spatial heterogeneity of the potential wind erosion amount. There was obvious spatial inconsistency between the potential wind erosion amount and the soil conservation rate, indicating that the correlation between them was not high. However, the spatial inconsistency between them has significant impacts on the soil conservation amount, especially in the southwest part of the study area, where there was a large area of high-coverage vegetation. There was a high vegetation coverage rate in oases in the southwest part of the study area, but the potential wind erosion amount is very low in this region, which leads to the extremely low soil conservation amount and fails to give full play to the potential of the high-coverage vegetation to reduce the soil erosion. The soil conservation amount is influenced by the potential wind erosion amount and the vegetation coverage rate; both of them generally show obvious spatial heterogeneity, leading to the high location dependence of the soil conservation amount, to which sufficient consideration should be given in the ecosystem management and land management.

Spatiotemporal Variation of Evapotranspiration

There was a significant spatial heterogeneity of ET, the spatial pattern of which showed no significant change during the entire period (Fig. 9). The annual ET ranged from 12.31 mm to 1344.07 mm during 2000–2008. It is very low in most part of the study area, where it generally ranged from 32 mm to over 100 mm, and it is high in only the oases, East Juyanhai, and the regions along the Heihe River. The highest ET was generally found in the forests, water body, as well as irrigated croplands, while the lowest ET was found in the desert area and Gobi area. In particular, the highest ET in 2005 and 2008 occurred in the water body of East Juyanhai Lake, which has reappeared since 2003. By comparison, ET was generally below 50 mm in the desert area, where the land surface is mainly covered by bare rock with sparse vegetation. There were widespread sandy land and Gobi Desert in most part of the study area, where the vegetation coverage rate was generally very low and the water availability is very low, while the high-coverage vegetation such as the cultivated land and forests was generally distributed in the oases and the regions along the main stream of the Heihe River, where there is high water availability for the vegetation growth and ET. Besides, the annual ET showed an increasing trend during the first half of the period (2000–2005), but a decreasing trend after that, with the average ET reaching 74.55 mm, 88.32 mm, and 84.88 mm in 2000, 2005, and 2008, respectively, and the overall increase was still significant in the entire study period. In addition, there was also obvious variation of the monthly ET, which is generally high during the growing season (from April to October) and low during the nongrowing season (Fig. 7). It is noticeable that there was obvious temporal inconsistency between the ET and the soil conservation amount. Most part of the ET occurred in the summer

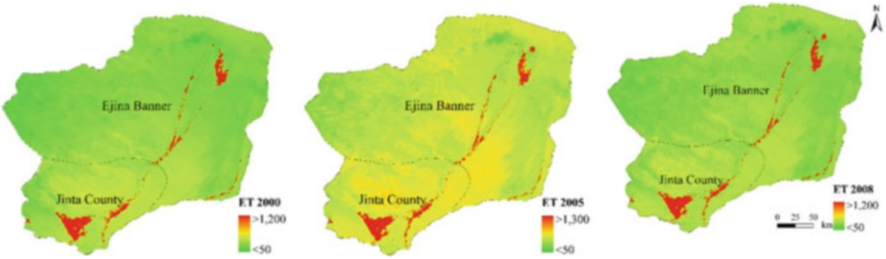

Fig. 9 Spatial pattern of the annual ET in 2000, 2005, and 2008 (Reprinted from Deng and Zhao (2015) with permission of Sustainability)

and autumn, while most part of the soil conservation amount concentrated in the spring, indicating only a part of the ET was used to provide the soil conservation service. What's more, since the precipitation of the study area is very limited (approximately 37 mm), it has very limited impacts on the change of ET; other factors such as the water diversion of the Heihe River and land use and land cover change may have played a key role in influencing the spatiotemporal variation of ET.

Spatiotemporal Variation of the Water-Use Efficiency for Soil Conservation

The WUE-SC in the study area showed significant spatial heterogeneity and ranged from 0 to 98.69 t·mm^{-1} during 2000–2008, indicating that approximately 98.69 t soil loss had been reduced by using 1 mm ET in a 1 km grid cell at most. The WUE-SC was generally below 1 t·mm^{-1} in most part of the study area, and the regions with high WUE-SC mainly concentrated in the northeast part and southeast part of the study area, showing a spatial pattern similar to that of the soil conservation amount during 2000–2008. For example, the highest WUE-SC occurred in the low-coverage grassland and Gobi Desert near the northeast broader region and low-coverage grassland, shrub forest, and sandy land near the northeast broader region, and the WUE-SC is also very high in the medium-coverage or low-coverage grassland in some part of the Ejina Oasis. Besides, the average WUE-SC reached 1.10, 0.89, and 1.68 t·mm^{-1} in 2000, 2005, and 2008, respectively, which was very low on the whole and showed a first slight decreasing and then rapidly increasing trend during 2000–2008 (Fig. 4). In addition, the spatial pattern of WUE-SC for soil conservation kept consistent in most part of the study area, only with some slight fluctuation, but it changed significantly in some regions in the southeast part and northeast part during 2005–2008. The WUE-SC decreased by 1–37 t·mm^{-1} in most regions in the northeast part of the study area, and it increased in only a few regions in the northeast part, with the increment showing a decreasing trend from the broader to the inner part. In particular, the WUE-SC has decreased very obviously in the water body of East Juyanhai, which has reappeared in 2003 due to the increased water diversion. By comparison, the WUE-SC increased significantly in the

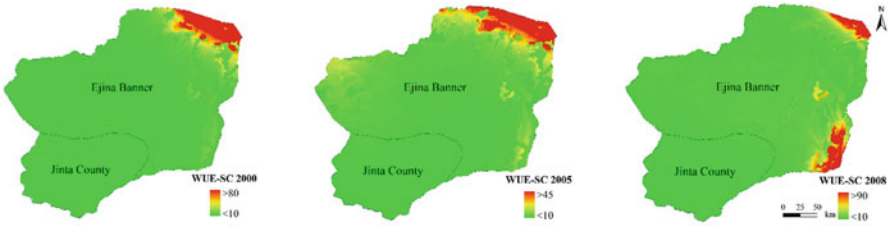

Fig. 10 The water-use efficiency for soil conservation (WUE-SC) in 2000, 2005, and 2008 (Reprinted from Deng and Zhao (2015) with permission of Sustainability)

southeast part of the study area during 2005–2008, with an increment of 1–10 t·mm^{-1} in the regions around Gurinai Lake and even 10–97 t·mm^{-1} in some part near the southeast broader (Fig. 10).

It has been reported that uneven changes in environmental factors can lead to the spatially heterogeneous responses of water-use efficiency to environmental change; the change in the WUE-SC is also due to the uneven changes in environmental factors. The average WUE-SC decreased by 19.09% during 2000–2005; the average ET increased by 18.47%, while there was no significant change in the soil conservation amount (decreasing by 5.42%), indicating that the change in the WUE-SC was mainly due to the change in the ET during 2000–2005. By comparison, the average WUE-SC increased by 88.76% during 2005–2008; the ET only decreased by 3.89%, while the soil conservation amount increased by 82.15%, suggesting the change in the soil conservation amount made great contribution to the increase of the average WUE-SC. Besides, there was no obvious change in the soil conservation rate during 2005–2008, reaching 57.36% and 55.98% in 2005 and 2008, indicating that the vegetation coverage change didn't lead to significant change in the soil conservation amount. However, during 2005–2008 the potential soil loss increased remarkably by 88.76%, which led to the significant increase of the soil conservation amount and consequently the improvement of the average WUE-SC. In particular, the potential soil loss increased most obviously in the southeast part of the study area, which is close to Badain Jaran Desert, with the increment of 1000–5000 t/km^2 and the increment rate of 20%–50% in most part of this region. Although there was no significant change in the soil conservation rate and the ET in this region, the remarkable increase in the potential soil loss made the ability of the vegetation to reduce the wind erosion fulfilled, leading to the significant increase of the regional soil conservation amount and improvement of the overall WUE-SC of the study area.

The overall low WUE-SC in the study area may be due to the spatiotemporal inconsistency between the potential soil loss and the vegetation coverage rate. For example, the potential soil loss is very low in most part of the study area, where the main land cover type is unused land and with low vegetation coverage, leading to the low soil conservation amount and consequently the low WUE-SC. Besides, the vegetation coverage rate is also very low in most part of the regions with the high potential soil loss; although ET is low in these regions and the soil conservation amount may be high, the soil conservation rate is generally very low, which indicates there is still some scope to increase the soil conservation amount and improve the WUE-SC. In addition, the potential soil loss is generally very low in the regions with a high vegetation coverage rate, especially in the western part of the study area, and the ability of the vegetation to reduce the wind erosion in these regions is not fulfilled, and the high ET due to high vegetation coverage rate leads to the even lower WUE-SC. What's more, the vegetation coverage is generally high in the summer and autumn; while the wind erosion which leads to the high potential soil loss mainly occurs in the spring, the temporal inconsistency between the vegetation coverage rate and the potential soil loss may also contribute to the low WUE-SC.

Changes of the Agricultural Water-Use Efficiency and TFP Rate

The results reveal that distinct disparities exist among different areas with regard to agricultural water-use efficiency. Figure 11 shows that the highest agricultural water-use efficiency appears in Ganzhou, with the value higher than 0.9 for most years, while the agricultural water-use efficiency in Jinta is comparatively low, with the values of many years lower than 0.5 during 2003–2012. In terms of the changes in agricultural water-use efficiency, disparities also still exist in different counties, with Ganzhou, Minle, and Linze showing slight changes while Jinta, Sunan, and Suzhou presenting relatively considerable fluctuations. Specifically, the agricultural water-use efficiency keeps high in Minle and Linze, whereas obvious declines occur since 2012, which is synchronous with the vegetable and livestock production development. In 2012, Minle and Linze produced a large variety of vegetables which may induce water loss. In Sunan, the agricultural water-use efficiency is lower than 0.5 before 2009; however, it improved markedly and approximated to the level of other counties during 2010–2012. Suzhou experienced the fluctuations with the rising at the beginning, declining in the middle, and increasing again. In general, the trajectory of the agricultural water-use efficiency change is consistent with the industrial adjustment, especially the development of cultural industries.

The results based on the Malmquist total factor productivity index showed a fluctuated variation pattern for TFP growth rate (Fig. 12), with its value more than 1 during 2003–2004, 2006–2007, 2009–2010, and 2011–2012 and less than 1 in 2004–2005, 2005–2006, 2008–2009, and 2010–2011 and no obvious change during 2007–2008.

Impacts of Driving Factors on the Agricultural Water-Use Efficiency

Undoubtedly, agricultural water-use efficiency changes are attributed to various physical and socioeconomic factors as well as their coupling effects. In this study, we focus on the influences of socioeconomic factors and choose a series of indicators, such as average net income of each rural resident representing the rural resident estates, change rate of investment in fixed assets, gross domestic product (GDP)

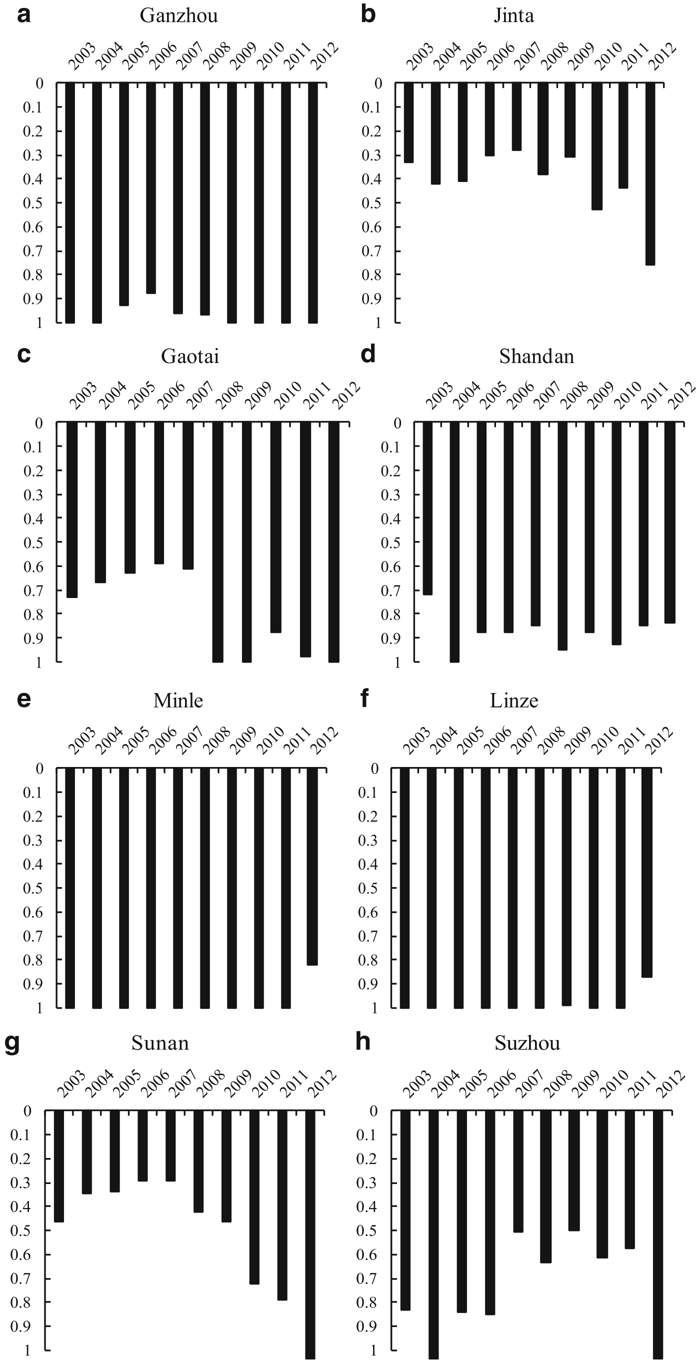

Fig. 11 County-level agricultural water-use efficiency in the Heihe River Basin during 2003–2012 (Reprinted from Guofeng Wang et al. (2015) with permission of Physics and Chemistry of the Earth)

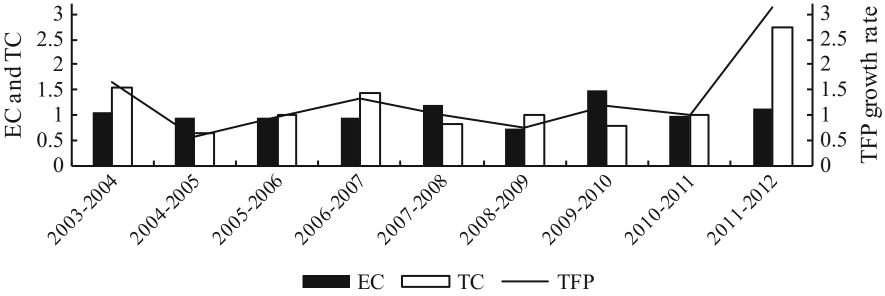

Fig. 12 TFP growth rates and Malmquist decomposition results in agricultural production areas in the Heihe River Basin (results for the whole study area where EC refers to technical efficiency change and TC refers to technical change) (Reprinted from Guofeng Wang et al. (2015) with permission of Physics and Chemistry of the Earth)

representing economic growth, the proportion of the agricultural industry value, the second industry value to GDP representing the industrial structure, the planting area of the corn and wheat, effective irrigation area, disaster area, and other crops representing the planting structure adjustment (Table 8).

There is a remarkable variation in the industrial structures in different counties, thus in the proportions of the output value of the three industries in GDP. In 2012, Suzhou had the lowest agricultural output value proportion, whereas Gaotai exhibited the highest agricultural output value proportion (Fig. 13).

The average net income of each rural resident (+0.08%) has positive impacts on the agricultural water-use efficiency. This is because higher net income enables farmers to use better agricultural facilities, e.g., irrigation machines and equipment, which can consequently improve the agricultural water-use efficiency.

Economic growth identified by the GDP at the local extent (−0.07%) will have negative effects on the agricultural water-use efficiency. It is justified that the growth of GDP is largely attributed to the development of industrial and service sectors, whereas agricultural sectors contributed a confined proportion, indicating the possibility that increasing the water consumption lowers the agricultural water-use efficiency.

The proportion of primary industry (+0.03%) has positive effects. Coupled with the economic development, the role of agriculture among the three industries will be gradually undermined, and it is the same case for the role of agriculture in improving the water-use efficiency. In order to promote the development of agriculture, the local people will make more investment in the agricultural irrigation infrastructure, which can consequently improve the agricultural water-use efficiency.

The wheat planting area (+0.22%) and other crop planting area (+0.16%) had significant positive effects on the agricultural water-use efficiency. Besides, the coefficient of the wheat planting area is larger than that of other crops, indicating that the changes of wheat planting area will have more powerful influence on agricultural water-use efficiency. It is feasible to improve the agricultural water-use efficiency by enlarging the planting area of wheat.

Table 8 Tobit regression results on the impacts of driving factors on agricultural water-use efficiency

Variables	Coefficient	Standard deviation	95% confidence interval
Corn planting area	0.003 (−0.06)	0.05	(−0.11, 0.10)
Wheat planting area	0.22*** (8.33)	0.03	(0.17, 0.27)
Other crop planting area	0.16*** (3.23)	0.05	(0.06, 0.26)
Average net income of each rural resident	0.08*** (3.57)	0.02	(0.03, 0.12)
Effective irrigation area	−0.07*** (2.90)	0.02	(−0.12, −0.02)
Disaster area	0.06*** (2.35)	0.03	(0.009, 0.11)
GDP	−0.04** (−1.61)	0.02	(−0.09, 0.02)
Proportion of primary industry	0.03 (1.23)	0.02	(0.06, 0.01)
Proportion of secondary industry	−0.06 (−2.58)	0.02	(−0.11, 0.01)
Change rate of investment in fixed assets	0.01** (0.80)	0.02	(−0.02, 0.05)
Constant	0.78 (45.77)	0.02	(0.74, 0.81)

Note: t statistics in parentheses; * significant at 10%; ** significant at 5%; *** significant at 1% (Reprinted from Guofeng Wang et al. (2015) with permission of Physics and Chemistry of the Earth)

The results of the Tobit model showed that increasing the investment, modification on plantation structure, and adjustment on industrial structure contributed to improving the agricultural water-use efficiency. Increasing 10% fixed assessment investment is capable of improving agricultural water-use efficiency by 0.1%; expanding 1% of the wheat area can improve agricultural water-use efficiency by 0.22%. As a result, during upgrading the industrial structure, it guarantees the agricultural water consumption and avoids low efficiency and waste.

Summary

Irrigational expansion of the agricultural oasis will inevitably enlarge the water demand and limit the ecological sustainability in HRB. Therefore, effective measures should be adopted to control the overexpansion. Rural labor forces should be gradually guided to transfer from the planting industry to non-planting industry and then to a nonagricultural industry. The policies of grain-for-green and grain subsidies should be appropriately adjusted. The grain subsidy in HRB should be canceled or

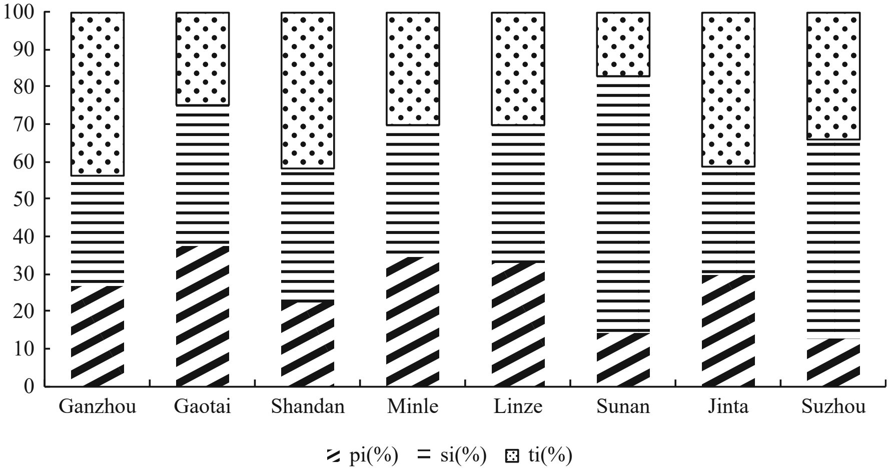

Fig. 13 Proportions of three industries in 2012 (*pi*, *si*, and *ti* refer to the proportion of the output value of the primary industry, second industry, and tertiary industry in local GDP, respectively) (Reprinted from Guofeng Wang et al. (2015) with permission of Physics and Chemistry of the Earth)

gradually reduced. However, the compensation of grain-for-green subsidies should be increased.

In this study, taking the Heihe River Basin in the Northwest China as a case study area, we have applied an integrated model to analyze the agricultural water-use efficiency. The importance of improving the agricultural water-use efficiency has been justified; the results revealed that the strengthening of agricultural infrastructure and increasing the percentage of agriculture and the planning structure both have positive effect on the improvement of agricultural water-use efficiency. But the influence from technological advancement is more powerful. In China, there are more than 459 irrigated areas with different irrigation technique levels, with a considerable number having the problem of high crop water-use efficiency but low agricultural water-use efficiency. In this sense, the accurate measurement on the agricultural water-use efficiency and its driving factors is conductive to the efficient water resource utilization.

Improving water-use efficiency is a complex process, in which the systematic and regional perspectives are in an anticipation to be integrated to seek the water-saving scheme in arid areas. Water conservation in crop and industry is suggested to be combined to improve the regional agricultural water-use efficiency. At regional level, regulations on improving agricultural water-use security by improving agricultural water-use efficiency are expected, and the zoning and categorization approaches are also advised to be implemented in precision management on agricultural water consumption in arid areas.

Impacts of water allocation on farmer income distribution need to be further investigated for regional policy implication of water resource management in different regions of China. Studying regional diversification of water use will contribute to understanding the knowledge of a comprehensive system of watershed management and reinforce the relationships between water allocation and farmer income distribution changes and trade-offs between rural and urban areas. For instance, water-saving for yield increase in northeastern China, water-saving for economic efficiency in Northwest China, water-saving for urban expansion in the middle of northern China, water-saving for pollution mitigation in southern China, and water-saving under regional climatic characteristics in the mountain area may further contribute to this issue. Furthermore, policies, reviews, and studies of water-saving are further needed to fulfill the strategic plan of "water-saving society" in China, for instance, the cost-benefit analysis dealing with relationships between water quota management and irrigation efficiency, the relevant subsidy of irrigation and monitoring system assessment, market-oriented water allocation and smooth transmission mechanism of water management, and so forth.

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Mitigating Climate Change Impacts for Optimizing Water Productivity

Zhongxiao Sun, Feng Wu, Aisha Arowolo, Chunhong Zhao, and Xiangzheng Deng

Contents

Introduction 246
  Climate Change in Heihe River Basin 246
  Water Productivity in Heihe River 248
Methodology and Data 249
  SWAT Model 249
  CGE Model 254
Results of Climate Change on Water Productivity 256
  Changes of Glaciers 257
  The Effect of Glacier on Streamflow 258
  Water Balance Component 259
  Water Productivity 260

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Mitigating Climate Change Impacts for Optimizing Water Productivity 264
Research Findings on Decision-Making for Water Management 265
Improving the System and Institution Design for Water Management 269
Reforming Management to Actualize the Optimal Water Allocation 272
Summary 275
References 277

Abstract

In ecologically fragile areas with arid climate, such as the Heihe River Basin in Northwest China, sustainable social and economic development depends largely on the availability and sustainable uses of water resource. However, under the influence of the rapidly changing climate and human activities, the Heihe River Basin undergoes serious water shortage and water productivity decline. In this chapter we adopted a semi-distributed conceptual hydrological model (SWAT – Soil Water Assessment Tool) coupled with a glacier melting algorithm to investigate the sensitivity of streamflow to climatic and glacial changes in the upstream of the Heihe River Basin. The glacier mass balance was calculated at daily time-step using a distributed temperature-index melting and accumulation algorithm embedded in the SWAT model. Specifically, the model was calibrated and validated using daily streamflow data measured at Yingluoxia Hydrological Station and decadal ice volume changes derived from survey maps and remote sensing images between 1960 and 2010. This study highlights the effects of glacier melting on streamflow and their future changes in the mountainous watersheds. Further, we used improved CGE model to analyze the difference and change between different industries in middle stream of the Heihe River Basin. Simulation results indicate that industrial transformation and development of water-saving industries will also improve water productivity. Lastly, we put forward some strategies on how to mitigate climate change impacts for optimizing water productivity from three perspectives: (1) scientific research needed by scientists, (2) management and institution formulation needed by governments, and (3) water resource optimal allocation by the manager at all administrative levels.

Keywords

Water productivity · Climate change · Water yield · Sustainable development · Streamflow simulation · Water balance · Glacier melting · Snowmelt · SWAT · CGE model · Heihe River Basin

Introduction

Climate Change in Heihe River Basin

Water resource is the foremost element for production, living, and ecosystem (Fang et al. 2007); however, the rapidly changing climate coupled with population growth has aggravated water shortage at a global scale. The percentage of the world population that suffered from water shortage increased from 2% in the early 1900s to 35% in 2005 (Kummu et al. 2010). China, one of the countries in the world with the most serious water shortage, has only 2185 m^3 per capita, which is below the average level of the world (Martin-Carrasco et al. 2013). Therefore, water resource is becoming a restricted production factor of sustainable development (Yu et al. 2008). In particular, Water resource is vital connection between the economy and ecosystem for arid and semiarid areas (Rijsberman 2006). The North and Northwest China have less than 20% of available water although the total area of these places account for almost half of the whole China (Zhou et al. 2012). Therefore, the problem of water shortage is getting more and more attention worldwide (Bakker 2012). There are lots of elements affecting the water resource, and climate change, one of the main factors, has begun to have a serious effect on water availability, which will be to greater extent in the future (Bates et al. 2008; Vörösmarty et al. 2000). During the research about stress of water demand growth in agriculture, industry and urbanization, the Intergovernmental Panel on Climate Change (IPCC) (Change 2007) found that the sensitivity of semiarid and arid regions to climate change is relatively high. Hence, researchers increasingly pay close attention to the effect of climate change on water issues, including surface water and groundwater (Kim et al. 2013). It is a common sense that human activity will cause climate change and then affect water resource. The amount of usage of municipal water has increased from 200×10^8 m^3 to 4400×10^8 m^3 during the last century (Bao and Fang 2007). Climate change will increasingly be more uncertain with population increase and the intensified human activities, and consequently more serious water issues.

Heihe River Basin (HRB), the second largest inland river in China, which is located in arid region of Northwest China, has characteristics of higher rate of evaporation and smaller amount of precipitation as with other arid areas (Fig. 1). Due to the comparatively simple natural process and socioeconomic activities, HRB is an ideal experimental region, and many research works about water management, policies, environmental protection, and ecosystem service have been carried out (Cheng et al. 2014; Guo et al. 2009; Qi and Luo 2005). The typical trait of HRB is that the source of water is from the snow melt in the upper stream, major water usage and consumption of socioeconomic activities are concentrated on middle stream, and in the end the water flows into downstream for ecosystem service. Unfortunately, the irrational usage of water caused serious environmental deterioration and ecological degeneration since the 1950s (Cheng et al. 2014). However, limited water resource is not able to meet the demand of rapid increase for agricultural irrigation and manufacturing production, such as the expansion of irrigated area and the development of manufacture. As a result, large amount of water consumption in middle stream caused water shortage and severe decrease of groundwater level in the downstream in HRB (Cheng et al. 2014; Xi et al. 2010). A number of studies analyzed the hydrological process and the water problems of the HRB (Cheng et al. 2014; Ding et al. 2009; Xi et al. 2010). These research works have put forward some approaches and schemes for water management. However, some knowledge gaps on the spatial variability of water and water efficiency in the HRB ought to be stressed.

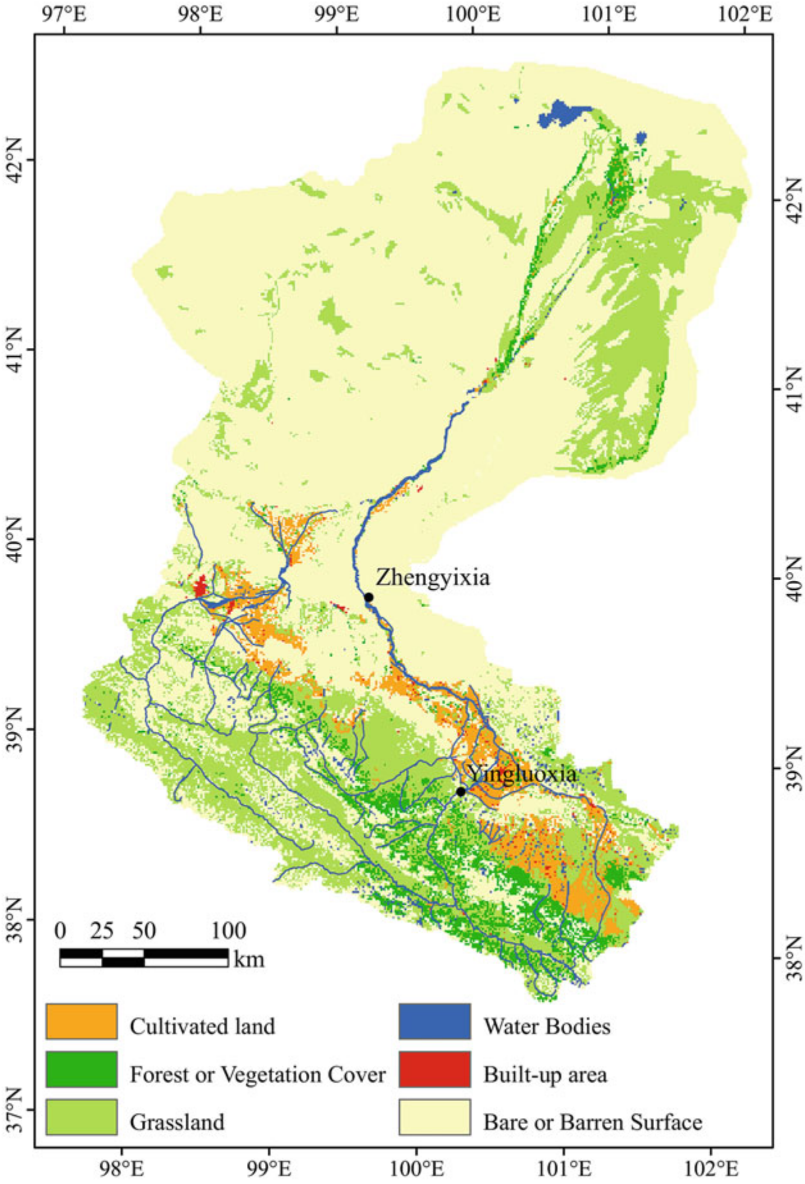

Fig. 1 Location of the Heihe River Basin

Water Productivity in Heihe River

With more and more water issues, the value of water is drawing more and more close attention, and water is changing from public goods to decisive production factor. Water productivity, the output per cubic meter water, is a proper measurement for water value. The output can be physical output, and also economic value of output. Climate change will cause water resource change, and then change water productivity. Therefore, migrating climate change impacts for optimizing water productivity is critical problem in HRB, and is necessary for water resource management.

The most direct influence on water in HRB is the streamflow variation due to climate change. Climate change will affect hydrological processes seriously; however, the degree of influence is still uncertain (Immerzeel et al. 2014). Meanwhile, snow and glacier melting, primary water resource in HRB, contributes about 30–50% of water discharge in arid areas (Viviroli and Weingartner 2004; Yin et al. 2014). It is necessary to analyze the response of glacier variation to climate change and estimate and predict streamflow variation due to glacier variation. Generally speaking, water resources will decrease because of climate change in glacier-fed region and will influence socioeconomic development throughout the entire basin (Hagg et al. 2007; Luo et al. 2013). The most common method for estimating the influence of climate change on water resource is large-scale simulation of hydrology (Fontaine et al. 2002). The ideal simulation is the long-term impacts of glacier melting, and usually the greatest challenge is complex hydrological process and low quality climate data in many of the river basins (Hock 2003; Howells et al. 2013).

Streamflow trait will be altered by climate change substantially, and even worse melting or complete wastage of glacier will be caused by climate change during next decades (Thorsteinsson et al. 2013). From the perspective of precipitation which will influence the amount of runoff and especially the largest accumulation of snow, changes will usually happen between the late winter and the early melting season, but from the view of temperature, alteration mainly affect runoff time. It is an effective way to analyze the contribution of climate change to the variation of runoff using model simulation (Luo et al. 2013).

Methodology and Data

SWAT Model

The Soil and Water Assessment Tool (SWAT) simulation model has been widely applied in some watersheds where streamflow concentrated on rainfall events (Castillo et al. 2014; Zheng et al. 2012). Some scholars are trying to improve the snow melting algorithm for streamflow simulation related to the effect of climate change (Zheng et al. 2012). Nevertheless, long-term impact on glacier and snow melting about hydrological process is still underexplored. Therefore, reliable model on glacier melting in SWAT still require accurate parameterization. SWAT, a semi-distributed hydrological model using geography data, is good at dealing with hydrological process at watershed scale. Besides the elementary unit of SWAT is Hydrological Response Units (HRUs) which are the sub-watershed linked with river network subdivided by entire watershed. Every HRUis on behalf of a combination of land use, slope and soil, and hypothesis on HRUs is nonspatially distributed without dependency or interaction. SWAT has been applied to deal with so many water issues relating to quality and quantity (Pradhanang et al. 2011). The core components of model are hydrology, soil temperature and properties, land management, pesticide, plant nutrients and growth, bacteria and weather. The variables about meteorology in SWAT include relative humidity in daily or sub-daily time steps, wind speed, precipitation, temperature, and solar radiation. In addition to these, hydrological routine in SWAT also contains evapotranspiration, discharge and snow melting. In the research, hydrological process connected with glacier melting at watersheds, and then runoff from snow melting feed water resource in the spring, Thus the SWAT model added a glacier melting and a snowmelt process module using some equations to describe the relationship between temperature and glacier melting in this study.

1. Simulation of glacier mass balance

Ice volume is the first priority in the long-term simulation of streamflow in glacier-fed watersheds. There are several steps we followed to calculate glacier runoff. Firstly, typical mass balance gradients for alpine glaciers are assumed to be -0.009a^{-1} for the ablation and -0.005a^{-1} for the accumulation area (Huss et al. 2008a), thereafter, we used Digital Elevation Model (DEM) to acquire mass balance distribution. We also set the area-averaged mass balance of the glacier surface to zero. Secondly, we define a balance ice flux as the total amount of the ice volume gain and loss during a year at intervals of 300 m. Thirdly, an ice flow law in an integrated form (Glen 1955) was solved for the ice thickness h on the central flow-line.

$$h = \sqrt[5]{\frac{q}{\frac{2}{5}hA\left(S_f \rho g \sin \bar{a}\right)}} \tag{1}$$

Where q (m^2/s) is ice flux normalized with glacier width; g is the acceleration of gravity; A is the rate factor of the ice flow law (Glen 1955); S_f is used to account for the valley shape (Nye 1965); ρ is the ice density; and $\bar{a}$ is the slope of the glacier surface. A is calibrated to optimize agreement with the radio-echo sounding profiles. We assumed $A = 6 \times 10^{-15}\ \text{s}^{-1}\ \text{kPa}^{-3}$ which is consistent with a previous study (Huss et al. 2008b). $S_f = 0.6$ is cited from a literature (Nye 1965), and $\overline{a}$ is equal to the mean slope along the flow-line. Finally, the spatially distributed values of h were connected by accounting for the local surface slope at every grid cell and by assuming $h \sim (\sin\ \overline{a})^{3/5}$. This proportionality presents the redistribution of ice along the cross-flow section. The selected proportionality factor guarantees that the previous total ice volume is unchanged. Surface melt rate M_{gla} is computed as follows:

$$M_{\text{gla}} = \begin{cases} \left(F_M + r_{\text{ice/snow}} I\right) T_B : T_B > 0^{\circ} C \\ 0 \qquad\qquad\qquad\quad : T_B \leq 0^{\circ} C \end{cases} \tag{2}$$

where F_M is a melt factor; $r_{\text{ice/snow}}$ is radiation factor between ice and snow; I is the clear-sky direct radiation; and T_B is the band-averaged temperature (°C). The site-specific parameters F_M and $r_{\text{ice/snow}}$ are further calibrated by direct observations.

$$\frac{dh}{dt} = -(1-f)M_{gla} - S + F \tag{3}$$

where f is ratio for melt water refreezing; M_{gla} is melt rate of glacier in given day (mm H_2O); S is sublimation rate of glacier in given day (mm H_2O); F is glacier accumulation rate in given day (mm H_2O), and t is the time step in day. Therefore, the depth of water equivalent of glacier mass is expressed as:

$$V_{gla} = \frac{h \times A_{gla}}{\rho_i} \tag{4}$$

where ρ_i is the bulk density of ice, usually, 0.9 kg m^{-3}. To capture the seasonal and gradual pattern of the accumulation, we develop an algorithm to account for the accumulation of glacier mass. Turnover of snow to ice is assumed as a ration of water equivalent of snow over ice given as below:

$$F = \beta \times SNO_i \tag{5}$$

where SNO is the water content of snowpack over ice on day i (mm H_2O); β is an accumulation coefficient which is assumed to be changing seasonally and given as follows (Luo et al. 2013):

$$\beta = \beta_0 \left\{ 1 + \sin\left[\frac{2\pi}{365}(t-81) \right] \right\} \tag{6}$$

where β_0 is a basal accumulation coefficient.

2. Snowmelt routing algorithm

As above mentioned, snowfall appears usually as the form of snowpack or snow cover in ground storage. We set a threshold of snow-melt temperature to calculate snow accumulation. If mean air temperature in a day is below this threshold, the form of precipitation is regarded as snow within an HRU, on the other hand, the precipitation will be treated as rainfall. When snowfall happens, the equivalent water will be added to the snowpack. In the model, the snowpack is intensified as snowfall proceeds, and is weakened as the snow melts. The mass balance of snowpack is computed as follows (Neitsch et al. 2005):

$$SNO_i = SNO_{i-1} + R_{\text{day}} - E_{\text{sub}} - SNO_{\text{mlt}} - SNO_{\text{gla}} \tag{7}$$

where SNO_i is the water content of snowpack on day i (mm H_2O); SNO_{i-1} is that on day $i-1$ (mm H_2O); R_{day} is the precipitation amount on a given day (added only if the average daily temperature T_{ave} is $<T_{s-r}$) (mm H_2O); and E_{sub} is the amount of sublimation on a given day (mm H_2O). SNO_{mlt} is the amount of snowmelt on a given day (mm H_2O), and SNO_{gla} is the amount of glacier converted from snow on a given day (mm H_2O). Further information on the equations used in SWAT to calculate snow sublimation has been described in the SWAT Theoretical Documentation (Neitsch et al. 2005).

3. Snowpack temperature

Because of spatial heterogeneity and various factors, snowpack distribution cannot be uniform throughout the entire given area. The situation is that some areas are free of snow; however, some other areas are covered by thick snow. When the simulation of streamflow is carried out, in order to calculate snowmelt accurately, these regions will be handled specially. In this study, a depletion curve expresses the seasonal growth and decay of snowpack as a function of the amount of present snow in the basin. This curve is based on natural logarithm (Neitsch et al. 2005). The snowpack temperature on the current day is calculated as follows:

$$T_{\mathrm{snow}}(i) = T_{\mathrm{snow}}(i-1) \times (1 - l_{\mathrm{snow}}) + \overline{Tav} \times l_{\mathrm{snow}} \tag{8}$$

where $T_{\mathrm{snow}}i$) is the snowpack temperature on a given day (°C); $T_{\mathrm{snow}}(i-1)$ is that on the previous day (°C); l_{snow} is the snow temperature lag factor; and $\overline{Tav}$ is the mean air temperature on the current day (°C). As l_{snow} approaches 1.0, the mean air temperature on the current day will increasingly influence the snowpack temperature when the snowpack temperature from the previous day exerts increasingly less influence.

4. Snowmelt process

The common method for researching snowmelt process is to use temperature index with elevation band approach (Hock 2003). There are many factors affecting snowmelt, such as melting rate, temperatures of snowpack and atmosphere, and area coverage of snow. Melted snow is calculated as the form of runoff and percolation in SWAT model. The rainfall energy produced by the fraction of snowmelt is regarded as 0 while calculating snowmelt, which is assumed that the rate of melt is uniform for 24 h in a day.

Two other r major variables related to spatial meteorological parameters, including snow volume and temperature. One of the advantages of SWAT is that it is able to a watershed into a maximum of ten elevation bands, and then simulate snow cover or snowmelt at each elevation band (Fontaine et al. 2002). The temperature and precipitation at each band were adjusted accordingly:

$$\begin{aligned} T_B &= T + (Z_B - Z) \times \mathrm{d}T/\mathrm{d}Z \\ P_B &= P + (Z_B - Z) \times \mathrm{d}P/\mathrm{d}Z \end{aligned} \tag{9}$$

where T_B is the band-averaged temperature (°C); T, Z, and P are temperature (°C), elevation (m), and precipitation (mm), respectively, which are measured at the weather stations; Z_B is the midpoint of band elevation (m); $\mathrm{d}T/\mathrm{d}Z$ is the temperature lapse rate (°C/m); P_B is the band-averaged precipitation (mm), and $\mathrm{d}P/\mathrm{d}Z$ is the precipitation lapse rate (mm/m). Ten elevation bands were set up for the snow-glacier-dominated watershed with vertically equal distance from the mean elevation of the centroid of the sub-watershed. $\mathrm{d}P/\mathrm{d}Z$ and $\mathrm{d}T/\mathrm{d}Z$ were set to be 0.5 (mm/km) and −0.5 (°C/km) following local lapse rate calculation. Therefore, the snowpack temperature (T_{snow}) and mean daily temperatures were used along with a melt coefficient to calculate the potential volume of melt water. We coupled the glacier melting algorithm to snowmelt process as:

$$M = \alpha((T_{\mathrm{SNOW}} + T_B)/2 - T_m) + M_{\mathrm{gla}} \tag{10}$$

where T_m is the snowmelt base temperature, which is the mean air temperature at which snowmelt occurred. The appropriate melt coefficient approximately ranged between 2 and 6 mm/deg. The snowmelt coefficient was calculated as:

$$\alpha = (\alpha_{\max} + \alpha_{\min})/2 + \sin([(\text{day of year})\pi/366])((\alpha_{\max} - \alpha_{\min}))/2 \tag{11}$$

where $\alpha_{\max}$ is the maximum snowmelt rate during a year. $A_{\min}$ is the minimum snowmelt rate during a year.

5. Model performance evaluation

Following a standard hydrological model performance criterion, we used E_{ns} and R^2 as model evaluation indices in this study. Model performance was high when $E_{ns} > 0.5$ and $R^2 > 0.8$. Here, E_{ns} is the relationship strength between observed value $Q_{o,i}$ and simulated value $Q_{m,i}$ at time t. E_{ns} lies between $-\infty$ and +1, which indicates that the model performance is higher when the E_{ns} is closer to +1. The square of Pearson's product moment correlation, R^2, presents the proportions of total variance of measured data that can be explained by simulated data, which indicates that the model performance is higher when R^2 is closer to 1.

$$E_{ns} = 1 - \frac{\sum\limits_{i=1}^{n} \left(Q_{o,i} - Q_{m,i}\right)^2}{\sum\limits_{i=1}^{n} \left(Q_{o,i} - \overline{Q}_o\right)^2} \tag{12}$$

$$R^2 = \frac{\left[\sum\limits_{i=1}^{n} \left(Q_{o,i} - \overline{Q}_o\right)\left(Q_{m,i} - \overline{Q}_m\right)\right]^2}{\sum\limits_{i=1}^{n} \left(Q_{o,i} - \overline{Q}_o\right)^2 \sum\limits_{i=1}^{n} \left(Q_{m,i} - \overline{Q}_m\right)^2} \tag{13}$$

where E_{ns} is the Nash–Sutcliffe coefficient; $Q_{o,i}$ is the observed runoff in i years; $Q_{m,i}$ is the simulated runoff in i years; and n is the length of the time series. E_{ns} and R^2 closer to 1 indicate that the model predicts more accurately.

CGE Model

Computable General Equilibrium (CGE) model, is an ideal form of expression for simplified economic system, and there are three assumptions for general CGE model. First, zero profit condition, which means that total revenue equals to total cost, because the original hypothesis is constant return to scale and perfect competition, and all revenues of all enterprises are used to purchase intermediate input or production factors. Second, market clearing condition, gross value of output of enterprises equals to intermediate gross purchasing value, which means that supply equals to demand at each market, including factor market. Third, making both ends need, in order to make maximum profits, household income from rent of production factors all purchase commodities in the market. We can easily infer three major characteristics through the name of CGE model, the first one is computable, CGE model is not theoretical economic model, instead, it is a computable model based input output table or social accounting matrix to describe the subject behavior within economic system. Thus the most important part is to make accurate data, which is closely related to the quality of simulation. The second is general, the whole economic system is as an entirety and uses the view of universal relation to study interaction of all market, rather than chooses a sole market as the study object.

Ordinary CGE model includes several basic modules as follows; of course, we can add some modules based on the need of our study. The first and the most import module is production process; production functions are the basic model to describe the behavior of enterprises, and are the core of neoclassic economy. In addition, production functions describe the pattern of combination of input of production factors and the transformation process from resource and input to commodities and services. The second is income distribution modules, the distribution in the module includes transfer payment between income of factors and household, between government and foreign remittance, besides the module also consists of intermediate sectors which distribute operating surplus. The third is final demand module; it contains household demand, government expenditure, personal and public investment, inventory and export. The fourth is trade module, which includes import demand, export supply, and export demand. The fifth is commodity market, in the model, import and export meet the assumption of “small country,” which means that export and import will be satisfied and the price will not be affected, and export demand assumes is infinite. The sixth is factor market equilibrium, the supply and demand of factor must be equal. The seventh is macro closure, we need to set exogenous variables to make the number of variables equal to the number of equations, which can get the unique solve.

In the research we improved the ORANI-G, a single-country CGE model, through adding the water as the production factor into the model (Fig. 2).

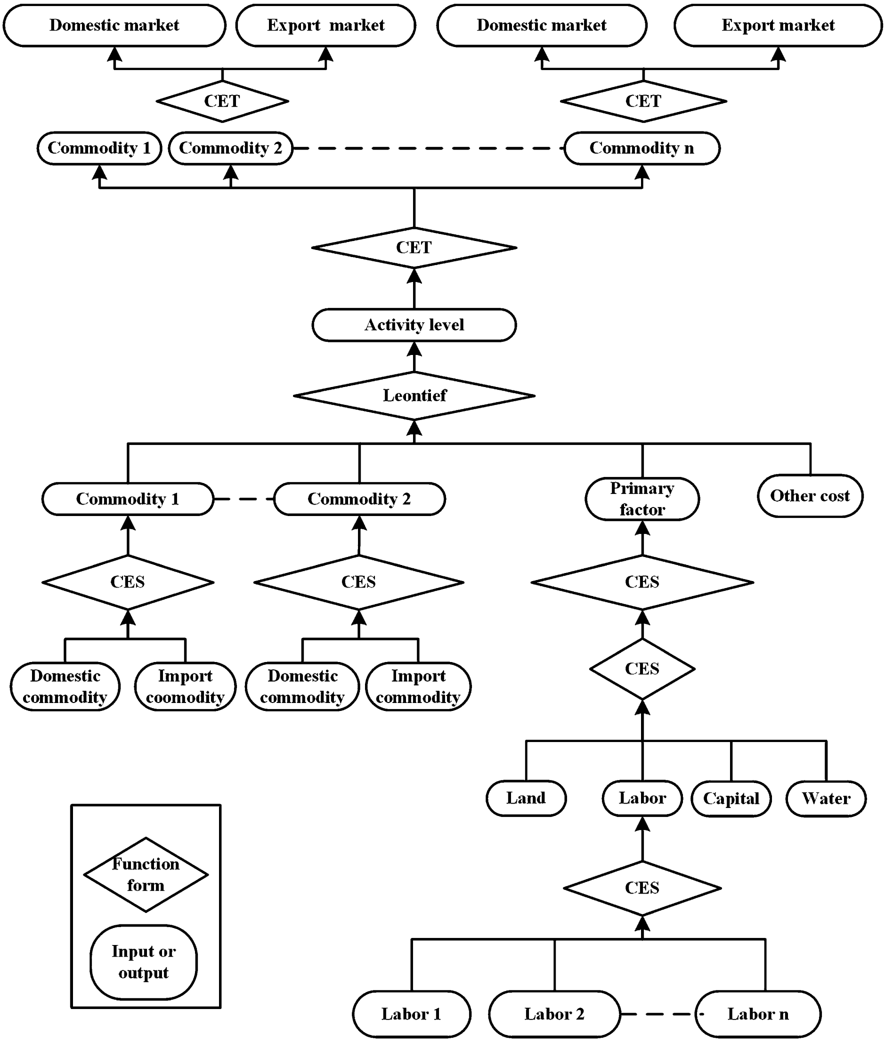

Fig. 2 A nested CES production function in the ORANI-G model (Reprinted from Zhan et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

$$LND_i = slnd_i \cdot \left[\frac{POPRM_i}{PLND_i}\right]^{\sigma oprm_i} \tag{14}$$

$$LAB_i = slab_i \cdot \left[\frac{POPRM_i}{PLAB_i}\right]^{\sigma oprm_i} \tag{15}$$

$$CAP_i = scap_i \cdot \left[\frac{POPRM_i}{PCAP_i}\right]^{\sigma oprm_i} \tag{16}$$

$$\begin{aligned} &POPRM_i \\ &= \left[slnd_i \cdot PLND_i^{1-\sigma oprm_i} + slab_i \cdot PLAB_i^{1-\sigma oprm_i} + scap_i \cdot PCAP^{1-\sigma oprm_i}\right]^{\frac{1}{1-\sigma oprm_i}} \end{aligned} \tag{17}$$

$$WTR_i = swtr_i \cdot \left[\frac{PPRIM_i}{PWTR_i}\right]^{\sigma prim_i} \tag{18}$$

$$OPRM_i = soprm_i \cdot \left[\frac{PPRIM_i}{POPRM_i}\right]^{\sigma prim_i} \tag{19}$$

$$PPRIM_i = \left[swtr_i \cdot PWTR_i^{1-\sigma prim_i} + soprm_i \cdot POPRM_i^{1-\sigma prim_i}\right]^{\frac{1}{1-\sigma prim_i}} \tag{20}$$

where LND_i is land input in the *i*th commodity; LAB_i is labor input in the *i*th commodity; CAP_i is capital input in the *i*th commodity; WTR_i is water input in the *i*th commodity; $PWTR_i$ is water price; $PLND_i$ is land price; $PLAB_i$ is labor price; $PCAP_i$ is capital price; $LABO_o,i$ is *j* type of labor input in the *i*th commodity; $PLABO_o,i$ is *j* type of labor price in the *i*th commodity; $slnd_i$ is the share of land input in the *i*th commodity; $slab_i$ is the share of labor input in the *i*th commodity; $scap_i$ is the share of capital input in the *i*th commodity; $soprm_i$ is the share of intermediate input; $\sigma prim_i$ is CES of land–labor–capital; and $\sigma oprm_i$ is CES of water-CES (water–land–capital).

Scenarios

Simulation with multiple scenarios was carried out to analyze the impacts of water supply change on GDP and calculate the water productivity. We set four scenarios that changing rate of water supply in all sectors, agricultural sector, industrial sector, and urban construction, under which the change rate of water supply was set to be -10%, -5%, -4%, -3%, -2%, -1%, 1%, 2%, 3%, 4%, 5%, and 10% respectively. The scenario without change in the water supply was used as the baseline scenario, and the results under other scenarios were compared with the result under the baseline scenario. In order to analyze the influence of water supply decrease on the economic development in Gansu Province, this study simulated the change rate of the output of various goods when the water supply decreases by 1%, according to which the response of the output of different sectors to the water supply change was analyzed.

Results of Climate Change on Water Productivity

The process of hydrology in the upper stream will affect water use of entire basin, so the more accurate in upper stream, the better for the water management of entire basin. Calibration and validation, the guarantee for the simulation, employed daily data of observation in 2009 and 2010 from Yingluoxia Hydrological Station which is the demarcation point between upper stream and middle stream. E_{ns} and R^2, standing for the accurateness of model, are very good in this paper (the values of E_{ns} are 0.88 and 0.87 separately in 2009 and 2010; the values of R^2 are 0.87 and 0.89 in 2009 and 2010, respectively). Further, comparing the simulation results with observed data from Yingluoxia Hydrological Station, we failed to reject the significance of parameters of the SWAT model, and hence, the model is appropriate for simulation in the upper stream. We identified and listed the most sensitive parameters. The temperature lapses rate (TLAPS) is the most sensitive parameter since it is directly related to the melting process of snow and glacier. Snow melting occurs mostly from March to June in a sub-watershed. The snow melting factor on June 21st was parameterized to be SMFMX, which is the maximum melt rate; any increase of SMFMX drives snow melting. The snow temperature lag factor TIMP is also linked with SMFMX because it is based on the previous situation. Along with TIMP surface water lag time, SURLAG plays an important role in the model performance as a melted snow routing process is related to the geology of the watershed, where the melted water mainly flows to the surface runoff covering the impervious rock formations. SMTMP is sensitive since it indicates the starting and ending of melting and considers the availability of snow melting on a specific day, and the model-simulated streamflow, especially the peak values, is significantly influenced by the variation of SMTMP. Both calibration of the model the validation of the simulation results show that the model performed well in simulating the runoff variation due to glacier melting and climate change in upstream Heihe River Basin.

Changes of Glaciers

Changes of temperature and precipitation were both different seasonally in mountains from 1960 to 2010. The result found that annual precipitation gradually increased, though precipitation decreased in autumn and spring, and increased in summer and winter. On the other hand, annual average temperature increased slowly, while temperature increased mostly in winter and slightly in autumn, but it is relatively constant in summer and decreased a little in spring. The annual growth rate of precipitation is 1.2%, and at the speed of 14.84 mm per decade in summer, nevertheless, the rate is much lower in winter. Although there was obvious variation between seasons of temperature and precipitation in Qilian Mountains in past 50 years, the trend of two critical variables increased as a whole.

The change in temperature and precipitation would cause glacier changes inevitably, whose accumulation will be affected by these two variables seriously. The precipitation would increase with elevation below 4700 through the observation data in study area. Such as, the annual precipitation increases by 16.9 mm/100 m and the precipitation increases by 10.9 mm/100 m in summer along with elevation (Fig. 3). Nonetheless, once the elevation surpassed the 4700 m, the precipitation would decrease, so precipitation increase ought to attribute to the

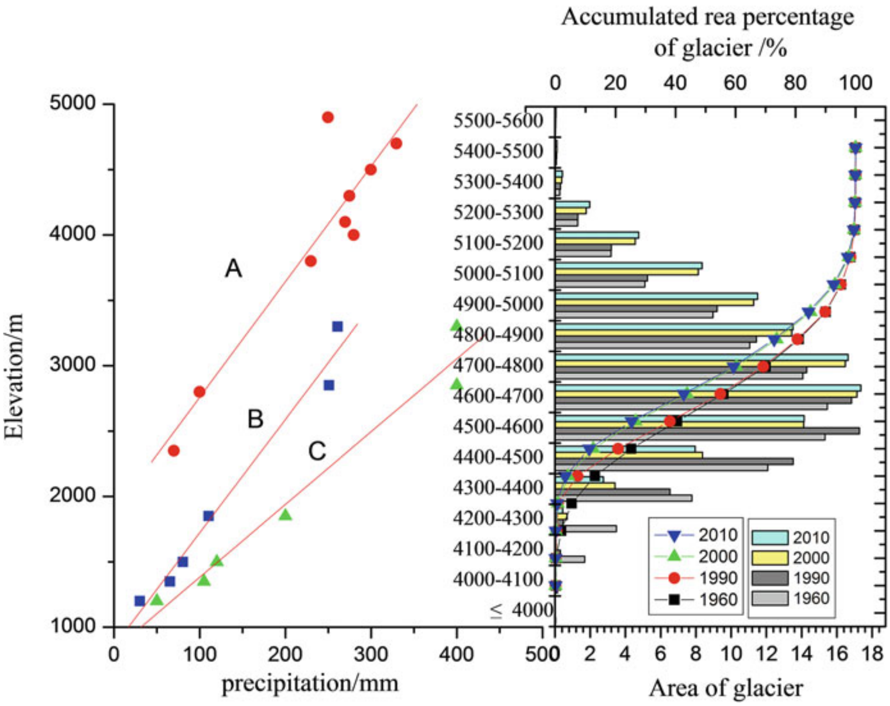

Fig. 3 The distribution of glaciers by precipitation at different elevations (Reprinted from Wu et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

glacier accumulation. In fact, temperature increase would cause rainfall rather than snowfall, which brings about shrinkage of glaciers, increases snowmelt, and upsets water balance. The situation is worse in winter due to glacier accumulation would not compensate the loss in summer. Thus the glacier is speeding up melt.

The Effect of Glacier on Streamflow

Watersheds in mountain have the majority of geographical features, which includes frozen soils, accumulative snows and mountain glaciers. These are particular sensitive to the climate change. Precipitation is the most crucial factor influencing streamflow based on the models about streamflow response to climate change in HRB. Comparing the results of the SWAT model and the SWAT model coupled with the glacier melting algorithm, we found that the glacier contributed 8.9% to streamflow in 2010. In particular, the highest rate of streamflow increase is 2.7×10^7 m^3 in spring, which equals to 0.96% of total streamflow per year. The significant increase of streamflow in spring was likely connected with increasing glacier melting (Fig. 4). In general, the streamflow increased along with precipitation

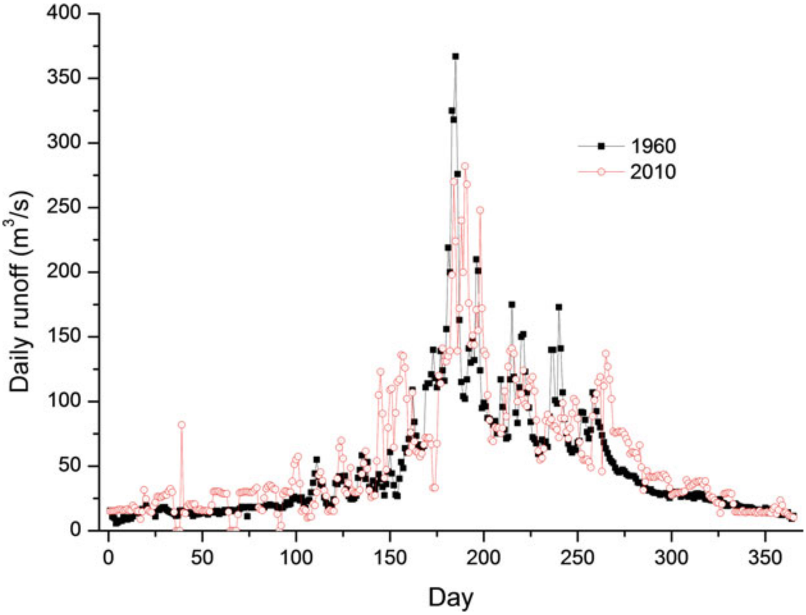

Fig. 4 Comparison of the simulated daily runoff between SWAT and SWAT coupled a glacier melting algorithm in 2010 (Reprinted from Wu et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

growth and decreased with rise of temperature. Nonetheless, stable precipitation attributed to the 1.6% increase of streamflow because snowmelt and glacier melting increased by 1 °C, and the same percentage will decrease if the temperature decreases by 1 °C. The runoff depth would increase by 12.3 mm if the temperature is kept stable and precipitation is increased by 10% when ignoring the effects of glacier melting on streamflow. Besides, runoff depth would decrease by 2.32 mm if the temperature increased by 3°C and the precipitation stayed stable (Fig. 5). Thus, the increasing temperature in spring and summer contributed to streamflow positively because the growth of glacier melting, snowmelt, and annual precipitation. With the gradual increase of precipitation and temperature, the streamflow in HRB is increasing marginally after a counterbalance of evapotranspiration and infiltration loss (Fig. 6).

Water Balance Component

Water balance about spatial distribution in SWAT model contains glacier melting, rainfall and streamflow from sub-watersheds. Simulated water-yield by SWAT model includes three parts, lateral flow, surface runoff and shallow groundwater runoff. Lateral flow attributed to most of mountainous runoff, about 54.5%. Streamflow is more intensive and more glaciers in the east than that in the west of

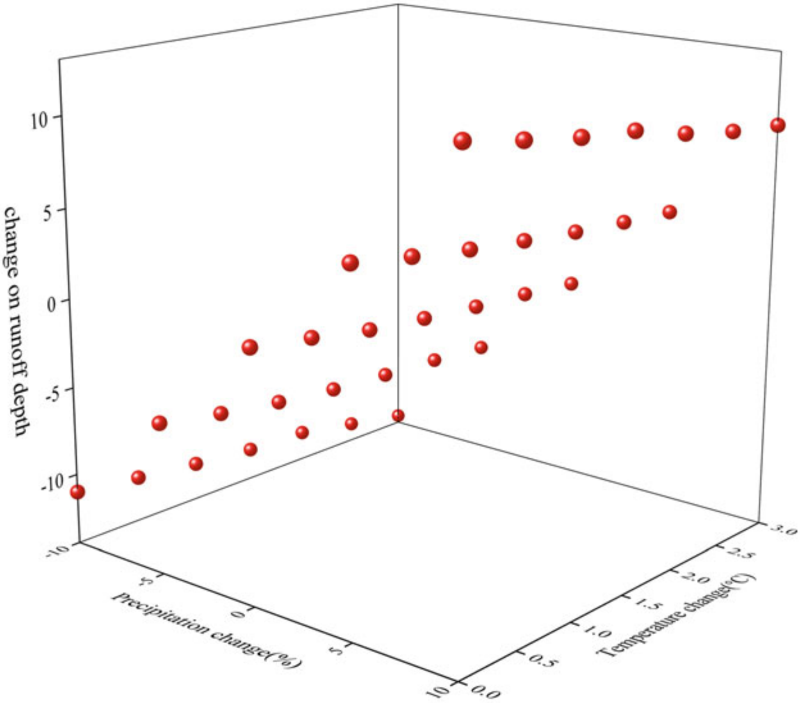

Fig. 5 Simulated relevant changes on the runoff depth with regard to climate changes (mm)

HRB. The simulated result about water balance in 2010 is shown in Fig. 5, and the range of precipitation in sub-watersheds in upper stream is from 240 to 760 mm, however, the potential evapotranspiration which is higher in east than west, was about two times than that of precipitation, and on the other hand, the actual evapotranspiration is a little lower than the precipitation, from 150 to 300 mm. Besides, simulated results of glacier melting were still higher in east than the west and demonstrated that the range of precipitation was from 200 to 500 mm. Eliminating the evapotranspiration, infiltration and tributary streamflow, and the increase of streamflow, from 0.5 to 4 mm, is attributed to glacier melting.

Water Productivity

The climate change affected water balance in upper stream in HRB seriously, which will influence water use in entire basin. The major socioeconomic activities concentrated on the middle stream, water productivity is an appropriate indicator to measure the value of water, and therefore it is important to analyze water productivity in middle stream in HRB (Table 1).

From the result of the improved ORANI-G model and the definition of water productivity, the average water productivity for all industries is 0.47 USD/m^3.

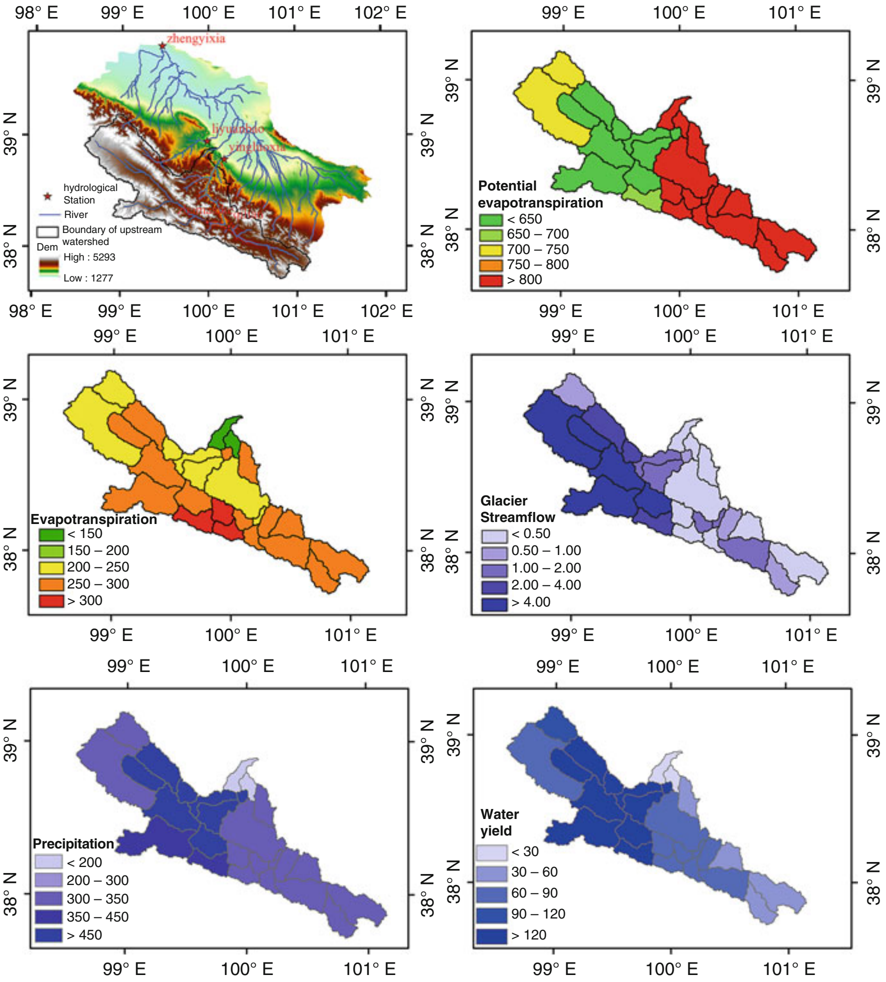

Fig. 6 Distribution of water balance component in the upstream Heihe River Basin in 2010 (Reprinted from Wu et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

Based on the Tables 2, 3, and 4, we found that values of water productivity are different from industries, and are 0.16, 2.23, 4.21 USD/m^3 for agricultural sectors, manufacture sectors, and service sectors, respectively. Comparing with the marketed prices of water in agricultural sectors, manufacture sectors, and service sectors, which are 0.013 USD/m^3, 0.33 USD/m^3, and 0.4 USD/m^3, water productivity is higher than market price. Particularly, underestimated water price indicated severer water scarcity than real expression in economic system. In other words, water productivity can be improved through optimizing water allocation etc. Water productivity in agriculture is 0.16 USD/m^3, which is approximate

Table 1 Water productivity in Gansu (Unit: %)

Water supply change	Water input changes	GDP changes	Water productivity in GDP
−10	−11.374	−5.293	0.465
−5	−5.687	−2.646	0.465
−4	−4.55	−2.117	0.465
−3	−3.412	−1.588	0.465
−2	−2.275	−1.059	0.465
−1	−1.137	−0.529	0.465
0	0	0.000	0.465
1	1.137	0.529	0.465
2	2.275	1.059	0.465
3	3.412	1.588	0.465
4	4.55	2.117	0.465
5	5.687	2.646	0.465
10	11.374	5.293	0.465

Table 2 Water productivity of agriculture industry in Gansu (Unit: %)

Water supply change	Water input change	Agricultural production change	Water productivity in agricultural production
−10	−9.312	−1.508	0.162
−5	−4.656	−0.754	0.162
−4	−3.725	−0.603	0.162
−3	−2.794	−0.452	0.162
−2	−1.862	−0.302	0.162
−1	−0.931	−0.151	0.162
0	0	0.000	0.162
1	0.9312	0.151	0.162
2	1.8624	0.302	0.162
3	2.7937	0.452	0.162
4	3.7249	0.603	0.162
5	4.6561	0.754	0.162
10	9.3122	1.508	0.162

to the value simulated by Wang (Wang et al. 2008) that is 0.11 USD/m^3, and water productivity is much lower in agriculture than that of manufacture and service sectors. Therefore, industrial transformation will improve water productivity.

The inputs including labor, capital, water, and land would cause change of economic production directly or indirectly, and these changes will be simulated by improved ORANI-G model we adopted while water use changes. When the CES elasticity between water and other input factors is 0.05, and water use decreases by 1%, the change of economic production in model will vary in different sectors (Table 5). From the perspective of percentage change in different sectors, the most obvious change was in agriculture, which decreased by 0.381%; however the least

Table 3 Water productivity of industrial industry in Gansu (Unit: %)

Water supply change	Water input change	Industrial production change	Water productivity in industrial production
−10	−0.723	−1.605	2.219
−5	−0.361	−0.802	2.223
−4	−0.289	−0.642	2.221
−3	−0.217	−0.481	2.219
−2	−0.145	−0.321	2.213
−1	−0.072	−0.160	2.229
0	0	0.000	2.221
1	0.072	0.160	2.229
2	0.145	0.321	2.213
3	0.217	0.481	2.219
4	0.289	0.642	2.221
5	0.361	0.802	2.223
10	0.723	1.605	2.219

Table 4 Water productivity of urban construction in Gansu (Unit: %)

Water supply change	Water input change	Urban construction change	Water productivity in urban construction
−10	−0.107	−0.454	4.200
−5	−0.054	−0.227	4.200
−4	−0.043	−0.181	4.201
−3	−0.032	−0.136	4.202
−2	−0.021	−0.091	4.198
−1	−0.011	−0.045	4.198
0	0	0.000	4.200
1	0.0107	0.045	4.198
2	0.0215	0.091	4.198
3	0.0322	0.136	4.202
4	0.0429	0.181	4.201
5	0.0537	0.227	4.200
10	0.1073	0.454	4.200

obvious change was in education, which decreased by only 0.019%. Because most water was used for agricultural production, improving water productivity in agriculture will mitigate water scarcity in arid region. In comparison with change in economic production driven by water, service sectors are less sensitive; however, values of water productivity in service sectors are the highest. Therefore, as mentioned above, the water from agriculture production to service sectors would improve water productivity. Water productivity is a crucial indicator for measuring economic value of water, and industrial transformation will optimize water productivity. However, climate change will have an impact on the change, and there are a lot of adaptation measures mitigating climate change impacts for optimizing water productivity.

Table 5 Sectoral economic production changes by water input decrease 1% under CES of water to other factors at 0.05 in Gansu

Sectors	Economic output change (%)
Agriculture	−0.381
Forest	−0.295
Livestock	−0.052
OAgriculture	−0.044
CoalExtWash	−0.187
ExtPetGas	−0.095
ExtMetal	−0.166
ExtNmetal	−0.193
ManuPaper	−0.262
ProFuelFood	−0.135
OPSPEqu	−0.263
OManufacture	−0.230
ManuArtwork	−0.169
RecyWaste	−0.277
ProdSuppEPHP	−0.146
ProdSuppGas	−0.209
ProdSuppWtr	−0.266
Construction	−0.234
TransWare	−0.041
Post	−0.089
Information	−0.016
WholeRetail	−0.018
HotelCater	−0.025
Finance	−0.074
Estate	−0.010
ServBusin	−0.043
Research	−0.080
ServTech	−0.079
EnvManage	−0.086
WtrManage	−0.071
ServResident	−0.030
Education	−0.015
PubManage	−0.019

Mitigating Climate Change Impacts for Optimizing Water Productivity

Considering the water scarcity character of the HRB, it is important to clarify the coupling relationship between water, ecology, and social economy, reveal the driving mechanism of the socioeconomic system on the evolution of water resource, improve the systems and institution designs for water management, and explore innovative approaches on optimal water allocation.

Research Findings on Decision-Making for Water Management

There are significant differences in ecosystem structure among the upper, middle and lower reaches. Industrial and agricultural water demand in the middle reaches and ecological water consumption in the lower reaches form the mechanism of interaction of water supply and demand with the water producing in the upper reaches. Therefore, research works on the HRB should firstly focus on simulation of hydrologic process of the basin with the help of complex systematic modeling technology (Bracken and Oughton 2009). Granted by the "Major Research Plan on the HRB" initiated by the National Natural Science Foundation of China, Chinese scholars have conducted a series of research works, which are focused on the hydrologic process as well as the impacts of human activities on water resource. These research works basically conceptualized the basic laws of eco-hydrological process in the HRB, and revealed mechanisms on water cycling, ecological system evolution as well as the coupling mechanism between them.

The modeling work on the HRB is highlighted by model integration and mainly based on subregional modeling. There have been a lot of research works on hydrological process, groundwater, water resource, land use, land surface process, ecology, and social economy of the HRB based on a series of related models (Cheng et al. 2014). The model integration on the upper reaches of the HRB takes the distributed hydrological model as the core, and realized the model coupling in a series of issues including the characteristics of runoff from mountainous sub-watershed, the unity of atmosphere–vegetation–soil–permafrost–snow cover. As for the model integration in the middle reaches in the HRB, these research works are focused on coupling troubles among the surface water, groundwater, and the ecological models. For example, there was a study coupling SiB2 (land surface model) with aquifer flow, which significantly enhanced the capability of simulate evapotranspiration and surface–groundwater interaction, and achieved systematic simulation for hydrological cycle in the middle reaches of the HRB. More comprehensively, a genuine farmland eco-hydrological model was established by integrating MODFLOW (Groundwater model), Hydrus-1D (soil water model), WOFOST (crops growth model) models, coupling the land surface process module and stomatal–photosynthesis module. In addition, the model has certain capability of prediction and decision support. For instance, if the model is used to optimize irrigation system, it can save 27.27% irrigation water than the existing irrigation system. These studies have proved that the coupling model can be used to analyze ecological system and the interactions of the hydrological cycle, and guide the water-saving practices on agriculture.

Another important consideration in model integration is modeling environment. It is the visual computer software platform that supports the efficient development of integration model, convenient connection among existing models or modules, module management, data pretreatment and parameter calibration. The application of modeling environment in the integrated research of the HRB has mainly two directions: one is to use the existing international mature model to realize the coupling modeling environment to solve the key problems in integration issue. Considering the defects of existing modeling environment in the flexibility, another direction is to develop a new modeling environment. In this aspect, some Chinese scholars established the new modeling environment to explore the hydrology and land surface process. By using highly efficient and flexible module and data transfer mechanism, this environment has realized the flexible extensibility and reusability of the module. Based on this platform, some case studies of the modeling integration of the HRB have been implemented. For instance, the hydrological model TOPMODEL and the evaporation module from Noah (land surface process model) can be coupled together to make TOPMODEL be more reasonable when considers the effect of vegetation on water balance. In addition, with the help of this modeling environment, the question that “who supplies, how much, how to fill” about water on ecological compensation of the upper reaches of the HRB has been answered.

Generally, studies in HRB meanly focused on the eco-hydrological processes, water use mechanism of the typical plants and their characteristics when response to stress. A series of eco-hydrology process model had been introduced, interpreted, or set up (Li et al. 2009), including the Noah for ecological and hydrological processes, MODFLOW models for groundwater process, SWAT model for distributed hydrological processes, and HYDRUS model and the systematic conceptual model of Goulburn Broken Catchment for atmosphere–hydrology–vegetation interaction. At the upper reaches of the HRB, the integration research on eco-hydrology process revealed the interaction mechanism between ecological system and hydrologic system, enhanced the cognition of mechanism on water resource formation and transformation, and laid the foundation for water resource evolution research under climate change. At the middle and lower reaches, the eco-hydrological integration research clarified the relationship between the transformations of different kinds of water resource, illustrated the interaction and coupling mechanism between the water cycle and vegetation structure, rebuilt the spatial–temporal distribution of water resource in the historic periods and forecasted it in the future.

However, the basin is a complete system for cooperative development and evolution of the human society as well as ecology. The HRB is an ideal case for integration study of “Water-Soil-Gas -Biology-Human” (Cheng et al. 2008, 2014). Human activities have become the main driving force for hydrological circulation, and the social–economic water dimension rather than the natural hydrological dimension has become the driving water circulation, but research works on the former is very weak (Li et al. 2010). Model on either single process cannot comprehensively simulate the characterization of the process, behavior and interaction mechanism of the whole system.

Based on the modeling and integration analysis, the Decision Support System (DSS) is vital to achieve the adaptive water management in the HRB. At present, there are two types of DSS: Research-oriented DSS and Application-oriented DSS. Research-oriented DSS for the HRB is a scientific model integrating "Water–Soil–Gas–Biology–Human." It tries to integrate the expert knowledge and experience of the HRB to build a spatially explicit model with scenario analysis method. For the development of the Research-oriented DSS, it has integrated multiple hydrologic models, and coupled many GIS functions to support coupled work of multidisciplinary model. Also, it has made technical breakthroughs on the mismatch of the models at different spatial–temporal scales. Through providing scenario-driven decision-making strategies graphically and multiobjectively, and providing various auxiliary decision tools, it is expected to be a new generation of DSS for river basin integrated management. For the Application-oriented DSS, some water management DSS can analyze the climate and human activities at the middle reaches of the HRB. It is also able to study the planting structure of different crops, spatial–temporal distribution of water requirement with different hydraulic engineering conditions. Finally, it can realize the simulation of water resource allocation process at multilevel (the whole basin, administrational district, and irrigation region) and evaluate the influence of various water resource management strategies.

Taking the arid climate and the unique relationship among the three reaches of the HRB into consideration, there should be an innovative framework and research components for DSS for the HRB based on the existing studies (Fig. 7). Spatially, water consumption of the HRB mainly concentrated in the middle reaches, where industrialization and urbanization are evident. Institutionally, there is a history of water right and water price system and institutions in the HRB, especially in the middle reaches where irrigation agriculture is preformed widely. Naturally, the desertification process exacerbated the deterioration of the ecology and change of oasis area. Also, the future climate change will greatly influence the hydrological process and water supple, that is, the precipitation as well as the solid glacier in the upper reaches. Therefore, as a unit of the whole scientific framework of the DDS, we should firstly comprehensively consider and make multiple scenarios analysis on the impacts of water right system reform, industrialization and urbanization, land use change, change of oasis area and climate change on the HRB. This work can be conducted on basis of existing knowledge, data and regional models. The scenarios analysis results would help to deepen and widen the recognition of the mechanism and linage of a series of factors within the ecology and economy of the arid area.

Secondly, the water resource utilization in the HRB is often confronted with the contradiction between ecological service and social and economic development. Therefore, it is necessary to realize the modeling integration between the social–economic model and eco-hydrological model for the optimization of watershed management. Also, Millennium Ecosystem Assessment put forward the idea

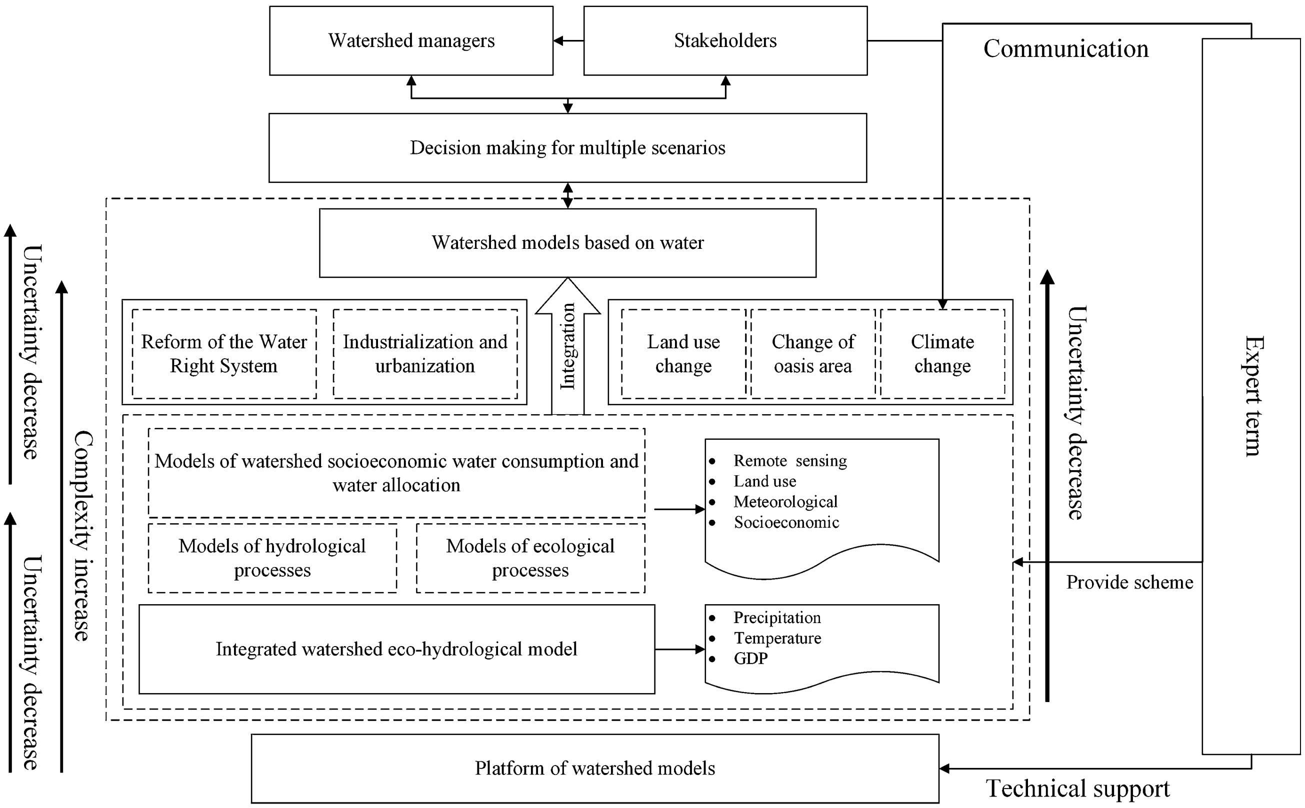

Fig. 7 Framework and components for a DSS for the integrated water management in the Heihe River Basin

that “Regulating water supply service on ecosystem by means of economy and market is the preferred method of management”. The balance between the water supply and demand is the core to integrate the social–economic model and eco-hydrological model as separate module. The work on model integration needs to analyze the water supply capacity, water consumption structure, water efficiency and water demand trend at multilevel (whole basin, administrational district, and irrigation region). Specifically, it needs to clarify the interaction mechanism among the water supply in the upper reaches, the industrial water consumption in middle reaches and ecological water consumption in the lower reaches.

Further, the water management system is indispensable for the whole framework of the DDS. In practice, due to the absence of proper water management system, the conflicts among counties often arise because of competition on water use and jurisdictional mandates of the related stakeholders. An integrated watershed water management system should comprehensively consider the ecology, hydrology, and socioeconomy in the basin, in order to provide scientific support for the water security, ecological security, and sustainable development of the inland river basin. Last but not least, water optimal allocation strategies should be involved to explore the regulation measures under different natural and social scenarios. In recent years, a series of studies have been carried out on understanding the impact of human activities (irrigation, livestock activities, and institutional change) on water (Wang et al. 2009). However, compared to the study on the eco-hydrological process and modeling research on the HRB, the mechanism studies water resource allocation is relatively weak. In this sense, both the system and institution design for water management and the optimal water resource allocation would be extended in the follows.

Improving the System and Institution Design for Water Management

In recent years, the integrated management of the HRB has drawn great attention from Chinese government. Yellow River Conservancy Commission (YRCC) of the Ministry of Water Resources has organized a series of tasks such as “Water problems and solutions of the HRB,” “Ecological environment problems and solutions of the HRB,” as well as “Safeguard measures of water management of HRB” to improve the systems and institution design of water management. Further, Chinese government set up Heihe River Bureau, an institution that belongs to the YRCC, in the year 1999. A major task of this Bureau is to lead the project on uniform water management and water distribution throughout the HRB. Before that, water was used mainly for forest and grassland irrigation, groundwater recharge, and replenishment of the rivers in East Juyan Lake in lower reaches. Unfortunately, there has been no fundamental improvement for the water solutions.

Globally, there is a long-standing and widespread recognition that the river basin is the natural unit for water management (Warner et al. 2008; White 1957). For instance, the USA began to set up institutions to comprehensively manage river basins from 1930s. Created in the year 1933, the Tennessee Valley Authority (TVA) in 1933 is a river basin authority for the unified planning and full development of water resource on a river basin scale in order to achieve comprehensive regional socioeconomic development (Warner et al. 2008; White 1957). Specifically, a far-reaching work was the Universal Soil Loss Equation (USLE), an empirical predictor for soil loss by water erosion (Cardei et al. 2009). It was built based on systematically analysis of observation data from more than 10 thousand runoff regions in 30 states in Eastern America in 30 years.

The last decades witnessed growth in research examining partnerships for integrated water resources management (IWRM) in different global regions. It is now employed globally in various physical, socioeconomic, cultural, and institutional settings. Compared to traditional approaches to water problems, IWRM takes a broader holistic view and examines a more complete range of solutions. It has promoted the water management move into the substantial scientific research period, with good public participation mechanism and considering water, ecology, and social economy in the basin scale (GWP 2004; Alcamo et al. 2007). Water managements of basins in Colorado, Sacramento are based on the IWRM model. IWRM was also applied to water management practices in Murray–Darling Basin in Australia, River Rhine Basin, and The River Thames Basin in Europe and received satisfactory results (Tortajada et al. 2005; Giri et al. 2012; Mitchell 2005). In addition, the Arabia region paid great attention to the groundwater management and wastewater reuse, and considered that IWRM must be considered when building the institutional framework; countries belonging to the Southern African Development Community (SADC) also tried to improve the water efficiency in arid areas with the help of IWRM method to confront the food crisis and poverty.

One representative work on integrated river basin management is reflected in Water Framework Directive (WFD) implemented by EU in the year 2000. Taking over 10 years to develop, the objective of WFD is to build a comprehensive monitor and management system for all water bodies and develop programs and measures to formulate an up-to-date watershed management plan for dynamic water management. The basic requirement is that the watershed management plan must be comprehensively presented, making it clear that how to achieve the targets (ecological conditions, water conditions, chemical conditions, and protected scope) within the required time. In addition, it must carry on the economic analysis to effectively consider the cost and benefit of all the stakeholders as for all the measurement, making itself truly participating in watershed management planning work. Although this command has been implemented for nearly 10 years, the management condition of these cross-border rivers are still in the stage of national independent development and management, and the mechanism of cooperation and negotiation within countries still need to improve. With the rapid globalization and economic development, the development of the basin dynamics will continue to increase, so how to realize the basin management across administrative boundaries is an urgent problem (Table 6).

In particular, there are some similar problems on water management among Murray–Darling River Basin in Australia, the Nile River Basin in Egypt, and the

Table 6 International water management strategies at typical watersheds and its inspirations for the Heihe River Basin

	Management modes and strategies	Inspiration
Mississippi valley in the USA	It has a comprehensive management system operated by multiple sectors and organizations at multiple levels, including the military, institutions composed of representatives from federal government and state government, nongovernmental organizations. The division of labor is clear-cut, avoiding confliction caused by duplication of work. A number of organizations at different levels to coordinate the interests of all parties concerned.	Strengthen the legal system, and establish a series of watershed management regulations to constraint the behaviors from various stakeholders. Manage the whole basin rely on sub-basin as the unit by sharing information and cooperating by various institutions. Relying on the nonengineering measures, instead of engineering technology.
Murray–Darling River Basin in Australia	Developed organization systems, which included three levels: The first level is the Ministerial Council in the national level, which is the highest decision-making body; the second level is the executing agency from the Ministerial Council, including the river basin committee and its office. The third level is the community advisory committee, which is responsible for communication between the council and the community, and emphasizes public participation in watershed management.	Authority for watershed management should be established on consultation mechanism. The full participation in proposal making is the key to implement. An effective organization system can guarantee the implementation of the protocol. Introduce a new theory and method in the water distribution, separate the water right from the land right and provide water for trading to formulate water market. Make the watershed management process more scientific, democratic, transparent and fair.
Rhine River basin in the EU	This river applied international coordination and management mechanism early. Countries along the coastal signed agreements and regulations, as well as built different kinds of organization in the last centuries. The International Commission for the Protection of the Rhine (ICPR) was established in 1950 as the first intergovernmental body for protection against pollution in the Rhine and has made great success. ICPR set up supervision organizations and various professional groups, achieved remarkable success	Give preference to prevention and source controlling, formulate detailed, standardized strict to regulate basin development. Pay emphasis on real-time monitoring and evaluation of the watershed management measures implement for timely adjustment. Increase storage capacity both in cities agriculture area to reduce water loss and soil erosion. Prohibit developing in riverbed. Present new concept of river ecosystem management, and pay attention to the river health function, socioeconomic factors as well as the support from modern science and technology.

HRB. For instance, the responsibilities for water management in response to drought is unclear, water management authorities based on sub-river basin have not paid enough attention compared to government management authority based on administrative regions, and economic and legal measurement still need to be improved. To some extent, the comprehensive water management in Murray–Darling River Basin and the Nile River basin can provide useful experiment and lessons for the water management in the HRB. The successful river management model and experience in Murray–Darling River Basin include water management based on sub-watershed rather than administrative regions, three layers coordination (decision level, execution level, and coordination level), market management strategy such as trade in water rights, as well as regular legal system based on interstate water compact. In addition, as for water management in arid region, Egypt is setting up the Nile River Forecast Center (NFC) for controlling Nile water resource, in order to achieve the Goal "Maximum exploiting of existing water resource, restricting the projects that can pose a threat to water quality and water resource" by the year 2017. The prediction of river flow using the remote sensing, geography information system, and global positioning system (3S) technology can provide the basis for management and decision. Moreover, it emphasizes on the drainage reuse in the agricultural field, and strengthens the utilization of rainfall resources through the implementation of farmland rainwater harvesting project. It reduces the rice planting area through the adjustment of planting structure and promotes drought resistant crops, thus effectively reducing the water consumption on agricultural production.

Reforming Management to Actualize the Optimal Water Allocation

Aside from scientific framework and institutions, the reform of water resource management needs investigations and studies at multiple levels to provide key parameters for DSS based on water demand of production, life and ecology. First and foremost, it is necessary to carry out investigation at the irrigation district level to clarify the water management system in each irrigation district. By this method, we can evaluate the performance of the water management systems, such as "water price" and "water right." By doing so, we understand the current situation as well as the transformation character of existing water policies, and then clarify the impact mechanism on agricultural department and ecological systems. Secondly, we have to further our research at the administrational level, making clear the WUAs, water-consuming situations, water association system, and other socioeconomic features. The performance evaluation for WUAs can clarify the situation of WUAs (organization, incentive mechanism, and institutional arrangement), the evolution character of the WUAs as well as its impacts on the agricultural production and the water efficiency.

Furthermore, the third level of investigations should focus on the household level to clarify water use of different crops, agricultural activities, and their socioeconomic characteristics. By doing so, we can analyze the impacts of various policy scenarios on water demand. For example, the land use patterns, labor force allocation, crop production and food security, and agricultural input–output benefits can be affected by different land use patterns and economic behavior of farmers in different water resource allocation scenarios. In addition, the income compensation policies, the adjustment on irrigation water price, and the progress on irrigation technologies are also related to various policy scenarios on water demand. Based on the above three levels of investigations, the useful and key parameters for the DSS can be obtained, thus providing suggestions and recommendation for the management, institution, and policies to build a water-saving society.

As for the water efficiency in the HRB, the existing water management strategy should be improved firstly. Establishing water management system based on the theory of "water rights, water market" is an important method to improve the allocation efficiency of water. Although water managers in the middle reaches of the HRB introduces the "water right" for water resources management, the leverage function is failed to play a role because of the deficient water rights trading market. Research shows that market-oriented water management framework is beneficial to allocate water and improve water efficiency (Pigram 1999). How to allocate the water resource among multiple regions and industries efficiently is the vital joint of augmenting the water use efficiency to sustain the balance between ecology and economy, and also within the related economies.

Research on the optimal allocation of water resource in China is to build the input–output model and the Computable General Equilibrium (CGE) model, both including the water resource account (Deng et al. 2014a; Wu et al. 2014; Zhao et al. 2010).The extended input–output model and CGE model can be used at basin and county level to analyze the impacts of water right transformation and industrialization (Deng et al. 2014b). Other partial equilibrium models can be used to allocate the water resource among the irrigated areas according to the crop pattern, irrigation rate and other agricultural attributes, and these are the core of the system to calculate and improve the water efficiency. Some scholars explored the effects of water market regulation strategies such as the reform of water price and the transaction of water rights through building input–output model in the Yellow River Basin.

In addition, with the development of computer modeling technology, CGE model has become an effective tool to explore the effects of policies on water management. For instance, the CGE model had been used in Beijing to evaluate the economic policies on the water price and water allocation (Deng et al. 2014a). A number of indicators of water consumption were established to analyze the structural relationships between economic activities and their physical relationships with the water in Zhangye (Wang et al. 2009). Other relevant studies at different scales includes the impact of water allocation on socioeconomy of different districts in Yellow River basin, the economic impact of South-to-North Water Diversion Project on different Administrative Region (Berrittella et al. 2006; Feng et al. 2007). The social and economic data used in most of these studies are static and on a single period, which are unfavorable for the scientific research applied to water management.

In this sense, it is necessary to build multisector dynamic CGE model for water allocation to comprehensively consider the effects of technological progress, the water rights system, water market on water demand (industrial water, ecological

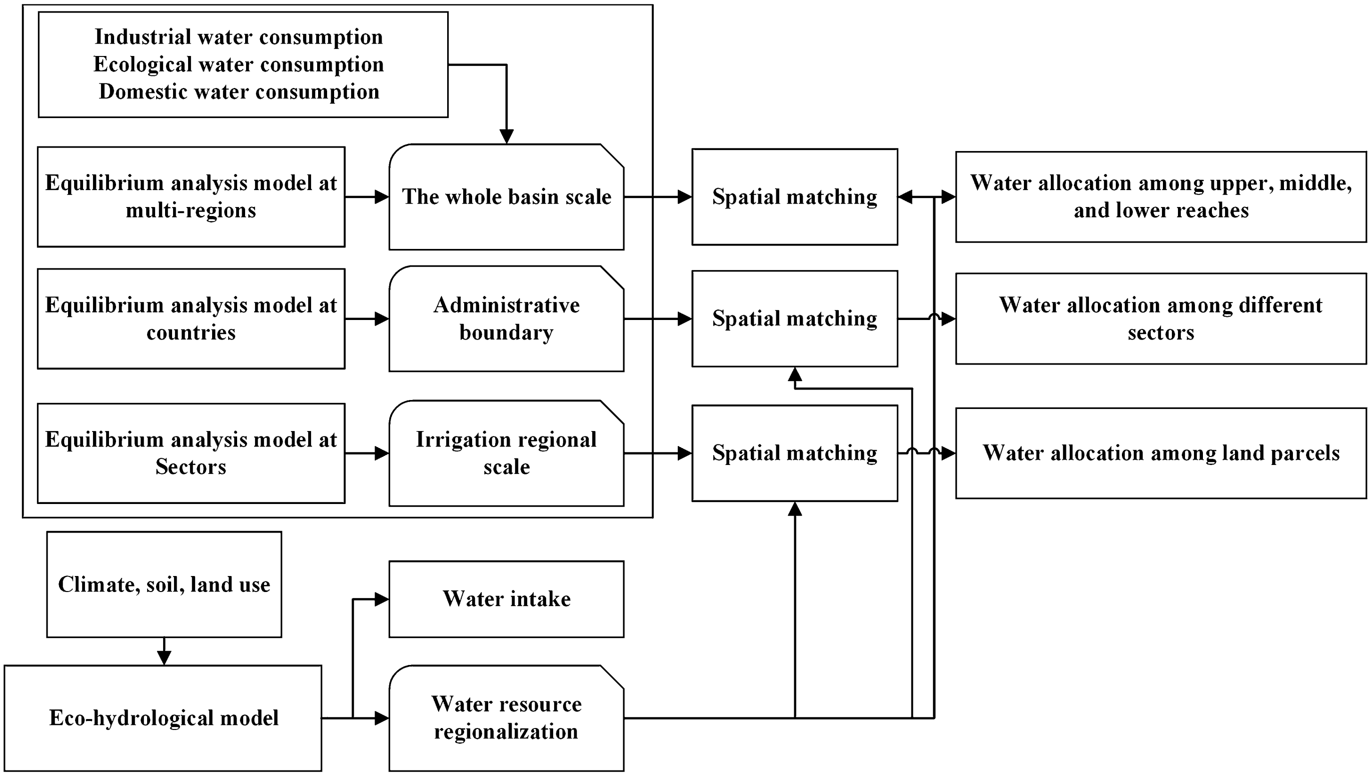

Fig. 8 Multilevel water allocation strategy among irrigated area, counties and sections of basin in the Heihe River Basin

water, and domestic water), and water efficiency (Fig. 8). The framework of CGE model should incorporate the water and land use resource as the production inputs into the production function to characterizes the configuration on the water and land resources in various social and economic sectors under market price adjustment. The rationality of water rights allocation of the river basin is that it can clarify a series of complex relationships, such as the contradiction between water supply and demand; the competition among different sectors; the water coordination among upper, middle, and lower reaches; the investments about different water projects; the benefits of economic and ecological water consumption; as well as the contemporary and future water consumption. Only in this way, can we achieve a relatively fair, acceptable water allocation scheme.

Summary

In this chapter we discuss how to mitigate climate change impacts for optimizing water productivity. Firstly, we present an approach to investigate the contribution of glacier melting and climate change to streamflow by coupling the SWAT model with a glacier melting algorithm. We examine the performance of the improved SWAT model in the upstream Heihe River Basin where topography is complex and the runoff is influenced by snowfall, glacier, and climate change. This is the first attempt for predicting future streamflow in the upstream Heihe River Basin. The approach is proved to be effective in simulating glacier melting to describe streamflow changes influenced by climate changes. Technically, calibration is performed using the automatic SWAT-CUP tool. The simulated streamflow better matches with our observed records. The analysis of water balance shows that the glacier melting influences the marginal changes of streamflow, infiltration, and evapotranspiration. The model performance is statistically improved by using the elevation band approach, and thus this approach is highly recommended to be applied for similar mountainous watersheds. The simulation results indicate that the glacier melting made about 8.9% contribution to streamflow in 2010. However, such an increasing trend of glacier runoff is not sustainable since the glacier recession will sufficiently decrease glacier area and thus reduce the melt-water volume in the long run. Our study reveals that alpine glacier of the upstream area is significantly unbalanced in the regional water resource under the current climatic condition, and the glacier would disappear in upstream Heihe River Basin over the next 40 years, which might further aggravate future water scarcity in the Heihe River Basin. The average snowline will rise by 100 m for each degree of warming, and the glaciers will also retreat. The results also indicate that the streamflow increased with precipitation rise, and decreased with temperature rise, without considering the contribution of glacier. The elevation around 4700 m is the threshold of the glacier change, below which there will be likely less glacier. Meanwhile, the 4700 m elevation is also the tipping point of precipitation change.

Due to the relationship between upper stream and middle stream in Heihe River Basin, we used and improved the ORANI-G model by introducing the water resource into the CES production function. Based on the definition of water productivity, we analyzed water productivity changes caused by change of the water input. The results firstly show that the current water productivity is underestimated. Secondly, agricultural water use accounts for the largest part of water consumption, and therefore enhancing agricultural water productivity can greatly mitigate the water shortage. Thirdly, the water productivity of the agriculture industry is lower than that of the secondary and tertiary industries. This indicates that reformation of the industrial structure and development of water-saving industries can also mitigate the water shortage. Fourthly, the results of sensitivity analysis show that CES changes have relatively small impacts on production in each sector, but a higher CES of water to other production factors can still contribute to sustainable development.

Finally, we came up with some strategies to mitigate climate for optimizing water productivity. With an increasing competition for water across sectors and regions, the river basin has been recognized as the appropriate unit to analyze and confront the challenges of water management. Especially, the HRB is facing competition problems for water uses among domestic, industrial, and agricultural sectors, and between users and ecological needs. Therefore, coupling of the eco-hydrological model and social–economic model is to optimize the necessary premise of integrated river basin management. Generally, conflicts of priorities on water resource coupled to the severe natural conditions make it urgent to build a successful water management system for different stakeholders in the HRB. In this sense, establishing a DSS for water management is an important method to realize the adaptive water management for the sustainable development of the HRB. Contemporarily, there are a series of worldwide research works on water management in river basin. Some counties have presented and improved their own policies and regulation measures based on their own water problems and national conditions. All of these provide some experience for integrated water management of the HRB. Nevertheless, the basin is a dynamic, multivariate unbalanced, open dissipative “unstructured” or “semi-structured” system. Considering driving characters of two dimensions (Nature-Society) for water reallocation, there did not exist modes or systems, which could be copied or applied to the HRB directly.

Throughout studies on the HRB and other inland rivers, it can be identified that promoting water management from water demand management to water consumption management is an important direction for scientific and sustainable development of the HRB. Furthermore, from the institutional perspective, a spatially and dynamically effective water allocation scheme is a strategic need for rational and efficient use of water in the HRB. In view of the abovementioned structure and efficiency of the current water consumption situation, a pressing matter of the moment for reforming the water management systems in the HRB is to improve the water right system based on the water demand in production, human living, and natural ecology.

In summary, it is necessary to establish an integrated water management system based on the water carrying capacity in order to provide support for the strategic decision-making at watershed scale for sustainable development of the HRB. In addition, establishing an integrated model on river basin with a clear physical process, powerful functions, and strong applicability has universal significance. It can also be applied to many inland basins in China, as well as other inland river basins which are distributed over all the continents of the world and accounts for 11.4% of the global land area, and provide significant support for sustainable development of regions with severe water shortage, fragile environment, and rapid development demand.

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Impacts of Water Scarcity on Socioeconomic Development in Inland River Basins

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Contents

Introduction 282
Case Study Area 285
Methodology and Data 286
  Structure and Accounts of WSAM 286
  SAM Multipliers and Decomposition 288
  Data 290
Results and Discussion 292
  Regional Economic Structure Analysis 292
  Scenario Analysis 294
Discussion and Conclusions 302
Appendix 303
References 303

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Abstract

Provisioning services for socioeconomic development are important hydrological ecosystem services that humans obtain from freshwater. The conflict between water scarcity and economic development in arid regions affects water utilization among different sectors. A water resource embedded social accounting matrix (SAM) can help to analyze the relationship between water resource utilization and socioeconomic development. In this paper, a water resource embedded SAM was constructed in Gaotai County, Northwest China, and the SAM multiplier model was applied to explore the economic structure, feedback mechanisms, and water flows among different sectors. Furthermore, scenario analyses were conducted to simulate the impacts of different policies on regional economic development and water resource utilization patterns. Through the multiplier analysis, we found that agriculture is less productive than the secondary industries because of its low development stage and lack of deep processing chains. However, the influence of agricultural sectors on the whole economic system outweighs the influence of the secondary and tertiary industries. Results also indicated that expanding agricultural exports can promote rural employment and improve rural household welfare, but will also lead to water resources outflow and aggravate water conflicts among different water users. At last, the simulation results of price reform showed that agriculture water price increase will cause a chain effect among different sectors. Water price increases by one unit will lead to the price of agricultural products, industrial products, and labor increase by 0.03, 0.018, and 0.005 units, respectively, and the Consumer Price Index increases by 0.005 units.

Keywords

Social accounting matrix · National economy · SAM multiplier · Irrigation water price · Water scarcity · Heihe River Basin

Introduction

Physical and economic water scarcity and limited or reduced access to water are major challenges facing human society (Bakker 2012; Cosgrove and Rijsberman 2014). During the past century, water utilization has increased sixfold globally (WWAP 2015). Climate change, industrialization, and changed human consumption patterns have further aggravated the conflicts between water demand and water supply from both global and regional perspectives (Piao et al. 2010; Grafton et al. 2013; Haddeland et al. 2014). This irreversible trend has led to water resource shortages becoming a major constraint to socioeconomic growth and ecological security, especially in arid and semi-arid regions. In these regions, water demand continues to increase under the pressure of urbanization and population growth. Consequently, water resource management is faced with ongoing issue of how to improve water use efficiency and promote water productivity.

Water is an important factor of production contributing both directly and indirectly to economic activity across all sectors and regions. Water scarcity may therefore go beyond having important consequences for people, society, and ecological systems but may also pose a threat to economic growth. Low water productivity has attracted increasing attention as water has become increasingly regarded as one of the most critical resources in the world's sustainable development (Xiangzheng Deng et al. 2014). Take an example of China, because of the imbalance in the distribution and timing of precipitation, over 80% of the water resources are concentrated in the southeastern part of China where the arable area is only 35% of the country's total arable area of 95 million ha. In contrast, the water resources in the northern parts of the country account for less than 20% of the total, whereas arable land accounts for 65% of the total. Therefore, it is significant to figure out a mechanism of water productivity and improve it. Economic changes at various spatial and temporal scales for those factors can physically alter surface energy for water balance through the changes in Net Primary Productivity (NPP) of vegetation (Haiming Yan et al. 2015) and natural resource productivity. Under such phenomenon, sustainable water management has become an issue of major concern over the past decade. It has become increasingly clear that the pressing problems in this field have to be tackled from an integrated perspective taking into account environmental, human, and technological factors and in particular their interdependence. In order to emphasize the need for an integrated approach, the concept of Integrated Resource Management (IWRM) was introduced, including resource infrastructure, technology, and all environmental factors of mankind.

The value of water and the ecosystem services it provides have received more attention recently. According to the definition by the Millennium Ecosystem Assessment (MEA), ecosystem services are "the benefits people obtain from ecosystems" (MEA 2005). Humans receive an array of services from freshwater, including provisioning services, regulating services, cultural services, and supporting services. These ecosystem services are commonly referred to as hydrological ecosystem services (Barbier 2007; Brauman et al. 2007). The provisioning services of freshwater, such as water supply for drinking, power production, industrial use, and irrigation, are important for promoting the economy because they are directly or indirectly linked with social activities and production. As a primary input to all goods and services, the available quantity and quality of water can affect the production of goods and services and thus influence economic activity. Therefore, the economic and social attributes of water resources have been emphasized in the integrated water resource management frameworks (Cheng et al. 2014; Deng et al. 2015; Jiang et al. 2014).

When considering the economic attributes of water, issues related to sustainable water utilization and water scarcity alleviation should be discussed and addressed under the framework of the national economy. Researchers and policy makers are exploring ways to coordinate economic production and water use (Rosegrant et al. 2000; Sivapalan et al. 2012; Hack 2015). An input-output (I-O) table, embedded with the natural resources account, is frequently used to evaluate the economic value of resources in various sectors at both national and regional scales. Many researchers have linked water utilization with socioeconomic production by adding water accounts into the I-O tables (Hubacek et al. 2009; Deng et al. 2014; Dalin et al. 2015). This simple method of adding a set of row vectors in the I-O table has been widely adopted for investigating water resource consumption triggered by economic development. This method has also been used for allocating water resources among different economic sectors and determining the marginal value of water (Velazquez et al. 2006; Guan and Hubacek 2008; Deng et al. 2014). Although the extended I-O models that incorporate water accounts can help analyze virtual water flows among different production sectors in an economy, they are not appropriate for modeling the whole economic system. I-O models do not take into account the transactions and transfers of income between different types of economic agents, such as households, enterprises, governments, and external institutional sectors in the economic system (Wyeth & Holland 1993; Pyatt 1999).

A social accounting matrix (SAM) is an extended I-O table that adds factors for production and institutional sectors (households, firms, and government) (Stone 1978). SAM is a system of country/regional accounts in matrix format. It includes interindustry links between transactions normally found in I-O accounts and income transactions and transfers between different types of economic entities, such as households, governments, businesses, and external institutions (Pyatt and Thorbecke 1976). The SAM includes a series of interrelated subsystems that, on the one hand, give an analytical picture of the economy during a particular accounting period and, on the other hand, serve as a tool that assesses the impact of changes on the flow. The matrix is a double-entry table that describes the structure of the economy. SAM summarizes all transaction activities in an economy within a certain period of time and provides a general picture of the socioeconomic structure of the national economy and income distribution. SAM is more nuanced than I-O models because it illustrates the links between production sectors and all entities in the economy, and represents the distributive and redistributive income processes in the national economic system (Li et al. 2004).

As (Pyatt 1988) originally emphasized, the SAM not only provides a convenient form to present a set of national accounts, but also indicates the underlying structure of a consistent policy model of an economic system. As a basis for an economic model, the SAM is especially suited to provide measures of interdependencies among sectors, factors, and institutions, and thus to explore the wider implications of specific policy measures. Unlike the traditional macropolicy models where instruments and targets are identified, respectively on the basis of government control and planning, the SAM-based models rely more broadly on the distinction between the accounts that can be modified exogenously, and those that are endogenously affected by these modifications. Furthermore, in the SAM context both the levels of the exogenous accounts (for example, the level of public investment in one or more sectors) and the parameters (for example, the tax rates) can be used as policy instruments (Pyatt and Thorbecke 1976; Thorbecke 2003). SAMs have been applied to policy analysis for a variety of issues, such as industrial transformation, employment, income distribution, and poverty reduction-related policies (Parikh & Thorbecke 1996; Thorbecke 2000; Akkemik 2012).

In recent years, along with I-O models, SAM models have been used widely in the context of resource management (Morilla et al. 2007; Calzadilla et al. 2010; Cazcarro et al. 2010). Llop (2013) used I-O analysis to evaluate how water is reallocated within the economy in response to changes in final demand and changes in the technical water requirements of economic activities and consumers. Morilla applied the Social Accounting Matrix and Environmental Accounts (SAMEA) multiplier analysis to water resources and greenhouse gas emissions to evaluate the economic and environmental efficiency in Spain (Morilla and Cardenete 2011). SAM has also been used to investigate the impact of land reform policies in Zimbabwe throughout the national economy (Juana 2006).

Adding water resource accounting to the traditional SAM model to form the water resource embedded social accounting matrix (WSAM) model is an innovative way to form a comprehensive framework for understanding the relationship between water and socioeconomic development. There has been very limited research that has taken water and the related hydrological ecosystem services into consideration in national economy analysis. The SAM model enables a quantitative analysis to help clarify how water flows among different sectors. In addition, SAM-based models rely more broadly on the distinction between the accounts that can be modified exogenously, and those that are endogenously affected by these modifications, compared to traditional macropolicy models. Therefore, SAM is an important tool for exploring the distribution mechanism of water in the national economic system when external shocks occur, such as investment changes and industrial transformation (Cazcarro et al. 2010).

In this paper, we use a simple version of the general equilibrium model, namely SAM embedded with water accounting, to predict the impacts of socioeconomic development changes on water resource balances and social welfare. Different scenarios were set to simulate the future economic development and water resource utilization patterns, and provide guidance for future economic development planning and decision making. The remainder of this chapter is organized as follows. Section "Case Study Area" gives an overview of the study area. The framework and methodology for WSAM compilation and SAM multiplier analysis are explained in section "Methodology and Data." The results of the SAM multiplier analyses and the different policy scenarios are given in section "Results and Discussion." Finally, section "Discussion and Conclusions" concludes with policy recommendations.

Case Study Area

The Heihe River, the longest inland river in Gansu province and the second largest inland river in China, originates from the Qilianshan Mountains and ends in Lake Juyanhai in Inner Mongolia. The Heihe River flows through three major geomorphological units: the southern Qilian Mountains in its upper reaches, the Hexi Corridor in its middle reaches, and the northern Alxa High Plain in its lower reaches. The majority of water in the middle reaches is used for agriculture irrigation, meaning that there is little water left to maintain the ecological services in the lower reaches of the river in Ejina Banner (Qi), which has led to serious deterioration of the downstream ecological environment. To alleviate the conflict between agricultural water use in the middle reaches of the Heihe River and the ecological water demand in the lower reaches, a water allocation program was officially launched in 2000. Through water diversion, the downstream ecological environment has improved in recent years. However, the internal water competition is now much fiercer in the middle reaches since there is less water supply but with more agricultural, industrial, and domestic water demand.

Gaotai County, located in the middle reaches of the Heihe River Basin, is a typical arid to semi-arid region in the Gansu Province, Northwest China. With flat topography, fertile soil, and ample sunshine hours (up to 3000 h per year), it has been nominated as one of the county-level national commodity grain production bases located in the Hexi Corridor. Water used for agriculture accounts for more than 95% of the total water use. The annual precipitation is less than 200 mm and prevents dry land farming. Therefore, irrigation water is taken from the Heihe River. Since the water diversion plan started in 2002, more water was allocated to the lower reaches for ecological restoration, and water for economic production in the middle reaches was dramatically reduced. The benefits of the water diversion plan have been questionable because it has had a limited effect on improving water use efficiency and has led to rampant exploitation of groundwater. Rapid expansion in the agricultural sector and the economy in general has resulted in a very high demand for water resources. Agriculture is highly dependent on groundwater – about 35% of the irrigation water comes from groundwater. Because of a lack of effective groundwater resource management, overexploitation of groundwater has caused a continual decline in groundwater levels and poses a significant threat to local ecological security. As an important hub located on the One Belt One Road economic zone and the choke point of the new bridge connecting Asia and Europe, Gaotai County is experiencing new economic opportunities. Increased socioeconomic development and accelerated urbanization and industrial transformation require more water to be diverted from agriculture to other uses. As a result, environmental–economic conflicts will be exacerbated by the increasing dependency on scarce water resources, and increasing environmental degradation will pose new threats to the area (Cheng et al. 2014). Therefore, there is an urgent need to analyze water use structures and to create strategic economic plans to alleviate water stress and promote water use efficiency in the study area.

Methodology and Data

Structure and Accounts of WSAM

SAM is a national economic accounting system that incorporates the input-output relationships and national income accounts in a matrix. It provides a snapshot of the economy for a specific year by giving an overall and comprehensive view of the income flows between production sectors, economic sectors, and institutional entities, and the factors affecting these flows (Thorbecke 2000). SAM is typically a square matrix that records flows of transactions among all economic agents and sectors in an economy. A cell A_{ij} in the SAM refers to a payment from an account j (i.e., a production activity or sector, an institution, or a production factor) to another account i. Columns represent payments/expenditures and rows represent receipts/income. The total payments and total receipts must be balanced: the row sum must equal the column sum for the same account.

There are two ways of constructing SAM: top-down or bottom-up. In this paper, the top-down method is applied. A highly integrated macro-Social Accounting Matrix (Macro-SAM) was constructed first. Generally, there are six categories of accounts in Macro-SAM: (i) Activity (including production sectors); (ii) Commodities (the output of production sectors); (iii) Primary production factors (labor and capital); (iv) Institutional entities (households, firms, government, and the Rest of the World (ROW)); (v) Trade (import and export); and (vi). Capital formation (public and private gross fixed investments). To investigate the role of water provision services in the national economy and how they will be influenced by socioeconomic development, the water resources account was added to SAM as part of the capital to form the water-SAM (WSAM) used in this paper. There are 14 accounts in total, including commodity, activity, four input factors (labor, capital, surface water, and groundwater (because groundwater depletion is pervasive in the study area, the water account was further divided into surface water and groundwater accounts to explore how groundwater has been used and influenced by socioeconomic development)), household, firms, government, capital, and stock. The accounts setting for SAM is very flexible and is not limited to those listed above. It can be adjusted and disaggregated based on the specific targets and sectors that are of interest. Both the expenditures (columns) and revenues (rows) are defined for any productive or institutional sector. If data are available, any of the above blocks can be further disaggregated into a sub-matrix depending on the objective of the analysis.

Macro-SAM can only provide very limited information regarding elaborate economic systems. Sectoral disaggregation is needed to further study the relationship between water consumption and the regional economic structure and industrial production. To do this, a Micro-SAM can be obtained through sector disaggregation. During disaggregation, the matrix elements of Macro-SAM provide control for the corresponding sub-matrix data. To take into account the industrial structure of Gaotai County, we rearranged the sectors into 26 economic sectors. A list of the economic sectors is presented in Appendix Table 8. An important aspect of the SAM constructed in this paper is that it disaggregates the agriculture into seven subsectors: wheat, maize, soil seed, cotton, vegetable, fruit, and others. This was because agricultural production is dominant in Gaotai County and consumes about 95% of the total water. Disaggregating agriculture into different crops will provide detailed information regarding the planting structure, and will facilitate further exploration of potential water saving plans and adaptations. The disaggregation and combination mainly uses the I-O table mentioned above. Each account of the Macro-SAM contains a sub-matrix, while some of the blank blocks are null. The Micro-SAM is a multidimensional matrix.

SAM Multipliers and Decomposition

There are three different economic models embedded in the SAM: the fix-price model, the flex-price model, and the general equilibrium model (Norton and Scandizzo 1981; Scandizzo and Ferrarese 2015). Although the fix-price models are less flexible than the other two types, they provide a simple and powerful framework to evaluate the possible effectiveness of exogenous income injections and demand-driven policy changes. In the fix-price models, input–output coefficients and prices are fixed, except for those that are varied exogenously as part of the policy experiments (Scandizzo and Ferrarese 2015). It is necessary to make a distinction between endogenous and exogenous accounts when implementing the SAM multiplier model. The endogenous accounts typically include industries, production factors, households, and firms, while the exogenous accounts include government, capital account, and the ROW. Consequently, the SAM multiplier model can be used to examine the impact of an exogenous shock on economic activities and actors. The changes in the exogenous accounts result in changes in the incomes, or production/consumption levels, of the endogenous accounts through the multiplier process. These multipliers are named as the SAM multipliers.

Multiplier analysis is the calculation of the effect of an injection into any endogenous account (a change in the vector x) on the income of all endogenous accounts (y_1, y_2 and y_3). This initial injection can be exogenous government consumption, investment, or demand for exports, and will generate an impact on the endogenous accounts through the multiplier effects. The multiplier matrix is derived from the matrix of expenditure propensities matrix A_n, which is obtained by dividing each entry in the endogenous accounts by its respective column total. Because the column vector equals the row vector, the total income of endogenous accounts can be expressed as:

$$y_n = (I - A_n)^{-1} x = M_a x \tag{1}$$

where the $n \times n$ matrix of M_a is the accounting multiplier, and shows the interlinkages among different sectors. In Eq. (1) x is the exogenous injection matrix, and includes transfers from government to households or enterprises, government consumption, investment, and export.

To better investigate the impacts of linkages across sectors, production factors, and institutions, the SAM multipliers can be decomposed into transfer effects, closed-loop effects, and open-loop effects (Pyatt and Round 1979). These three effects demonstrate the various forms of interdependencies across production activities and institutions. The relationships between the three decomposed effects are shown in Fig. 1.

1. ***Transfer effect*** (T): reflects the effects generated by an exogenous shock within a group of accounts, i.e., within the activities block, commodities block, and institutions block.

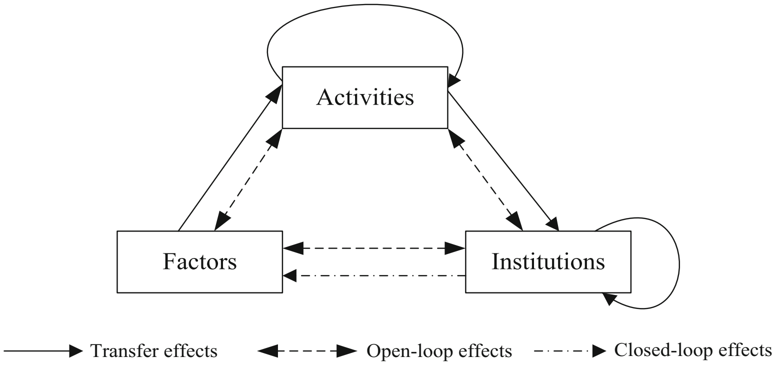

Fig. 1 Effects relationships within SAM decomposition (Reprinted from Zhou et al. (2017) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

2. ***Open-loop effect*** (O): measures the effects of a shock across any two different blocks (activities, commodities, institutions, and factors accounts).
3. ***Closed-loop effect*** (C): reflects the circular structure of the SAM and measures the cumulative effect of an exogenous shock on an endogenous account after the circular travel is completed (The circular travel runs from activities and commodities (i.e., production block) to household accounts, then to factor blocks, and then back to the original production block, which reflects the cyclical effect of income flows).

Let

$$A^* = \left(I - \tilde{A}_n\right)^{-1}\left(An - \tilde{A}_n\right). \tag{2}$$

By mathematical transformation, Eq. (1) can be written as:

$$y_n = \left(I - A^{*3}\right)^{-1}\left(I + A^* + A^{*2}\right)\left(I - \tilde{A}_n\right)^{-1} x. \tag{3}$$

The multiplier account is expressed as:

$$M_a = M_{a3}M_{a2}M_{a1} \tag{4}$$

$$\text{where}\, M_{a1} = \left(I - \tilde{A}_n\right)^{-1} \qquad M_{a2} = \left(I + A^* + A^{*2}\right) \qquad M_{a3} = \left(I - A^{*3}\right)^{-1}$$

$$M_a = I + (M_{a1} - I) + (M_{a2} - I)M_{a1} + (M_{a3} - I)M_{a2}M_{a1} = I + T + O + C. \tag{5}$$

M_a measures the sum of the direct, indirect, and induced impacts of the unitary increase in exogenous demand. T is the net contribution of transfer effects, O is the net contribution of open-loop effects or the cross-sector effects, and C is the net contribution of closed-loop effects.

Data

Data for SAM for regional economic analysis, especially at the county level, is not readily available. Different sources of data were used in this study, including a county-level I-O table, water consumption data, water tariffs, and trade and other socioeconomic data. Although the county-level I-O table is a prerequisite and the core of the county-level SAM, there is no available official county-level I-O table for counties in China because of difficulties in collecting and obtaining the necessary micro data. Therefore, the county-level I-O table used in this study was compiled from extensive household and institutional micro survey data collected in the Heihe River Basin with support from the National Natural Science Foundation of China. Details on how to apply I-O processes to the existing statistical and survey data to compile the county-level I-O table are given in Liu et al. (2009). The amount of water used by different sectors and the water price information were obtained from local water institutions. Other socioeconomic data were collected from the statistical year book for Gaotai County.

From the economic point of view, reading SAM by rows, we have the total of revenues of each sector that can be considered to be distinguished between endogenous or exogenous accounts. From the environmental point of view, reading by rows, the SAM includes the environmental inputs consumed as resources and, by columns, emissions and discharged pollutants to nature.

The SAM in our study consists of 26 production and commodity sectors, four institutions (government, representative household accounts, firms, and the ROW), and four production factors (capital, labor, surface water, and groundwater). The process of compiling SAM data required information-gathering skills. The important items, which can be collected from official statistics, were identified first. For example, the intermediate use of different activities, consumption of commodities by different agents, import and export of each sector, capital returns, and the payment for labor can be directly read from the I-O table. Items which cannot be obtained from official statistical sources directly, such as the production subsidies from central government, need to be inferred from other statistical data. In addition, items that are less important and lack data sources can be kept as residuals and treated as balancing items for the whole matrix. An example is the transfer payment from enterprises to households, which can be obtained from the margin between income and expenditure in the enterprise account.

The original SAM was initially unbalanced: row and column sums did not match in various accounts. An unbalanced SAM can be balanced using various methods. Two commonly used methods are RAS and cross-entropy (CE); the advantages and disadvantages of the two methods are explored in Robinson and El-Said (2000).

Table 1 Structure and accounts of the Macro-WSAM for Gaotai County

Income\ expenditure	Commodity	Activity	Labor	VA-capital	Water	Household	Enterprises	Government subsidy	Government revenue	Rest of the world (ROW)	Capital	Stock	Total
Commodity		Intermediate use				Household consumption			Government consumption	Export	Fixed capital formation	Stock	Total demand
Activity	Output												Total outputs
Labor		Pay for labor											Labor income
VA-capital		Capital											Capital income
Water		Water tariff											Water income
Household			Labor income	Capital income for household			Enterprise transfer payment	Government subsidy	Other payment by government	Household income from outside			Household income
Enterprises				Capital income for enterprises									Enterprises income
Government subsidy		Production subsidies							Government subsidies	Income from outside	Income of debts		Government subsidy
Government revenue	Import tax	Production tax			Water resources tariff	Individual Income tax	Enterprise direct tax						Government income
Rest of the world (ROW)	Import			Capital investment revenue					Transfer to ROW				ROW expenditure
Capital						Household savings	Enterprise savings		Government savings	Savings from outside			Total investment
Stock											Stock		Stock
Total	Total supply	Total inputs	Expenditure for labor factor	Expenditure for capital factor	Expenditure for water resource	Household expenditure	Enterprises expenditure	Government subsidy	Government expenditure	ROW income	Total investment	Stock	Total

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Usually, when the SAM model is used for multiplier analysis and the data sources are diverse, CE is the better choice. The main objective of CE is to assemble data of intersectoral transactions and institutional accounts and then, by minimizing the cross-entropy distance between the estimated SAM and the original unbalanced SAM, to obtain the optimal SAM (Robinson and El-Said 2000). More restrictions can then be imposed. Data from the I-O (input use across industries, factor accounts, value-adding, taxes, imports, and final demand by institutions) are kept fixed, and domestic sales figures (i.e., the intersection of the "Activities" row and the "Commodities" column) and the transactions across institutions (i.e., transfers among households, government, and ROW) are then estimated using the CE method. Because the official statistics are well organized and consistent, the differences between estimated and original unbalanced SAMs in this study are small.

Results and Discussion

Regional Economic Structure Analysis

Gaotai County is an important agricultural production base in arid and semi-arid Northwest China. New economic opportunities exist because of its strategic location on the One Belt One Road economic zone. The opportunity to boost the regional economy through industrial transformation has not yet been realized. Economic development and industrial structure transformation always involves income redistribution and production adjustment for the whole national economy. It is, therefore, important to consider the interlinkages between sector production and economic development, and the contribution of each sector to the national economy. The SAM multiplier model has been shown to be an effective tool for assessing these interlinkages and contributions. By implementing structural analysis for the whole economy using the SAM multiplier model, this paper will explore how each sector will influence the national economy.

Based on the SAM multiplier analysis, the average multipliers for different sectors are summarized in Table 2. The multipliers reflect the contribution of each sector to the whole economic system. From Table 2, it can be seen that transfer effects of agricultural sectors are generally smaller than the secondary industries, indicating that agriculture is less productive and plays a limited role in production linkages. The multipliers and transfer effects of the industrial sectors are much larger than other sectors. This indicates that the secondary industries induced a larger direct impact on other sectors during the production process. Therefore, in terms of economic production, the economic benefits induced by industrial sectors are greater than the agricultural sectors.

The adverse results from the closed-loop effects shown in Table 2 are large. However, the closed-loop effects of the agricultural sectors are much larger than those of the industrial sectors. The closed-loop effect is an indicator of a sector's strength in boosting the national economy, and is, therefore, not just an indicator of internal production processes compared with the transfer effects. The closed-loop

Table 2 Net SAM multiplier effects and its decomposition for the Gaotai County economy

	Multipliers	Transfer effects	Open-loop effects	Closed-loop effects
Sectors	M=	T+	O+	C+
Wheat	3.2138	0.7624	1.7272	0.7242
Maize	2.5003	0.0788	1.6966	0.7249
Oil crops	2.9165	0.0144	2.0000	0.9021
Cotton	3.0261	0.1240	2.0000	0.9021
Fruit	2.4719	0.0259	1.7093	0.7368
Vegetable	2.7149	0.1503	1.7734	0.7912
Other agriculture	3.0371	0.5152	1.7487	0.7732
Coal and natural gas	3.2142	0.9200	1.7546	0.5396
Mining	2.9389	0.5470	1.9373	0.4546
Manufacturing	3.3959	1.2284	1.5319	0.6355
Refined oil products	3.5020	1.3101	1.6244	0.5675
Fabricated metals	4.3576	2.0936	1.7076	0.5564
Electrical equipment machinery	3.6630	1.7034	1.4741	0.4855
Electricity and gas generation	3.5528	1.3064	1.7485	0.4979
Construction	3.7973	1.3794	1.7999	0.6179
Transportation services	3.6152	1.1785	1.8521	0.5846
Wholesale and retail	3.6807	1.3872	1.6780	0.6155
Hotels and catering services	3.4473	1.0754	1.8085	0.5634
Finance	3.5194	1.1637	1.6970	0.6588
Real estate and housing rental	3.3793	0.8413	1.9113	0.6268
Education and technology	2.9106	0.1562	1.9230	0.8314
Management of water conservation	3.4510	0.8075	1.9137	0.7298
Resident and other services	3.3178	0.8891	1.8295	0.5992
Health and social security	2.5903	0.4014	1.6248	0.5640
Culture, sports, and recreation	2.7263	0.4337	1.6369	0.6556
Public service and management	2.8766	0.0989	1.9160	0.8618

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effects indicate that agriculture can potentially make greater impacts on the national economy system than the industrial sector. This observation may appear incongruous: Agriculture is less productive than the industrial sector and it is at a relatively low development level. However, because of the cyclical effects of the factors and income flows between different accounts in the economy, the impact of agriculture on the entire national economy is substantial. This result is in accord with the economic conditions of Gaotai County, where agricultural output accounts for about 40% of the total GDP. In addition, the closed-loop effects of tertiary sectors, such as education, culture, health care, and other administrative sectors, are also larger than the secondary industries. The large effects of the tertiary sectors could be a result of their public nature and their role in supporting the regional economy by providing services and technology to other sectors. For example, education appears to be unproductive and does not exist to make profits. However, education helps to improve workers' knowledge and skills, which can promote productivity and social welfare in the long term.

From the above analysis, it is evident that the economic structure of Gaotai County is still agriculture-based, and faces problems such as low development levels, and a lack of a sound and substantial processing chain. Thus, the driving effects of the agricultural sectors in the production system are relatively smaller than the second industry. Development of agriculture by broadening the scope of the agricultural production chain, and research and development of agricultural science and technology may help to improve the situation and greatly promote local economic development.

Scenario Analysis

Gaotai County is an important transport hub and tourist destination, located on the economic belt of the Silk Road, and faces new opportunities for embracing rapid economic development. On the one hand, as an important agricultural production base in Northwest China, it should actively seize the strategic opportunity to develop modern, export-oriented agriculture methods and export agricultural products to Central Asia. On the other hand, to meet urbanization and industrial transformation, the labor intensive, traditionally agriculture dominated socioeconomic structure needs to be transformed, so that more labor can be released to the secondary and tertiary sectors. At the same time, tourism has been booming in recent years in Northwest China. The landscapes of the Loess Plateau and the indigenous customs attract increasing numbers of tourists from China and overseas. Tourist development will also lead to huge government investment in infrastructure, transportation, and public services. Thus, nonlocal stimuli may have potential impacts on the local economic structure, social welfare, and production decisions. This, in turn, will affect water allocation and flows among different sectors. Therefore, three different scenarios were constructed to explore how different policies will influence the national economy and how these policies will influence the water consumption patterns and water flows for different accounts and sectors.

Scenario A: Located on the One Belt One Road economic zone, and as a bridge connecting China with other central Asian countries, Gaotai County has many opportunities for boosting its economy. These opportunities include agricultural transformation, tourism, and transportation upgrading. There are large government investments in infrastructure, public services, and other facilities involving construction. This increases consumption. Thus, government investment will be a powerful injection to the whole economy and will drive the development of many economic sectors. This, in turn, will lead to income increases and redistribution among different economic entities. Therefore, this scenario is an exploration of how large government investments will influence the local economy, employment, and income.

Scenario B: As an important agricultural production base in Northwest China, Gaotai County takes full advantage of its opportunities to develop export-oriented agriculture and expand agricultural exports to Kazakhstan, Kyrgyzstan, and other Central Asian countries. This stimulation in agricultural exports will not only impact production within agricultural sectors, but will also further affect other industries. Agriculture accounts for more than one third of the local economy and consumes about 95% of the total water resources. Expanding agricultural exports will undoubtedly bring increasing pressure on local water resources, especially groundwater. The relationship between agriculture and other sectors, and the influence of expanding agricultural exports on water resources were modeled in this scenario.

Scenario C: Low agricultural water prices have been considered to be the main cause of low irrigation efficiencies. The possibility of improving irrigation water use efficiency by market mechanisms has received much attention from managers and researchers. Pricing water is considered an important water resource management tool (Venot and Molle 2008; Huang et al. 2010). In 2015, China implemented water tariff reforms, and Gaotai County was selected as a pilot area for water price reform. The price of surface water was increased from 0.1 yuan/m^3 to 0.15 yuan/m^3, and the price of groundwater was increased from 0.01 yuan/m^3 to 0.1 yuan/m^3. Agriculture is closely linked with other sectors. Therefore, agricultural water price reform will produce a series of chain reactions among other sectors. Furthermore, because water is an important input factor for numerous productive activities, changes in water prices will have wide-reaching effects on human welfare and on the production and investment decisions of entities. This study used the standard SAM multiplier analysis method to evaluate the effects induced by different economic development scenarios.

Influence of Government Investments in Different Sectors on Employment and Household Income

In Table 3, it can be seen that investments in different sectors cause the wage multiplier effects in agricultural sectors to clearly outweigh the effects in the secondary and tertiary industries. This indicates that labor in agricultural sectors is more elastic in response to outside stimuli and that investment in agriculture has a large effect on wages. Relatively speaking, the multiplier effects of the secondary industries are minimal. This indicates that the wage increase effect is small when there is increased investment in the secondary industries. This may be because the wage base of second industries is already much higher than for other industries, which, in turn, may be partly a result of the low wages in agriculture.

Household income is an important indicator of human welfare. It can be seen that the income multiplier of the agricultural sector is much larger than that of the industrial sector (Table 3). This shows that the agricultural sector has the greatest potential effect on human welfare, and that increasing investment and input in agricultural production will increase local household income. This is consistent

Table 3 Multiplier effects of investment in different sectors on the labor and household accounts

Shock on sectors	Multiplier effects	
	Labor	Household
Wheat	0.9281	0.9664
Maize	0.9608	0.9674
Oil crops	1.1962	1.2039
Cotton	1.1962	1.2039
Fruit	0.9769	0.9832
Vegetable	1.0485	1.0558
Other agriculture	1.0170	1.0318
Manufacturing	0.8150	0.8481
Electricity and gas generation	0.4886	0.6644
Electrical equipment machinery	0.5391	0.6480
Refined oil products	0.6557	0.7573
Fabricated metals	0.6221	0.7425
Coal and natural gas	0.5679	0.7201
Wholesale and retail	0.7332	0.8214
Hotels and catering services	0.5988	0.7518
Finance	0.8113	0.8791
Education and technology	1.0813	1.1095
Health and social security	0.6476	0.7526
Culture, sports, and recreation	0.8211	0.8750
Public service and management	1.1415	1.1500

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with the earlier wage multiplier analysis because wages are the main source of income. The results indicate that agriculture remains the pillar industry of Gaotai County, and it plays a significant role in the local economy and promoting human welfare.

The above analysis of the economic status of Gaotai County is in accord with the actual situation. In Gaotai County, the agricultural population accounts for 70% of the total population, and the rural labor force is mainly engaged in agricultural production, and the farmers' income is mainly from agricultural production. The industrial sectors are relatively undeveloped and lack competitiveness. Therefore, increased government investment in agriculture will significantly improve the rural employment environment and increase the wages of the rural labor force, thereby increasing the overall income of the society.

Influence of Adopting Export-Oriented Agricultural Policies on Other Sectors and Water Demand

Adopting the export-oriented agricultural policy and exporting agricultural products to Kazakhstan, Kyrgyzstan, and other Central Asian countries will rejuvenate economic development in Gaotai County. Wheat, maize, cotton, fruit, and vegetables are the main economic crops in Gaotai County, and the total cultivated area is

Table 4 Influence of expanding agricultural exports on different sectors

Shock on sectors	Multipliers of destination sectors			
	Manufacturing	Water production and supply	Wholesale and retail	Hotels and catering services
Wheat	0.1509	0.0011	0.0196	0.0057
Maize	0.1468	0.0011	0.0133	0.0038
Oil crops	0.1549	0.0013	0.0163	0.0044
Cotton	0.1549	0.0013	0.0163	0.0044
Fruit	0.1265	0.0011	0.0133	0.0036
Vegetable	0.1623	0.0012	0.0146	0.0041
Other agriculture	0.3654	0.0011	0.0268	0.0066

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370,000 ha. Expanding agricultural exports will not only stimulate agricultural production but will also affect production in other sectors because agriculture is the core industry and its products are used for production or sale in other industries. From Table 4, it can be seen that expanding agricultural exports will have potential impacts on sectors such as manufacturing, wholesale, retail, and hotels and catering services. Among these sectors, the influence on manufacturing is the largest, followed by wholesale and retail. The impacts on hotels and catering services, and the water production and supply industry are relatively small.

Agricultural exports will not only have an impact on interregional market but will also influence the regional water balance. In the concept of "virtual water trade," the import or export of agricultural products also involves the import or export of water embedded in the products. Water used in different sectors is shown in Fig. 2. Agriculture is the biggest consumer of water resources, and it is highly dependent on irrigation because the annual rainfall is less than 200 mm. Expanding agricultural exports will undoubtedly strongly influence the water flows among different sectors. Table 5 shows the influence of different crop exports on water resources demand. For example, when the export of corn increases by 1000 units, the cost of surface water will increase by 92 units. The water price is 0.1 yuan/m^3 for surface water. Thus, 920 m^3 of water is required for an extra 1000 units of corn exports, and the impact on groundwater is relatively small because only 100 m^3 of groundwater would need to be exploited in this situation.

With a fragile ecological environment and facing serious water shortages, Gaotai County has to deal with conflicts between uncoordinated ecohydrological protection and restoration, and socioeconomic development. Water resources are the main constraint to sustainable socioeconomic development, and the carrying capacity of water resources will limit the amount of water that can be used in agriculture. Therefore, in this scenario, it would be important to set appropriate agricultural export limits and use water capacity constraints to guide strategic development planning for agriculture.

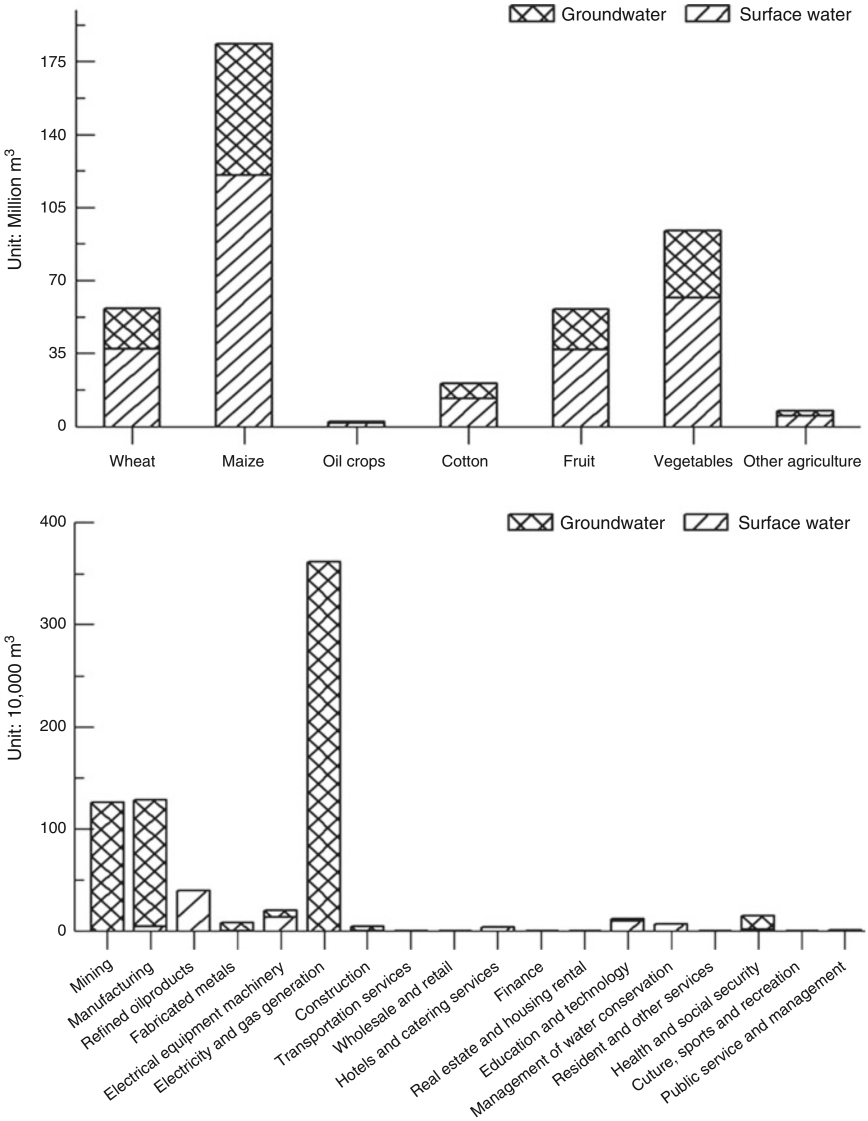

Fig. 2 Total amount of surface water and groundwater used by different sectors in Gaotai County, 2012: (**a**) water used by secondary and tertiary industry; (**b**) water used by agricultural sectors. (Reprinted from Zhou et al. (2017) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

Influence of Agricultural Water Price Reform on Prices and Social Welfare

Agriculture, as the main water-using sector in China, consumes about 60% of the total water resource. However, the rapidly developing industrial sector and an

Table 5 Influence of expanding agricultural exports on surface water and groundwater demand

Shock on sectors	Multipliers of water demand	
	Surface water	Groundwater
Wheat	0.1509	0.0011
Maize	0.1468	0.0011
Oil crops	0.1549	0.0013
Cotton	0.1549	0.0013
Fruit	0.1265	0.0011
Vegetable	0.1623	0.0012
Other agriculture	0.3654	0.0011

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increasingly wealthy urban population have started to compete with agriculture for water (Deng et al. 2014; Jiang et al. 2014). Because the diminishing surface water resources can no longer satisfy the demand for water for the purpose of irrigation, farmers have begun to rely more on groundwater resource. The increasing amount of groundwater used for agricultural purposes has made the overextraction of underground water a very serious problem in Northwest China. The overexploitation of groundwater, especially deep groundwater, can cause a number of environmental problems, such as land desertification and a reduction in the amount of natural vegetation cover (Deng and Zhao 2015). Furthermore, water use inefficiency and water waste are still prevalent and are the main reasons for the current water crisis in Northwest China. The irrigation water quotas and water consumption per unit of GDP are very high and the average irrigation quota per acre of farmland is 522 m^3, which is almost 25% higher than the national average, and the water consumption per 10,000 yuan GDP is 1736 m3, or 85% higher than the national average (Wang et al. 2007).

Underpricing of irrigation water is frequently identified as the primary cause of excessive use of water for irrigation. Many researchers and policy makers reckon that water in agriculture is consistently undervalued since users do not value it and thus lead to a chronically overuse of it (Seagraves and Easter 1983). Although agricultural water demand is high in Northwest China, the irrigation water price is relatively low, accounting for only one third of its production cost. The price elasticity of the derived demand for irrigation water is an economic measure that is often used to evaluate the effectiveness of price incentives in facilitating water conservation. There were studies on water price elasticity and its influence on water utility, and the previous research findings in several countries have revealed that the demand for irrigation water is inelastic because the price is too low (Schoengold and Zilberman 2007). Further, simulation analysis has shown that when the price of water is raised to a relatively high level, the pricing can promote water savings (Huang et al. 2010). On the other hand, some studies still doubt about the water saving effects and the economic consequences and other external effects like agricultural production reduction, rural poverty, and overutilization of groundwater resources brought by increasing water price (Venot and Molle 2008).

The current irrigation water price is very low in Zhangye, which can hardly cover its cost. Furthermore, the irrigation cost is only a small portion of crop farming, namely less than 10% of the total input of crop production. The local government has issued a standard for levying agriculture irrigation water tariff. The water tariff consists of two parts, the basic tariff and the metering tariff. Charges for canal, pipeline, and drip irrigation uses a unified price. For groundwater, the cost of irrigation is primarily the expense of power and pumping equipment. Water resource itself is almost free. No restriction is imposed on the volume of water extraction in each well, though digging new wells in principle requires the approval of water authorities. Farmers measure their irrigation cost by electricity and fuel bills and the concept of water cost is generally absent. In this context, the number of wells is thus continually increasing in recent years.

The improvement of agricultural water use efficiency by means of market mechanisms has received much attention from researchers and policy makers (Robert et al. 2002; Tiwari and Dinar 2002). In China, the low agricultural water price has been considered the main cause of agriculture's low water use efficiency. Although extremely lacking in water resources, the water use efficiency is very low in Gaotai County. As depicted in "Scenario 3," we modeled the impacts of agriculture price reform in Gaotai County. As an important input to numerous productive activities, changes in water prices will have impacts on the whole economy. Changes in water prices will alter production and investment decisions, and household expenditures. These changes will, in turn, influence the aggregate price level and hence inflation. Agriculture is the primary industry and closely linked with other sectors. The reform of water prices for agriculture will induce a series of chain reactions among different sectors. The impact of the water price reforms on prices for the different production sectors and for household incomes was evaluated using SAM modeling. The SAM price multiplier model depicts the price formation process of the whole economy when one sector's price changes. Intersectoral relationships were taken into account and the impact of changes to the cost of irrigation water on the price levels in the remaining production sectors were examined in a disaggregated manner.

Price multipliers for different sectors are shown in Table 6. The primary industries are the most responsive to surface water price change, whereas the secondary industries are the most responsive to groundwater price changes. The water use structure for different sectors in (Fig. 2) yielded results that were sensible because the secondary industries are highly dependent on groundwater. We carried out an aggregation of the sectors to obtain the standard three-industry structure to give a more meaningful perspective to the results.

It can be concluded from Table 7 that the overall impact of surface water price reform is greater than that for groundwater. This arises because surface water is the dominant water source for economic activity. When the surface water price increases by one unit, it leads to price increases of 0.03, 0.018, and 0.06 units in agriculture, secondary industry, and tertiary industry, respectively. Furthermore, the surface water price increase will also increase the cost of labor by 0.005 units, and the cost of living (CPI) by 0.005%. Thus, the overall result is that reforming agricultural

Table 6 Irrigation water price reform effects on different production sectors

Shock on sectors	Multiplier effects Surface water	Groundwater
Wheat	0.0058	0.0010
Maize	0.0917	0.0008
Oil crops	0.0051	0.0008
Cotton	0.0051	0.0008
Fruit	0.0801	0.0007
Vegetable	0.0217	0.0009
Other agriculture	0.0068	0.0020
Coal and natural gas	0.0108	0.0020
Mining	0.0352	0.0018
Manufacturing	0.0162	0.0079
Refined oil products	0.0083	0.0015
Fabricated metals	0.0369	0.0106
Electrical equipment machinery	0.0091	0.0021
Electricity and gas generation	0.0080	0.0015
Construction	0.0210	0.0031
Transportation services	0.0086	0.0011
Wholesale and retail	0.0075	0.0015
Hotels and catering services	0.0105	0.0014
Finance	0.0076	0.0019
Real estate and housing rental	0.0056	0.0014
Education and technology	0.0054	0.0011
Management of water conserve	0.0059	0.0010
Resident and other services	0.0052	0.0010
Health and social security	0.0042	0.0009
Culture, sports, and recreation	0.0061	0.0020
Public service and management	0.0054	0.0011

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Table 7 Irrigation water price reform effects on different economic agents and industries

Average	First industry	Second industry	Third industry	Labor	Capital	Households	Firms
Surface water	0.0309	0.0182	0.0065	0.0051	0.0021	0.0051	0.0021
Groundwater	0.0010	0.0038	0.0013	0.0008	0.0037	0.0008	0.0003

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water prices will lead to price increases in other sectors, resulting in an increase in living costs. Therefore, price policies should take full account of the cost implications in order to maintain farmers’ commitment to agricultural production and to avoid reducing farmers’ living standards.

Discussion and Conclusions

Water is the main constraint to socioeconomic development in arid and semi-arid Northwest China. Because the water balance is strongly influenced by socioeconomic activities, it is necessary to link water with the economic system when developing water resource management and use plans to improve water use efficiency and alleviate water scarcity. This paper linked water resources with the national economic system to investigate the role of water and its provision services in socioeconomic development. This was done by implementing the water resource embedded SAM. In addition, how water demand will be influenced under different economic development scenarios was simulated using SAM multiplier analysis.

By implementing the SAM multiplier model, we found that the influence of agriculture on the whole economic system outweighs the influence of the secondary and tertiary industries. Although agriculture is less productive than the secondary industries, it has an influence on the local economy. The main reasons for the poor performance of agriculture is that it is in the early development stage and because it lacks an associated and extensive processing and production chain. Therefore, there is a strong need to make agriculture more competitive by increasing investment in agricultural science and technology, and by expanding the agricultural production chain.

Impetus to socioeconomic development in Gaotai County would be provided by taking advantage of its strategic location on the One Belt One Road economic zone to develop export-oriented agriculture and increase agricultural exports to the adjacent Central Asian countries. The scenario analysis showed that increasing agricultural exports will increase employment and income, and promote the development of other sectors. However, increasing agricultural exports will lead to further outflows of water and the overextraction of groundwater because agriculture is highly dependent on irrigation. Agricultural water use efficiency should be improved to compensate the export-oriented agricultural policy.

Because water is a primary input factor for production, a change in water price may cause a chain effect among different accounts and entities. Irrigation water price reform will influence the agricultural sector the most and then the secondary industries. However, water price reform will have a double-edged sword effect – although it can promote the efficient use of water resources, it will also lead to an increase in farmers' production and living costs. In order to implement an integrated water conservation policy, the water pricing leverage should work together with other measures of water conservation, such as water rights, water user associations, and water quota control mechanism. Clearly defined and legally enforceable water rights and responsibilities of both water authorities and farmers enable them to sell saved water to other farmers or other sectors thus leading a reallocation of water resource to users who can produce higher added values. Moreover, water price effects on the whole socioeconomic system should be evaluated. Further study is also needed on how to balance efficiency and equity in water price tariffs.

There are limitations of the method used in this study. It is based on the Leontief model, which ignores the substitution possibilities that might arise from a change in relative prices. It further assumes constant returns, irrespective of the scale of production, and thus an infinite elasticity of supply for all sectors. The data for the SAM model are from diverse sources, which could influence the precision of the results. Therefore, the interpretation of the multipliers should be viewed with caution. Despite the limitations of the SAM model, the results are in accord with what is known about Gaotai County's socioeconomics and provide useful insights into the workings of an economy and how water plays a part in it. The approach is recommended for aiding water policy and economic development planning in other arid regions.

Appendix

Table 8 Sector disaggregation for WSAM

Agriculture	Wheat	**Tertiary industry**	Construction
	Maize		Transportation services
	Oil crops		Wholesale and retail
	Cotton		Hotels and catering services
	Fruit		Finance
	Vegetable		Real estate and housing rental
	Other agriculture		Education and technology
Secondary industry	Coal and natural gas		Management of water conservation
	Mining		Resident and other services
	Manufacturing		Health and social security
	Refined oil products		Culture, sports, and recreation
	Fabricated metals		Public service and management
	Electrical equipment machinery		
	Electricity and gas generation		

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Virtual Water Flow at County-Level of the Heihe River Basin in China

Yali Zhang, Qing Zhou, and Feng Wu

Contents

Introduction 308
Virtual Water Flows in the Heihe River Basin 310
  Data and Methodology 311
  Water Use Structure and Water Use Coefficient in the Heihe River Basin 315
  Virtual Water Flows at the River Basin Level 318
  Virtual Water Flows at the County Level 320
  Virtual Water Flows by Sectors 323
Water Stress and Water Scarcity 325
  Water Stress Index Adjustment 325
  Water Stress at the County Level in the Heihe River Basin 326
  Virtual Water Strategy Application Facing Challenges 328
Summary 330
References 331

Abstract

Water scarcity in arid regions can be addressed by using the virtual water concept in water resources management. This chapter used a compiled county-level input–output table to analyze virtual water flows for the Heihe River Basin in 2012 by applying a multiregional input–output (MRIO) model. The results showed that the Heihe River Basin is a net virtual water exporter at a scale of

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1.05 billion m^3, which accounts for one third of the total amount of the basin's water resources. The midstream area of the basin imports 96.31% of virtual water (2.04 billion m^3) and exports 88.84% of virtual water (0.94 billion m^3). In contrast, the upstream and downstream parts have limited virtual water flows. The agricultural sector largely consumes water in each county; maize or wheat production accounts for approximately 50% of the total water consumption. For most sectors, the virtual water content from surface water is greater than that from groundwater. The ratio of virtual surface water to virtual groundwater ranges from 1.20 to 2.91. The results for the water stress index indicated that most counties experienced water stress due to maize production. Greater attention needs to be paid to the adaptation and assessment of virtual water strategies in arid regions.

Keywords
Virtual water · Multi-regional input–output model · Water stress index · Heihe River Basin

Introduction

Arid land covers approximately 41% of the world's land surface. Water scarcity in arid and semi-arid regions has been severe (Vörösmarty et al. 2010). In water-scarce regions, water resource sustainability, ecosystem health, and socioeconomic development are dependent on water, which is the central determining factor (Palmer et al. 2015). The sharp conflict between freshwater demand and available freshwater resources is one of the largest threats to sustainable water supply in China and throughout the world. To address water shortage issues, management interventions have been made. These interventions include water diversion projects (such as China's South–North Water Transfer), implementing the use of water-saving technology, industrial structure adjustments, and using virtual water strategies. Virtual water was defined by Allan (1997) as "the water embedded in internationally traded goods" based on economic theory. According to virtual water principles, water-scarce regions with spatial mismatches in water and arable land availability can improve their food security by purchasing a portion of their food requirements through agricultural trade (thus acquiring virtual water) and cutting local food production (thus using less local water). A flourishing literature has been inspired on dealing with water scarcity through virtual water trade, whereas it is still under debate (Ansink 2010; Antonelli and Sartori 2015; Jia et al. 2017).

To mitigate water stress, some researchers believe that food trade to increase virtual water in water-scarce regions is an efficient use of water resources (Dalin et al. 2012; Chen and Li 2015). Different crop trades save or lose different volumes of blue and green water. Nevertheless, others have argued that the virtual water trade strategy as a solution to water scarcity is fallacious (Jia et al. 2017; Hoekstra et al. 2017). In practice, producing grain in some arid regions has a competitive advantage over humid regions. Input and output of virtual water trade depend on social-economic structure and water use efficiency rather than scarcity degree of water resources. The application of virtual water trade to improve water use efficiency in water-scarce regions was biased for several reasons: (1) no enough trade capital for traditional agricultural regions, (2) considering water as the only production factor while neglecting land, (3) lack of consumption pattern and production allocation in economic system. Furthermore, virtual water flows have varied effects on water stress for the water-receiving regions and the water-exporting regions. The key to mitigate water stress is improving water use efficiency, whereas the efficiency benefits will be highly compensated by the increased water demand caused by developed economy.

Social equity and adaptability can in theory result in the allocation of virtual water. Virtual water use is highly unequal, and is almost completely explained by social development status rather than water scarcity (Suweis et al. 2011). Urbanization leads to a change in the requirements from industry, which in turn leads to changes in urbanization rates and urban poverty rates. In addition, if a country (or region) is scarce in water resources but rich in socioeconomic resources, its social adaptability would lead to an industrial structure with relatively richer virtual water resources (Ohlsson and Turton 1999). Agricultural water use dominates national water demands and cannot be completely compensated for virtual water transfers. Virtual water strategies can increase social transactions, which should give priority to guaranteeing people’s purchasing power. The implementation of the virtual water strategy could lead to a lot of agricultural surplus labor force, and the unemployment status of agricultural labor force. As a consequence, two important indicators should be considered when solving the problem of agricultural surplus labor force with the application of the virtual water strategy, i.e., employment multiplier and “learning effect” of nonagricultural sectors. Economic efficiency and water use efficiency should be considered equally. Water price and quality should be driven by both supply and demand, since water is an economic good. Water use efficiency or water productivity represents the crops’ economic value. In general, agriculture sector largely consumed water resources with low additional value, and the only feasible approach is to save water resources by improving the water use efficiency. The theory of comparative advantage in implementing virtual water strategy could be used to learn the economic attractiveness of virtual water import and export (Wichelns 2010). The economic level in a country (region) can be reflected with the proportion of economic sectors (e.g., agriculture, industry, services) in the total GDP. Moreover, the virtual water strategy implementation will reduce the pressure of ecological water shortage and thereby change the regional food production mode (Vörösmarty et al. 2010; Hoekstra 2009). In general, the agriculture sector largely consumed water resources with low water productivity, and the only feasible approach is to save water resources by improving the water use efficiency. On the other hand, agricultural water use can be saved by introducing the virtual water strategy and reasonably decreasing the agricultural land area, thus indirectly increasing the ecological water use. Seeking a balance between agricultural production and ecological conservation is of important value to guiding the ecological sustainability in the ecologically fragile water-scarce regions (Hoekstra 2009). Virtual water concept brings global insights across countries for improving water and land management, fostering adaptation strategies to trans-boundary resource management.

Previous studies focused primarily on national-level and provincial-level virtual water issues. Only a few studies have addressed virtual water flows at the county level, and have addressed the feasibility of inter-basin virtual water strategies (Jia et al. 2017; Chen and Li 2015). Thus, the aims of this chapter are to address this knowledge gap by: (1) assessing the virtual water flows at the county level, river basin level, and sector level for the Heihe River Basin; (2) distinguishing between surface water and groundwater flows in virtual water import and export; and (3) evaluating the water stress status of the Heihe River Basin. This chapter will provide policy implications for water resources management from the perspective of virtual water and industrial structures in arid regions.

Virtual Water Flows in the Heihe River Basin

The Heihe River Basin, located in the arid regions of Northwest China, is the second largest inland river basin in China with an area of 116,000 km^2 and a mean runoff of 2800 Mm^3/a. In Northwest China, alternating high mountains and basins lie in the inland river basin. Runoff flow from the mountains is the determining ecological factor for the inland river basin. The oases cannot survive and become desertified without water. The main stream of the Heihe River originates from the Qilian Mountain, which is mainly located in Qinghai Province. The river flows through the Hexi corridor of the Gansu Province and terminates in the Juyanhai Lake on the Inner Mongolia Plateau (Fig. 1). The Heihe River Basin has been divided into upstream, midstream, and downstream areas by the boundary lines of two hydrological stations (Yingluoxia and Zhengyixia). The mountainous areas, usually distributed in the upstream areas of river basins, are water consumption areas and often undergo much more precipitation, snowmelt, and glacier melt. The historical mean annual precipitation declines sharply from approximately 338 mm in the upstream area to 127 mm in the midstream area, and 49 mm in the downstream area (China Meteorological Administration). Precipitation is scarce in the midstream and downstream areas of inland river basins, the midstream and downstream areas are water consumption areas.

There are relatively abundant water resources in the upstream areas compared to the other two areas, especially the downstream area. Hills dominate the terrain in the upstream area, where animal husbandry is the main income source for farmers. The midstream area consists of broad, flat plains that are suitable for irrigated agriculture, which accounts for the majority of the water consumption in the basin. In contrast, the downstream area is mainly desert. Discharge in the downstream area has decreased significantly, and more than 30 tributaries, as well as the terminal lakes, have dried up. The Heihe River Basin is an exemplary region in China experiencing water scarcity. With the rapid population growth, economic expansion, abrupt water

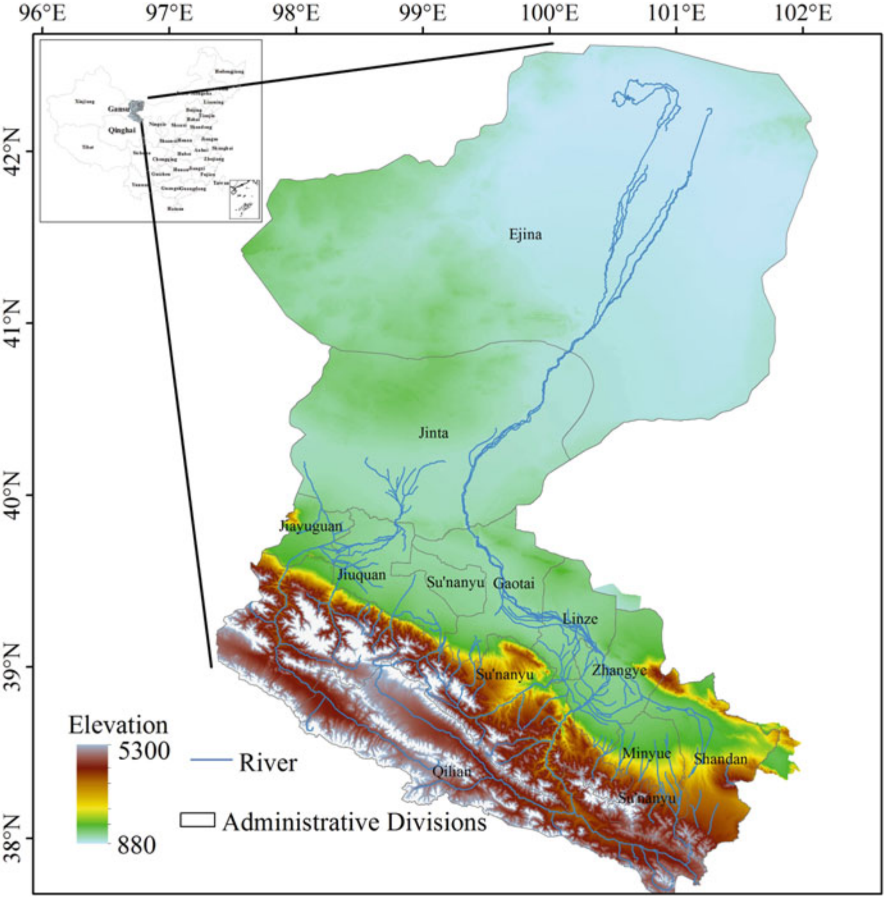

Fig. 1 Map of the study area (Reprinted from Zhang et al. (2017) with permission of Water)

exploitation, and irrational water allocation in the upstream and midstream areas of the river basins, the consumption of water increases dramatically and diminishes the water available for ecological processes, thus accelerating ecological degradation over the last five decades (Cheng et al. 2014). The terminal lakes dry up, sandstorms become more common, and the Populus euphratica forests die, causing a series of severe ecological disasters (Department of Geoscience, CAS).

Data and Methodology

Data Sources

The IO table at the county level of the Heihe River Basin was compiled and cited from the research project “the National Natural Science Foundation of China (Grant

No. 91325302).” With the support of “National Natural Science Foundation of the Heihe River Basin major research program,” the ecology-hydrological process and human disturbance on water resources were studied and explored in the Heihe River Basin. The IO table on water consumption at the sector level for 11 counties was obtained by the combination of survey methods and nonsurvey methods. The IO technical coefficients of key sectors at the county level were determined by survey methods and nonsurvey methods. Survey methods were applied to compile the input and consumption information of production in key sectors. Nonsurvey methods were adopted to obtain the technical coefficients of nonkey sectors from IO table at province level. The statistical data depicting regional economic structure, development speed, and technology improvement were reliable although the errors of these statistics exist. Total output values of sectors were derived from the Statistics Yearbook in 2012. The volumes of surface water and groundwater were collected from the Bulletin of first national census for water, which was conducted by the Ministry of Water Resources.

The Water Use Coefficients

The input–output model can quantitatively analyze the water use efficiency of each sector in the national economic system from two perspectives of input and output, and guide the regional industrial structure adjustment according to the calculation results of the key indicators of water use efficiency.

The direct water use coefficient of each sector can be expressed as:

$$q_j = w_j / X_j \tag{1}$$

For the first sector of the total output, the departments of the direct water consumption coefficient of q_j represents the direct water consumption coefficient for j sector; w_j is direct water consumption for j sector; X_j is the total output for j sector; the direct water consumption coefficient q_i in each sector constitutes line vector of water consumption coefficient $Q = (q_1, q_2, \ldots, q_n)$.

The line vector of water consumption coefficient Q in each sector pre-multiplication Leontief inverse matrix equals the total water demand vector H^d as follows:

$$H^d = Q\left(I - A^d\right)^{-1}. \tag{2}$$

$(I - A^d)^{-1}$ is Leontief inverse matrix, which means that the coefficient matrix is fully needed related to the final use. A^d represents direct consumption coefficient matrix $\left(A_d = x_{ij}^d / X_j\right)$. The total water demand vector $H^d = \left(h_1^d, h_2^d, \ldots, h_n^d\right)$ includes direct and indirect water demand in the production process. In other words, the amount of each economic sector is needed when the final consumption (use) increases one unit.

After introducing the direct water consumption coefficient and the total water demand coefficient, we need to calculate the direct water consumption and the total water demand. The amount of physical water consumed by the sector j is the direct water consumption of the sector j by multiplying the total output of the sector, which is derived from Eq. (1):

$$w_j = q_j x_w^d. \tag{3}$$

Local total water demand is total water demand coefficient h_j of sector j by multiplying the final use $y_i^d(i = j)$, as follows:

$$tw_j^d = h_j^d y_i^d(i = j). \tag{4}$$

tw_j^d represents local total water demand in sector j, which means that the direct and indirect water demand in all sectors of economic system in the production process of the final use of the product.

Multi-regional Input–Output Model

The multi-regional input–output (MRIO) model is a useful tool for capturing the economic relationships among different regions and sectors, and is based on the input–output (IO) table method formulated by Leontief. The MRIO model has the ability to trace the spatial transfers of ecological and environmental damage, and has been widely used to investigate virtual water footprints (Dalin et al. 2015; White et al. 2015; Mubako et al. 2013). This chapter applies the MRIO model at the county level for the Heihe River Basin. In the MRIO table, the Heihe River Basin consists of 11 counties, and the sectors have been aggregated into 48 sectors (Table 1). Input–output analysis has been subsequently further developed and applied in a large number of studies, and is adopted as an analytical framework developed by Wassily Leontief in the late 1930s (Miller and Blair 2009).

In the basic IO model, economic output can be expressed as the sum of intermediate consumption and final demand. The Leontief IO relationship is as follows:

$$x = (I - C)^{-1} y \tag{5}$$

where x is the vector of economic output, I represents the identity matrix, C is the direct IO coefficients matrix, and y is the vector of the final demand. $(I - C)^{-1}$ is recognized as the Leontief inverse matrix, representing the total production that each sector must satisfy the final demand of the economy, and expressing the total requirements of each sector in terms of both the direct and indirect inputs. The water resource is divided into groundwater and surface water in the IO table.

In this chapter, a MRIO model was employed to extend the standard IO matrix to a larger economy in which each sector in each county is assigned a separate row and column. The input–output (IO) method was developed by Wassily Leontief in the late 1930s. The IO model is based on data contained in national input–output tables. An IO table represents the flows of goods and services between economic sectors. Each sector of the economy in the IO table has one row and one column. Each entry in the i-th row and j-th column illustrates the flow from the i-th sector to the j-th

Table 1 The MRIO table at county level in the Heihe River Basin

	Middle use					Final use					Total output
Intermediate input	A^{11}	A^{12}	...	...	A^{1i}	F^{11}	F^{12}	...	...	F^{1i}	X_1
	A^{21}	A^{21}	...	...	A^{2i}	F^{21}	f^{21}	...	...	F^{2i}	X_2
	...	...	11 counties	...	...	...	...	11 counties	...	...	...
	...	...	...	Outside the basin	...	...	...	...	Outside the basin	...	...
	A^{i1}	A^{i1}	...	...	A^{ii}	F^{i1}	F^{i2}	...	...	F^{ii}	X_i
Surface water	W_{a1}	W_{a2}			W_{ai}						
Groundwater	W_{b1}	W_{b2}			W_{bi}						
Land	L_1	L_2			L_i						
Value added	V_1	V_2			V_i						
Total input	X_1	X_2	...	...	X_i						

sector. Equation (5) can thus be generalized to include imports from other counties, as formulated in Eq. (6):

$$\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} C_{11} & C_{12} & \cdots & C_{11} \\ C_{21} & C_{22} & \cdots & C_{21} \\ \vdots & \vdots & \ddots & \vdots \\ C_{n1} & C_{n2} & \cdots & C_{n1} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} + \begin{pmatrix} \sum_s y_{1j} \\ \sum_s y_{2j} \\ \vdots \\ \sum_s y_{nj} \end{pmatrix} \tag{6}$$

where x_j indicates the total output of production and consumption in region j, y_{ij} indicates each sector's output produced in region i and consumed in region j, and C_{ij} reflects the intermediate consumption; each column denotes the input from each sector in region i required to produce one unit of output from each sector in region j. Vector x reflects total output of all economic sectors (x_j) in each county. Final demand (y matrix) exhibits the sum of household consumption, government expenditure, capital formation, changes of inventory, and international export.

Virtual water flows (VW) are calculated as:

$$VW = k_c\,(I - C)^{-1} y \tag{7}$$

where k_c is a row vector of water consumption per unit of sectorial output.

Water Use Structure and Water Use Coefficient in the Heihe River Basin

According to the annual report of the Heihe River Basin in 2012, the total water consumption of the Heihe River Basin in 2012 is 2.548 billion m^3 (Table 2), of which the irrigation water, the ecological water consumption, the industrial water consumption, and urban and rural living water are 2.154 billion m^3, 236 million m^3, 0.81 m^3, and 78 million m^3, respectively.

Table 2 Water use in sectors of the Heihe River Basin in 2012 (10^4 m^3)

Counties	Life	Industry	Irrigation	Artificial ecology	Total water use	Natural ecology
Qilian	582	236	1145	106	2069	–
Sunan	334	571	640	180	1725	–
Shandan	841	1950	12,465	–	15,256	–
Minle	943	600	34,139	265	35,947	–
Ganzhou	2653	2152	76,758	2671	84,234	–
Linze	713	614	38,209	3421	42,957	–
Gaotai	769	783	45,515	2693	49,760	–
Ejina	165	660	–	4201	5026	65,674

From the regional distribution of water use in the basin, the water consumption is mainly concentrated in the middle reaches of the Heihe River Basin. The total water consumption of various sectors is 2.282 billion m^3, accounting for 89.5% of the total water consumption in the basin with is 2.071 billion m^3 of the irrigation water, 9 million m^3 of the ecological water consumption, 61 million m^3 of industrial water consumption, and 59 million m^3 of domestic water consumption. In the downstream area, water consumption is 229 million m^3, accounting for 9.0% of the total water use of the basin, while in the upstream area, water consumption is 38 million m^3, accounting for 1.5% of the total water consumption.

The Heihe River Basin is a resource-based water scarce area, and regional water resources is difficult to meet the local economic and social development and ecological water needs. According to the recent management planning of the Heihe River Basin, the future utilization of water resources in the Heihe River Basin needs to be further adjusted. The adjustment should include the control of irrigated area size, the adjustment of the industrial structure and agricultural planting structure, the development of characteristic agriculture and efficient agriculture, and the establishment of industrial structure and economic layout to adapt to Heihe River Basin water resources condition. Agriculture is the main water consumption sector in the Heihe River Basin, and there is a huge water saving space. According to the plan, the irrigated area of farmland in the middle reaches of the irrigation area decreased from 276 million acre to 254 million acre, and the water saving area increased from 53.85 million acre to 84.87 million acre. The farmland irrigation quota is reduced from 629 m^3/acre to 580 m^3/acre in 2020. Agricultural irrigation water demand from the current situation of 1.827 billion m^3 reduced to 1.546 billion m^3 in 2020 to achieve the goal of 280 million m^3 in agricultural water saving. Agricultural water savings are mainly transferred to the industrial and ecological sectors.

From the perspective of water use structure, direct and total water consumption coefficients of virtual water in the primary industry of the Heihe River Basin were the largest, while the smallest coefficients lied in the tertiary industry in 2012. The direct consumption of virtual water is from direct water use in the primary industry, and about 80% of the total water consumption coefficient is the direct water consumption coefficient. The proportion of the direct water consumption coefficient in the total water consumption coefficient of the secondary industry is only 30%, while the proportion of the tertiary industry is lower, only about 3%. This indicated that the second and tertiary industries mainly consumed indirect water. Obviously, the direct water-based industry consumes a lot of local water resources, while indirect water-dominant industrial sector can rely on imports or transfers to the water resources to increase the middle input, thus reducing the local water resources pressure. Table 3 listed the industrial water use coefficients in 48 sectors at county level in upstream, midstream, and downstream of the Heihe River Basin.

From a regional perspective, the difference in water use coefficients between regions is also significant. One of the smallest water use coefficient of the first industry is Ejin County, and the highest water use coefficient is Qilian County, with a difference of about 4 times. Gaotai County, Shandan County, Linze County, and Jinta County in the secondary industry take relative advantages on water resources

Table 3 Industrial water use coefficients at county level in upstream, midstream, and downstream of the Heihe River Basin

	Qilian County		Ganzhou County		Ejina County	
Sectors	Direct water use coefficient (m^3/YUAN)	Total water input coefficient (m^3/YUAN)	Direct water use coefficient (m^3/YUAN)	Total water input coefficient (m^3/YUAN)	Direct water use coefficient (m^3/YUAN)	Total water input coefficient (m^3/YUAN)
1	0.508424	5591.421	0.248759	2806.447	0.67112	7213.539
2	2.144524	23376.64	2.777295	30195.84	2.830771	30334.05
3	0.116855	1313.316	0.036387	475.6144	0.154249	1685.305
4	0.052801	573.086	0	41.97869	0.069698	741.9691
5	0.106518	1274.239	0.125702	1475.173	0.140604	1614.307
6	0.100226	1204.171	0.097356	1166.717	0.132299	1523.545
7	0.025291	681.4308	0.008297	428.5772	0.033384	764.6911
8	0.001034	206.6601	0	174.6717	0.001365	206.2758
9	0	181.5959	0	158.0077	0	177.6036
10	0.003383	342.0981	1.71E-05	265.0259	0.002771	327.9451
11	0.006443	288.9741	0	201.3893	0.005277	274.2446
12	0.00477	813.1379	0.003557	806.6113	0.003907	817.0885
13	9.81E-05	540.2689	0	536.3931	8.04E-05	545.0521
14	3.1E-05	351.2956	0	338.2182	2.54E-05	352.8515
15	0.002674	308.2184	0.005076	314.9515	0.00219	302.929
16	0.002956	342.343	0.004778	362.1138	0.002421	337.4972
17	7.07E-05	158.6914	0	147.8354	5.79E-05	158.2439
18	0.001145	329.009	0.001143	312.6067	0.000938	325.3912
19	0.003169	285.6216	0.001876	250.3703	0.002595	276.477
20	0.000269	272.8811	0	240.07	0.00022	268.0431
21	0.000182	291.4947	0.000449	266.7404	0.000149	286.4705
22	6.23E-05	222.7203	0	206.307	5.1E-05	220.1607
23	1.46E-05	202.9099	1.82E-05	194.3161	1.2E-05	201.5226
24	1.22E-05	232.5284	3E-05	218.1696	1E-05	230.2491
25	0	138.4506	0	133.528	0	137.1626
26	0	155.9327	0	150.5488	0	154.932
27	1.52E-06	329.102	3.75E-06	309.5311	1.25E-06	329.6299
28	0	30.88341	0	28.95183	0	30.59677
29	0.001856	574.4165	0.004387	504.3368	0.00152	548.3893
30	0.002622	171.974	0	138.888	0.002147	166.7323
31	0.569246	6041.75	0.625713	6557.857	0.46624	5000.156
32	5.42E-05	224.9238	3.49E-05	213.3527	4.66E-05	223.9351
33	6.9E-06	165.0326	0	155.104	7.19E-06	168.1274
34	0	102.8449	0	97.84684	0	103.2037
35	9.85E-05	105.0619	0	96.6537	1.32E-05	103.3423
36	0.000135	107.9574	7.05E-05	100.0391	5.55E-05	107.1323
37	0.000322	415.1455	0.000271	397.3486	0.000262	417.7359
38	0.000124	80.82765	0.000101	73.55852	6.88E-05	80.40831

(*continued*)

Table 3 (continued)

Sectors	Qilian County		Ganzhou County		Ejina County	
	Direct water use coefficient (m^3/YUAN)	Total water input coefficient (m^3/YUAN)	Direct water use coefficient (m^3/YUAN)	Total water input coefficient (m^3/YUAN)	Direct water use coefficient (m^3/YUAN)	Total water input coefficient (m^3/YUAN)
39	0.000105	47.69626	3.29E-05	41.78797	1.95E-05	47.90766
40	0.000237	197.9627	2.54E-05	184.4088	2.53E-05	196.4059
41	0.00281	216.6228	0	180.6458	0	188.9788
42	0.00064	115.164	0.000576	109.0575	0.000325	112.6899
43	0.018955	437.674	0.010423	360.7073	0.019309	444.099
44	0.000267	185.3946	3.42E-07	179.9219	2.08E-05	183.7729
45	0.001762	148.0615	0.002648	145.3635	0.001746	147.1065
46	0.000848	242.6886	0.000708	236.9535	0.000766	241.4216
47	0.000516	208.9176	4.92E-06	196.1031	1.5E-05	204.5231
48	8.57E-05	128.4303	1.72E-05	116.3538	3.45E-05	128.3258

utilization, with lower water coefficient below 0.1. The tertiary industry’s water use coefficient is generally low, and lowest direct water use coefficients exist in Shantan County and Sunan County.

To sum up, the Heihe River Basin is facing gradual water shortage. The local government should put the appropriate restrictions on the primary industry by increasing the water saving within the agricultural transformation, improving the proportion of efficient water-saving crops and agricultural production technology level. In the meanwhile, increasing the proportions of secondary and tertiary industry could ease water scarcity of the Heihe River Basin. In addition, it is necessary to fully combine the characteristics of the industrial structure of the water resources within the basin to rationalize the industrial layout of the river basin.

Virtual Water Flows at the River Basin Level

For thousands of years, sufficient water has been available to support grazing and agriculture in the Heihe River Basin. Land use patterns have been altered to support blooming populations. However, the Heihe River Basin, as China’s northwestern arid region, has experienced a common challenge recently. The Heihe River Basin was divided into three areas: upstream, midstream, and downstream. Each area has distinct characteristics in terms of water resources, economic structure, household income, and consumption patterns (Table 4).

The total amount of virtual water imported into the Heihe River Basin was 1.06 billion m^3, and the total amount of virtual water exported was 2.11 billion m^3. Based on the research results of Cai et al. (2012), in the Gansu province, which occupied the majority part of the Heihe River Basin, the net virtual blue water export accounted for 10% of the total natural runoff through food trade in the basin, and

Table 4 Socioeconomic characteristics of the Heihe River Basin (Reprinted from Zhang et al. (2017) with permission of Water)

Counties	Population (10^4)	Urbanization rate	GDP (Billion Yuan)	Industry structure (Primary industry: Secondary industry: Tertiary industry)
Qilian	4.70	–	0.52	24:38:38
Ganzhou	51.60	37.00	7.67	25:36:40
Sunan	3.64	30.80	0.94	21:61:18
Minle	24.00	13.90	1.92	37:33:31
Linze	14.70	16.00	2.18	32:43:25
Gaotai	15.80	16.00	2.09	41:37:22
Shandan	19.80	34.80	2.22	22:42:36
Suzhou	40.64	43.50	6.20	13:54:34
Jinta	14.70	23.80	2.40	30:30:40
Jiayuguan	18.59	88.90	14.40	1:82:17
Ejina	1.65	70.00	2.04	3:61:36

accounted for 25% of the total blue water use. Thus, the Heihe River Basin is a net virtual water exporter of 1.05 billion m^3, accounting for one third of the total water resources in this region. The upstream area (Qilian County) had small virtual water flows to and from the rest of the basin (Fig. 2). In this area, the vegetation has been seriously degraded by deforestation, overgrazing, and grassland reclamation since the 1950s. The glacier area in the Heihe River Basin has decreased by 29.6% over the past 50 years (Wang et al. 2011). The midstream area, which covers most areas of Ganzhou, Sunan, Minle, Linze, Gaotai, Shandan, Suzhou, Jinta, and Jiayuguan Counties, exported 96.31% of virtual water (2.04 billion m^3) to outside the basin, and imported 88.84% of their virtual water (0.94 billion m^3) from outside the basin. Rapid agricultural development accounted for increased water consumption in the midstream area of runoff from the mountainous areas. In the Heihe River Basin, the agricultural land increase of 75 million m^2 led to the increasing water consumption of about 5 million m^3. As a consequence of rapid agricultural development, both water use patterns and land use types underwent dramatic changes (Cheng et al. 2014). As with the upstream area, the downstream area (Ejina County) also had limited virtual water flows. The amount of physical water entering the downstream area decreased significantly from the 1950s to the 2000s as a result of the large expansion of irrigated farmlands in the midstream area.

Over 2004–2006, the water footprint of the Heihe River Basin was million m^3 $yr.^{-1}$, of which 960 million m^3 $yr.^{-1}$ were green and 800 million m^3 $yr.^{-1}$ were blue. Agricultural production is the sector with the largest water consumption, accounting for 96% of the water footprint (92% of crop production and 4% of livestock production). The remaining 4% was for industrial and domestic sectors. The water footprint of the "blue" (surface water and groundwater) component is 8.11 million m^3 $yr.^{-1}$. This indicates that blue water accounts for 46%, well above the world average and the Chinese average, mainly due to the water scarcity in the Heihe River Basin and high dependency on crop production. However, even in such

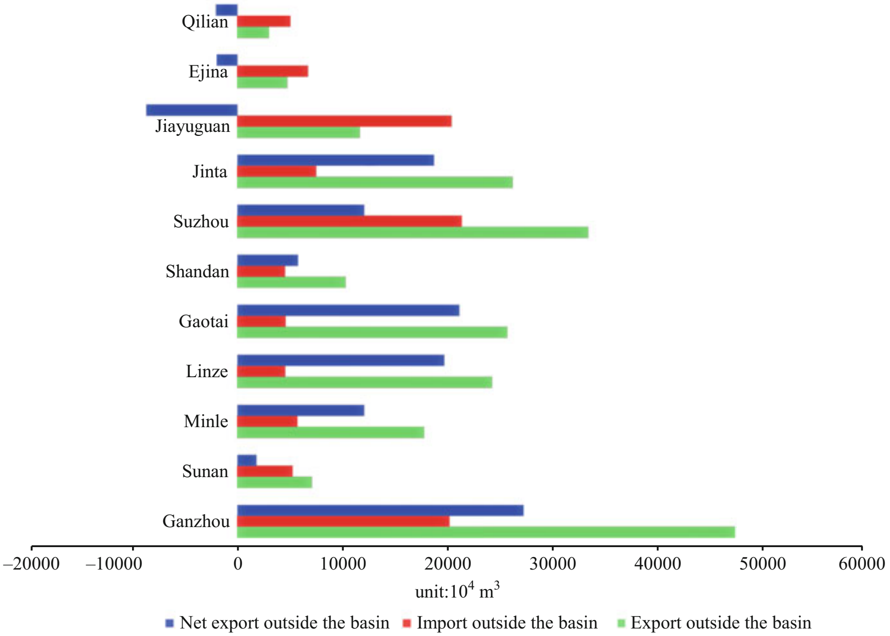

Fig. 2 Virtual water flows between different counties in the Heihe River Basin (Reprinted from Zhang et al. (2017) with permission of Water)

a river basin, the blue water footprint is still less than the "green" (soil water) water footprint, indicating the importance of green water (Zeng et al. 2012).

Virtual Water Flows at the County Level

Compiling a multi-regional IO table at county level is crucially vital to making appropriate policy for balancing economic development and water resources management at county level. An extended input–output table at county level is divided into three parts of sectors in the primary industry, secondary industry, and tertiary industry, respectively. From the perspective of policy-making, the output value of the tertiary industry to the provincial primary industry is more than that of the county level, which is estimated by the different proportion of other inputs in the tertiary industry's output to the primary industry (Deng et al. 2014).

The agricultural sector consumed the largest amount of water in each county in the Heihe River Basin (Table 5). The water consumption of the secondary and tertiary industries was less than that of agricultural production. Water consumption structures at the county level in 2012 showed that regions with grain production had high levels of water consumption; corn or wheat production accounted for the largest proportion (almost 50%) of total water consumption. For example, the water use for corn production in Ganzhou County accounted for 54.53% (449.07 million m^3) of

Table 5 Water consumption for key sectors at county level of the Heihe River Basin (10^4 m^3) (Reprinted from Zhang et al. (2017) with permission of Water)

Counties	Total water consumption	Agricultural sector	Corn production	Wheat production
Qilian	1694.21	1416.75	594.46	6.47
Ganzhou	82,351.67	79,302.18	5972.51	44,906.67
Sunan	11,780.58	11,434.79	4248.49	5050.66
Minle	26,248.54	25,456.54	9865.74	1891.69
Linze	40,860.99	40,027.45	721.33	23,529.22
Gaotai	42,757.56	42,029.49	5656.42	18,328.82
Shandan	14,949.32	13,731.75	6664.54	419.14
Suzhou	19,267.03	16,484.47	3087.09	1572.70
Jinta	10,337.30	2925.42	548.73	278.52
Jiayuguan	14,355.89	13,655.25	2556.02	1301.01
Ejina	1617.38	1010.80	114.83	376.62

total water consumption, while the proportion of consumption for wheat was 44.58% (66.64 million m^3) in Shandan County. The water consumption results can be captured in consumption coefficients for each sector. The coefficients in the agricultural sector of Zhangye city (including Ganzhou, Sunan, Minle, Linze, Gaotai, and Shandan Counties) was 0.15 m^3/yuan in 2012, which was 0.05 m^3/yuan higher than that of Jiayuguan County, and 0.02 m^3/yuan higher than that of the national level for China in 2002 (Chen et al. 2017).

In this chapter, the MRIO model was applied to quantify the amount of imported and exported virtual water at the county level for the Heihe River Basin in 2012 (Fig. 3). Qilian, Ejina, and Jiayuguan Counties are the primary importing counties, while Ganzhou, Sunan, and the remaining counties are the virtual water exporting counties. Table 2 presents the details for the amounts of imported and exported virtual water at the county level for the Heihe River Basin. Ganzhou County stands out as the county which contributed significantly to both imported (0.20 billion m^3) and exported virtual water (0.47 billion m^3). The intercounty virtual water flows in the basin showed that the top three exporters of virtual water are Ganzhou, Linze, and Gaotai Counties with amounts of 0.91, 0.71, and 0.66 million m^3, respectively. The largest receiver of virtual water from other counties was Suzhou County (1.13 million m^3). Ganzhou County was the next biggest receiver of virtual water (0.92 million m^3) from counties within the basin. The key to mitigating severe water consumption in the Heihe River Basin is to adjust industry structures, and thus to optimize water consumption structures.

Virtual water import implies increased water availability and might be one way to alleviate regional water stress. In contrast, the export of virtual water indicates increased water consumption, which contributes to water stress on local water resources (Bulsink et al. 2010; Zhang et al. 2011). A previous study on water consumption in the Hetao irrigation district showed that the export of virtual water contributed more pressure to water scarcity than local production (Liu et al. 2017). The interbasin virtual water flows (blue water) indicated that the total amount of

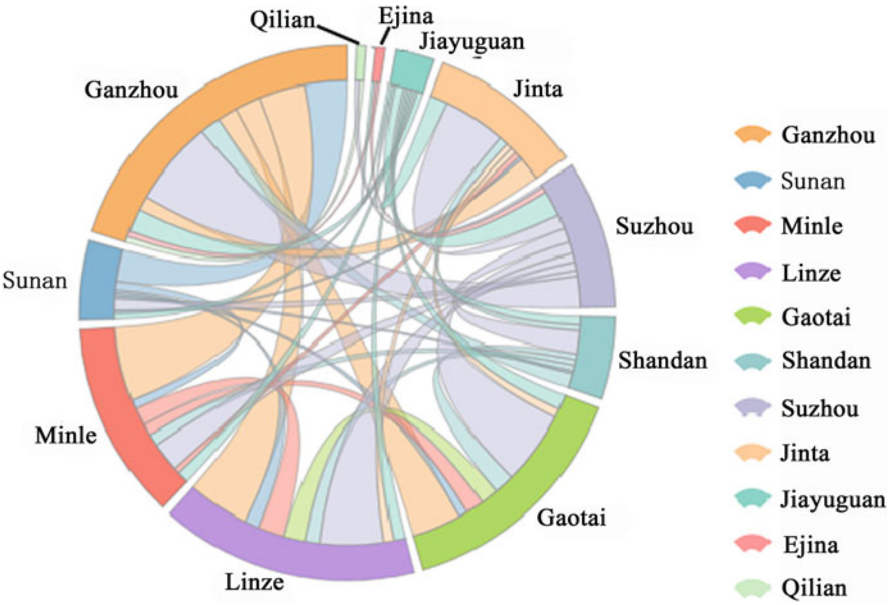

Fig. 3 Virtual water imports and exports at the county level for the Heihe River Basin. The color of the links refers to the counties (Reprinted from Zhang et al. (2017) with permission of Water)

Table 6 An account of the virtual water import and export at county level of the Heihe River Basin (unit: 10^4 m^3) (Reprinted from Zhang et al. (2017) with permission of Water)

Counties	Other counties in the Basin (Exporters)	Other counties in the Basin (Receivers)	Export outside the Basin	Import outside the Basin	Net export outside the Basin
Qilian	2.36	6.89	3043.54	5077.05	−2033.51
Ganzhou	91.19	92.57	47,302.46	20,123.45	27,179.01
Sunan	22.74	28.07	7096.40	5285.61	1810.79
Minle	54.77	37.96	17,769.94	5735.70	12,034.24
Linze	70.77	27.68	24,215.79	4571.68	19,644.11
Gaotai	66.12	26.08	25,678.01	4614.42	21,063.59
Shandan	21.87	30.24	10,309.50	4558.34	5751.16
Suzhou	42.10	112.98	33,327.96	21,301.00	12,026.96
Jinta	43.63	20.02	26,163.75	7503.92	18,659.84
Jiayuguan	9.73	37.93	11,665.25	20,318.16	−8652.91
Ejina	0.65	8.49	4763.28	6727.54	−1964.26

virtual water imported into the Heihe River Basin was 4.29 million m^3 and total virtual water exported from the basin was 4.26 million m^3 (Table 6). This indicates that there was 0.03 billion m^3 of virtual water imported specifically through interbasin transfers. This reinforces our observation that interregional trade makes little contribution to alleviating water stress in water-scarce regions.

Virtual Water Flows by Sectors

Figure 4 shows the virtual water flows at county level by sector in the Heihe River Basin (only amounts above 1.5 million m^3 are shown). Of the 48 aggregated sectors, only 23 sectors revealed both the import and export of virtual water. When all the counties were considered, the sectors with the highest virtual water import and export were the food manufacturing and tobacco processing industries in Jiayuguan County with 73.57 and 119.33 million m^3, respectively, while the sector with the lowest virtual water import and export for all counties was the textile industry with

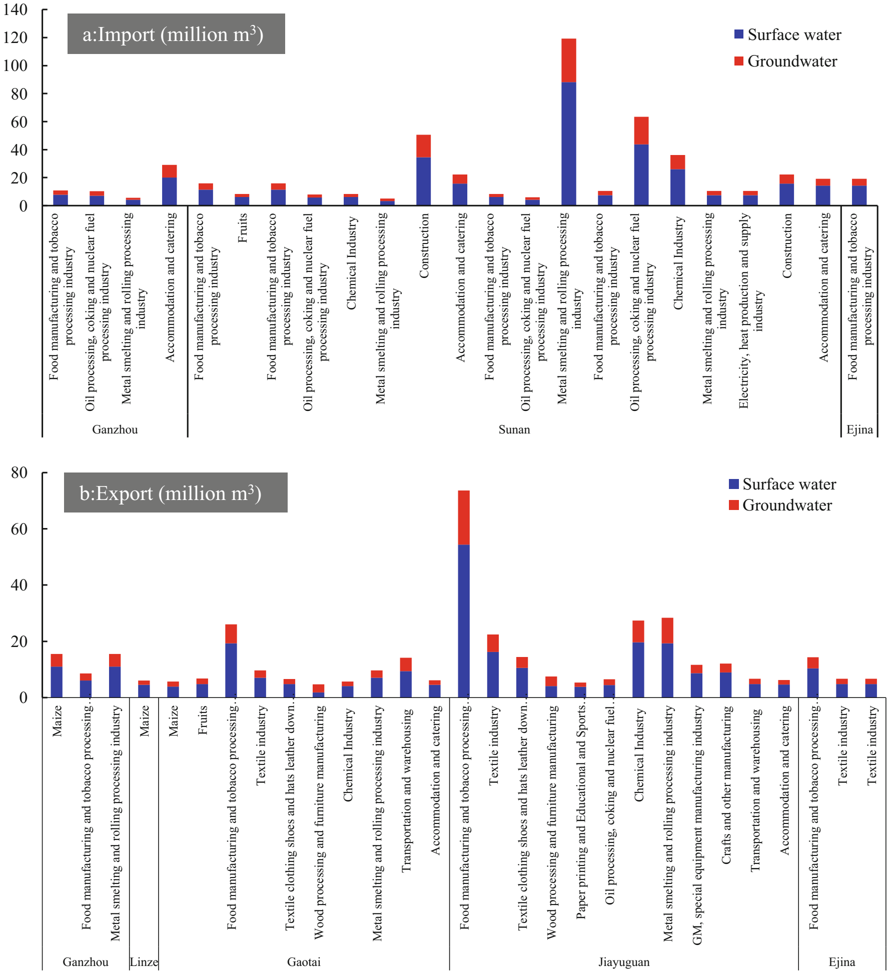

Fig. 4 The interbasin virtual water flows at the county level by sector in the Heihe River Basin. (**a**) virtual water import; (**b**) virtual water export (Reprinted from Zhang et al. (2017) with permission of Water)

1.44 and 0.20 million m^3, respectively. The sectors mainly responsible for virtual water import are the chemical industry, accommodation and catering, the food manufacturing and tobacco processing industries, and the metal smelting and rolling processing industries (Fig. 4a). In contrast, the sectors that mainly export more virtual water than they import are maize production; the textile industry; transportation and warehousing; and textiles, clothing, shoes and hats, leather down and its products (Fig. 4b). By making full use of the water saving effect of imported trade, water scarcity in China can be alleviated. First, agriculture and other sectors of imports including general machinery, equipment manufacturing industry, and petrochemical industry should be expanded. These industries in China's import and export trade has a high virtual water intensity. To strengthen the import of goods in these sectors, the tensions of China's water consumption can be better alleviated. China imported virtual water through three sectors: agriculture, petrochemical industry, general machinery, and equipment manufacturing industry (Chen et al. 2017).

In Ganzhou County, maize production dominated the largest contributor to the regional water stress, with a net virtual water export of 11.04 million m^3. The studies on virtual water at the sector level inhibited that food and agriculture are crucial sectors affecting virtual water trade interregionally (Zhang and Anadon 2014). The service sector's influence on water stress varied from county to county. For instance, the virtual water export by leasing and business services in Suzhou and Jiayuguan Counties was around 16.00 million m^3, while the virtual water import in Jiayuguan County (31.34 million m^3) was almost triple that of Suzhou County (11.19 million m^3). The leasing and business services sector in Jiayuguan County were presented to relieve the water shortage. Overall, the Heihe River Basin imported a small portion of virtual water (raw and processed food products) during the 10 years from 1997 to 2007 (Jin et al. 2016).

Most previous assessments of global water resources have focused on surface water. However, humans are overexploiting groundwater in many large aquifers that are critical to agriculture, especially in Asia and North America (Gleeson et al. 2012). Figure 4 also provides virtual water flows by distinguishing between surface water and groundwater. Clearly, almost all the sectors experienced more virtual water flows from surface water than that from groundwater, with the ratio of surface water to groundwater virtual water ranging from 1.20 to 2.91. An exception was the wood processing and furniture manufacturing sector in Suzhou County, where virtual water flows from groundwater exceeded those from surface water. This is possibly a result of Suzhou county having the highest utilizable groundwater resources (about 0.25 billion m^3) among all the counties. However, it should be noted that more than 50% of groundwater has been seriously degraded as a result of the overuse of fertilizers and pesticides (Dong et al. 2009). The discharge of high-concentrated pollution to surface flows from intensively pollution-generating production sectors (e.g., paper, chemicals, and textiles) has led to many major rivers in North China no longer being able to support any type of beneficial use because of their poor water quality. Water consumption in different sectors damaged water quality to some extent, which is vital for water-scarce regions. Policy about industry structure adjustment suggested that the sectors affecting water quality and consuming large amounts of water should be transferred to less-polluted and less-consumed sectors.

Over the past 6 years, the sum of virtual water imports in two sectors including agriculture and electric and water industry accounted for about 64% of China's total virtual water resources. The virtual water intensity of the exports of the sectors such as agriculture; electric and water industry; food, beverage, and tobacco products; textile, garment, and leather products industry in China is quite strong. Agriculture and services industry have no significant pull on the export of virtual water in China. However, agriculture and electric and water industry exported the most virtual water in China. Over the past 6 years, the total amount of virtual water exports in these two provinces accounted for about 80% of China's total virtual water exports. The sector of manufacturing industry is the main industry that drives China's virtual water exports. Food, beverage, and tobacco products; textile, garment, and leather products; petrochemical industry; general machinery; and equipment manufacturing industry exported virtual water of 387.3 billion tons in total among 2000, 2002, 2005, 2007, 2010, and 2012, accounting for 72% of the total amount of virtual water exports (Chen et al. 2017).

Water Stress and Water Scarcity

According to the United Nations, as of 2050, it will face a water problem of 2–2. 7 billion people, and per capita water will be reduced by more than one third over the next two decades. In these countries, China's water scarcity is the most serious, in which per capita available water resources is only 2300 m^3, lower than the world per capita of one-fourth population, ranked the 110th in the world, and is one of the world's 13 most water-scarce countries. China is well-known covering a temperate south and an arid north. There are also a large number of regional diversity in North and South China. The per capita available water resources in southern China are about 3600 m^3. The North China Plain exhibits the highest water scarcity, where per capita water availability is under 150 m^3, much lower than that in North China. In Northern China, water scarcity largely attributes to water use conflicts between upstream and downstream areas in the river basin, and between agriculture and the municipal and industrial sectors as well. In addition, more than 400 cities face water resources shortage in supply among China's 699 cities, and 110 cities face severe scarce water resources. This situation severely limits the sustainable development of China's national economy (He et al. 2011; Chen et al. 2017). Agriculture sector has been growing fast, and is the largest water consumer. Besides, water stress has given rise to deterioration of fresh water resources in terms of quantity (aquifer overexploitation and dry rivers, etc.) and quality (eutrophication, organic matter pollution, saline intrusion, etc.) (Cai 2008).

Water Stress Index Adjustment

Over the past few decades, the problem of water scarcity has increasingly been seen as a global systemic risk due to increased water demand and limited water supply

(Mekonnen and Hoekstra 2016). At present, various methods such as water resources vulnerability index, water stress index, international water management institute index, the water poverty index, and critical ratio are used to assess regional water shortage, water resources, acquisition, and capacity. Water stress is defined as the ratio of total annual freshwater withdrawals to total freshwater availability. In addition to that, the researchers should consider other different perspectives to learn more about water scarcity. Moreover, global water shortages were evaluated from a production perspective and demonstrated a mean annual basis for irrigation agriculture (A/Q), the domestic and industrial sectors (DI/Q), and their combinations (DIA/Q). Other researchers also took into account the large amount of water consumption and calculated the water scarcity associated with food production (Porkka et al. 2016; Liu et al. 2017). The Falkenmark indicators may be based on per capita usage of the most widely used water stress measures, which classified water resources in one area as no water stress (per capita 1700 m^3/y), water stress (per capita 1000–1700 m^3/y), water scarcity (per capita 500–1000 m^3/y), and absolute water scarcity (per capita <500 m^3/y) (Falkenmark et al. 1989).

This chapter adopts the water stress index (WSI) as defined by Pfister et al. (2009) and adjusts it for virtual water. The WSI concept represents the portion of water consumption that transfers freshwater to other users, thus indicating the pressures on renewable water resources. The *WSI* is expressed as:

$$\mathrm{WSI} = \frac{WC + VW_{ex} - VW_{im}}{Q} \tag{4}$$

where WC refers to water consumption. VW_{im} is virtual water import, and VW_{ex} is virtual water export. Q is renewable freshwater availability. Water stress is defined as moderate and extreme above a threshold of 0.4 and 0.8, respectively.

Water Stress at the County Level in the Heihe River Basin

Physical and virtual water use varied in different streams of the Heihe River Basin. The WSI formula was modified to accommodate virtual water flows. The results showed that physical water use, virtual water net imports, and renewable freshwater availability were the main causes of changes in water stress. Incorporating virtual water flows into water stress analysis permits a better understanding of what is causing water stress. Most of the 11 counties in the Heihe River Basin have experienced water stress, and had WSI values >0.4 in 2012 (Table 7). The areas with extremely high water stress included Sunan and Jiayuguan counties in the midstream area, and Qilian County in the upstream area. The WSI values for Sunan, Jiayuguan, and Qilian counties were 3.02, 2.17, and 1.69, respectively. However, Ejina County in the downstream area did not experience water stress and had a WSI value of 0.09. In fact, the physical water consumption and net virtual water import in the upstream and downstream areas were similar. This indicates that the large difference in water stress is driven by renewable freshwater availability (Table 7).

Table 7 Water stress index (WSI) at the county level in the Heihe River Basin (Reprinted from Zhang et al. (2017) with permission of Water)

Streams	Counties	Renewable freshwater resources (Billion m^3)	WSI
Upstream	Qilian	0.02	1.69
Midstream	Ganzhou	0.80	0.69
	Sunan	0.03	3.02
	Minle	0.40	0.36
	Linze	0.43	0.49
	Gaotai	0.34	0.63
	Shandan	0.13	0.70
	Suzhou	0.65	0.11
	Jinta	0.36	−0.23
	Jiayuguan	0.11	2.17
Downstream	Ejina	0.41	0.09

National-level studies on virtual water have revealed that several economically advanced provinces, such as the cities of Beijing, Tianjin, Shandong, Shanghai, Zhejiang, and Guangdong, have imported huge amounts of virtual water from outside to alleviate their water stresses (Dalin et al. 2015; Zhang et al. 2012; Wang et al. 2013). This is especially applicable to the city of Beijing. Other researchers found that virtual water was exchanged and traded from arid regions to wet regions, and from north to south (Zhang and Anadon 2014; Guan and Hubacek 2007). However, only about 5% of the total available water use can be attributed to net virtual water flows in north China (Guan and Hubacek 2007). Moreover, surface water has been polluted by highly polluting production sectors (e.g., paper, chemicals, and textiles), and groundwater has been seriously degraded by agricultural activities. Thus, groundwater overexploitation in the midstream areas of the Heihe River Basin should be highly valued.

The middle oasis area is the main social and economic development gathering place of the Heihe River Basin, among which Zhangye oasis agriculture district in the middle reaches played important roles. Eighty percent planting area of the basin are concentrated in the city of Zhangye. Zhangye City is located in the middle reaches of the Heihe River Basin, which belongs to the typical arid oasis of agriculture. It is an oasis area with relatively high historical development, rapid economic development, and relatively high development potential in the Hexi corridor. It is known as the place with South China-type scenery and golden Zhangye. Zhangye City exhibits a low level of urbanization, weak economic base, big agricultural proportion. The county's economic level varies a lot. In 2012, about 1.21 million people existed in Zhangye City, of which the urban population of nearly 450,000 people with the urbanization rate of 35.98%. Agricultural is the main production sector in Zhangye oasis, while industrial process is still in its infancy and thus economic development is lagging behind. In the allocation of water resources, agricultural water consumption accounts for more than 95% of total water consumption, while water use efficiency is only 40–50%.

The counties in Zhangye City have different regional economic differences due to terrain, agricultural infrastructure, and socioeconomic infrastructure differences. The city's nearly half of the output value is from Ganzhou County. Ganzhou, Linze, and Gaotai Counties are characterized with higher GDP because it is the core area of the Heihe oasis. However, Shandan and Minle Counties are covered with the piedmont plain, so their regional economic foundations are very weak. Sunan County is mainly located in the grassland pastoral areas with the less population by gathering of ethnic minorities, in which animal husbandry is the key economic sector.

Since the implementation of the water reallocation program, the water environment in the middle reaches has been slightly adversely affected. The surface water recharge decreased, and the groundwater exploitation increased, leading to the gradually decreased middle water level. However, the water supply in the middle reaches has barely changed. The amount of available water in the middle reaches is about 10^8 m^3. The ratio between surface water and groundwater utilization remained stable among Ganzhou, Liyuan River irrigation area. Nevertheless, in Linze and Gaotai irrigation areas, groundwater exploitation increased dramatically. For example, groundwater exploitation in Linze and Gaotai Counties increased by 505% and 40% respectively from 2000 to 2008 (Cheng et al. 2014).

Virtual Water Strategy Application Facing Challenges

Over the past 50 years, China's surface water and total water resources were reduced by about 5% and 4%, respectively (Liu 2013), while the inland river basin in China occupies one third of the total land area. Water issue becomes the crucial issue of socioeconomic development and environmental protection in inland river basins due to congenital water shortage and unreasonable use (Feng et al. 2007). With the population booming and the rapid economic development in the upstream and midstream areas of the Heihe River Basin, the consumption of water increases dramatically and diminishes the water available for ecological processes, thus causing a series of severe ecological disasters. Nowadays, water use capacity of the Heihe River Basin is about 3.36 billion m^3, among which agricultural water use accounts for 95% and extremely squeezes ecological water use. The competition for water between economy and ecosystem is also getting more intense. Therefore, the Heihe River Basin experiences multidimensional drives of human activities involving ecology, animal husbandry, agriculture, and industry.

From the viewpoint of water resource characteristics, water not only has natural properties but also possesses socioeconomic and ecological properties. Information about water scarcity only considers the water supply aspect, and neglects the water demand aspect (Dalin et al. 2015; Deng et al. 2014). That said, industrial structure's effect on water demand should be considered. Agricultural irrigation has a large water demand, while service industries need less water. Much research has been done on virtual water trade for relieving water stress (Feng et al. 2012; Hoekstra et al. 2012; Deng and Zhao 2015; Fracasso et al. 2016).

In 1999, Professor Allan suggested that a country could implement a virtual water trade strategy to import water-intensive products from another country and reduce the export of high water consumption products in order to import (virtual) water resources, thus saving water resources. Import or export of physical water is very expensive, so the trade of virtual water could overcome this shortcoming and is an effective way to deal with water scarcity in countries with water shortages (Allan 1999). Over the past two decades, trade flows and trade in virtual water have doubled in all countries (Dalin et al. 2012). With the rapid development of China's international trade, the virtual water trade strategy will alleviate the problem of water shortage to a large extent, adjust China's foreign trade structure, reduce the export of virtual water, and increase the import of virtual water. However, the application of virtual water strategies to improve water use efficiency was challenged due to comprehensive capacities of economic level, social equity, infrastructural construction, and potential eco-environmental effect.

The implementation of the virtual water strategy can lead to a lot of surplus agricultural labor force, and the unemployment status of agricultural labor force. As a consequence, two important indicators should be considered when solving the problem of surplus agricultural labor force under the virtual water strategy, i.e., employment multiplier and "learning effect" of nonagricultural sectors. The social distribution equity could be represented with the Hoover coefficients, which provided a more straightforward interpretation of inequality than the Gini coefficient.

Implementation of the virtual water strategy will reduce the pressure of ecological water shortage and whereas change the regional production mode and the local biodiversity. Consequently, two indicators should be involved in the suitability assessment of the virtual water strategy, e.g., constraint of water resources on the ecological conservation, impacts of the virtual water strategy on biodiversity. The water resource is one of the limiting factors of ecological conservation and sustainability in water-scarce regions, especially where there is serious ecological degradation. However, if the high water agriculture is replaced by urbanization rather than low water agriculture, it may lead to the decline of vegetation coverage, consequently causing desertification, soil erosion, and ecological degradation.

Water has to be considered as a social, economic, as well as an ecological good. Social-economic-ecological systems have powerful reciprocal feedbacks and act as complex adaptive systems. The core of implementing virtual water trade is selecting an appropriate route to develop the secondary and tertiary industries that leads virtual water flow to industry and service sectors by dint of positive feedback loop. The positive feedback loop is efficient due to the driving mechanism of putting virtual water in the secondary and tertiary industries. Nevertheless, when the feedback loop evolves, adaptability of the feedback loop should be considered by adding compensation mechanism of industrial transition. Consequently, integrating social, economic, and ecological systems is a vital step to determine whether the virtual water trade is appropriate or not. There has been no standard index applied to tell the application boundary of virtual water trade in the world. The establishment of standard index for water-scare regions is also critical for the mechanism of water price and water right of surface and ground water.

Summary

Water scarcity in arid and semi-arid regions has been severe. In the Heihe River Basin, water resource sustainability, ecosystem health, and socioeconomic development are dependent on water. According to virtual water concept, water-scarce regions with spatial mismatches in water and arable land availability can improve their food security by purchasing a portion of their food requirements through agricultural trade and cutting local food production. A flourishing literature has been inspired on dealing with water scarcity through virtual water trade. To mitigate water stress, some researchers believe that food trade to increase virtual water in water-scarce regions is an efficient use of water resources. However, others have argued that the virtual water trade strategy as a solution to water scarcity is fallacious for several reasons: (1) no enough trade capital for traditional agricultural regions, (2) considering water as the only production factor while neglecting land, (3) lack of consumption pattern and production allocation in economic system. Furthermore, virtual water flows have varied effects on water stress for the water-receiving regions and the water-exporting regions. The key to mitigate water stress is improving water use efficiency, whereas the efficiency benefits will be highly compensated by the increased water demand caused by developed economy.

This chapter used a firstly compiled county-level input–output table, which was supported by the research project of “National Natural Science Foundation of the Heihe River Basin major research program.” The MRIO model at county level of the Heihe River Basin was applied to analyze virtual water import and export in 2012. In the MRIO table, the Heihe River Basin consists of 11 counties, and the sectors have been aggregated into 48 sectors. The water resource is divided into groundwater and surface water in the IO table. The total amount of virtual water imported into the Heihe River Basin was 1.06 billion m^3, and the total amount of virtual water exported was 2.11 billion m^3. In total, the Heihe River Basin is a net virtual water exporter at a scale of 1.05 billion m^3, accounting for one third of the total amount of water resource. The upstream and downstream of the basin had little virtual water flows with the rest of basin, whereas the midstream exported 96.31% (2.04 billion m^3) of virtual water to outside the basin, and imported 88.84% (0.94 billion m^3) from outside the basin.

For specific counties, regions with grain production had high levels of water consumption; corn or wheat production accounted for the largest proportion (almost 50%) of total water consumption. For example, the water use for corn production in Ganzhou County accounted for 54.53% (449.07 million m^3) of total water consumption, while the proportion of consumption for wheat was 44.58% (66.64 million m^3) in Shandan County. Ganzhou County accounted for the most virtual water import and export with 0.20 billion m^3 and 0.47 billion m^3, respectively. The top three exporters in the interbasin virtual water flows are Ganzhou, Linze, and Gaotai Counties, and the amount of water exporting is 0.91, 0.71, and 0.66 million m^3, respectively. When it comes to the sector-based water consumption, corn or wheat production in agricultural sector alternatively accounts for the biggest proportion (almost 50%) of total water consumption.

For most of the sectors, virtual water content in surface water is greater than that in groundwater by distinguishing between the “surface water” and “groundwater” components of virtual water, and the ratio of surface water to groundwater ranges from 1.20 to 2.91. Specifically, food manufacturing and tobacco processing industry had the highest amount of import and export virtual water, and the amount reached to 119.33 and 73.57 million m^3 separately. On the contrary, textile industry had the lowest amount of import and export virtual water of 1.44 and 0.20 million m^3. The sectors mainly responsible for virtual water import are the chemical industry, accommodation and catering, the food manufacturing and tobacco processing industries, and the metal smelting and rolling processing industries. In contrast, the sectors that mainly export more virtual water than they import are maize production; the textile industry; transportation and warehousing; and textiles, clothing, shoes and hats, leather down and its products.

Importantly, maize production dominated the largest contributor to the regional water stress, simultaneously, the industrial sectors played a vital role in alleviating water stress. Spatially, most counties in the Heihe River Basin experienced water stress, and extremely high water stress presented in Sunan and Jiayuguan and Qilian Counties with water stress index (WSI) values of 3.02, 2.17, and 1.69, respectively. The application of virtual water strategy in arid regions should take into consideration the comprehensive capacity of economic level, social equity, infrastructural construction, and potential eco-environmental effect.

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Optimal Water Allocation Scheme in Integrated Water-Ecosystem-Economy System

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Contents

Introduction 335
Forecast Framework of Water Consumption in Integrated Water-Ecosystem-Economy System 337

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Definitions of Water Consumption in Production, Living, and Ecology 337
Study Area and Data Sources 338
Forecasts of Water Consumption in Production, Living, and Ecology in 2020 341
Optimal Water Allocation Scheme of WPLE in Integrated Water-Ecosystem-Economy System in Zhangye of HRB 344
Three Scenarios of WPLE 344
Optimal Allocation Model of WPLE 345
Scenario-Based Water Allocation Scheme of WPLE in Zhangye in 2020 349
Effects and Policy Implications of the Optimal Water Allocation Scheme of WPLE in Zhangye 354
Effects of the Optimal Water Allocation Scheme of WPLE 354
Policy Implications for the Optimal Water Allocation Scheme of WPLE 355
Summary 356
References 358

Abstract

The water crisis is one of the three crises that is persecuting the world. China is among the countries that face severe water shortages. Water scarcity and water pollution have seriously affected China's sustainable development in terms of the economy and society. Water resources per capita of China are only one quarter of world's average, and as much as 70% of China's rivers, lakes, and reservoirs are affected by pollution. Due to limited water resources, a crucial issue for the sustainable development of river basins relates to how to optimally allocate water resources and achieve a coordinated development of the economy, society, and ecology. On the basis of defining water consumption for production, living, and ecology, this chapter proposes a framework for forecasting and optimally allocating water consumption for production, living, and ecology (WPLE) in integrated water-ecosystem-economy system. Using Zhangye, in the middle reaches of the Heihe River Basin as the case study area, we forecasted and optimally allocated WPLE under three development scenarios, i.e., the conventional development scenario (CDS), the economy-priority development scenario (EPDS), and the environment sustainable development scenario (ESDS). In 2010, the proportions of WPLE in Zhangye were 87.73%, 2.74%, and 9.53%, respectively. In 2020, the proportions of WPLE will be 74.80%, 4.50%, and 20.70% under the CDS; 76.16%, 5.27%, and 18.57% under the EPDS; and 74.99%, 4.51%, and 20.50% under the ESDS. In the future, the proportion of production water consumption of Zhangye will drastically decrease, while the proportion of ecology water consumption will significantly increase. The main contradiction of the coevolution of WPLE of Zhangye is the competitiveness of production and living water consumption with ecology water consumption.

Keywords

Water allocation scheme · Production water · Living water · Ecology water · Water-ecosystem-economy system · Scenario analysis · Genetic algorithm · Heihe River Basin · Zhangye

Introduction

Water is an essential and irreplaceable resource for human survival and development. However, water crisis currently plagues the world, and about 40% of the world population in more than 40 countries face water scarcity (Li et al. 2015; Shi et al. 2015a). Water resources are affected by natural conditions, socioeconomic development, global climate change, and other factors (Liu and Chen 2006; Piao et al. 2010). The water resource management of integrated water-ecosystem-economy system is facing many serious problems such as the contradiction between water supply and demand, water pollution, and water ecosystem degradation (Sahrawat et al. 2010; Hirt et al. 2012). Over the past 50 years, surface water and total water resources in China have decreased by 5% and 4%, respectively (Wang and Cheng 2000). Currently, China is one of the many countries facing a serious water scarcity. In addition, the inland river basin, which accounts for one-third of the whole area of China, has experienced a more severe water crisis than other regions. Due to the inherent shortage and irrational use of water resources, the contradiction between water supply and demand in the Chinese inland river basin has become increasingly worse (Deng and Zhao 2015; Deng et al. 2015a), and water crisis has become one of the key issues influencing socioeconomic development and environmental protection in the inland river basin (Ma et al. 2005; Feng et al. 2007). Water scarcity and water environment degradation have seriously affected economic and social development in China.

Water resources are an important component of the integrated water-ecosystem-economy system and are also one key factor maintaining the eco-economic balance. The allocation of water resources in water-ecosystem-economy system directly influences the coevolution of water consumption of production, living, and ecology (WPLE) (Li et al. 2006; Guan and Hubacek 2008). The components of WPLE are not only closely correlated but are also mutually exclusive; any increase in one component could lead to a decrease in the other two types. For example, an increase in production water consumption could aggravate the water use pressure of urban and rural residents' living and ecosystem production. The increase of living water consumption could affect industrial and agricultural development and ecosystem improvement. Many studies have reported that the over pursuit of economic development has resulted in a series of ecological and environmental problems, such as rivers drying out, the drawdown of lakes, the shrinking of wetlands, and a decrease in biological diversity (Srinivasan et al. 2012). At present, China has to not only maintain a reasonable pace in terms of economic development but also must ensure national food security. Meanwhile, China is developing the ecological civilization construction to curb ecosystem degradation. How to effectively coordinate the relationships among integrated water-ecosystem-economy system and reasonable allocation of WPLE have become key issues affecting China's sustainable development (Shen and Speed 2009; Deng et al. 2015b). The forecast and optimal allocation of WPLE have become a great concern in water research.

Since the 1950s, the development of computer technology has improved the application of linear planning, nonlinear planning, integrative planning, and dynamic planning in the optimal allocation of WPLE (Li and Huang 2008; Guo et al. 2009; Lu et al. 2010). In addition, other new methods, such as fuzzy optimization, neural networks, and genetic algorithms, were also adopted in the research of the allocation of WPLE (Merabtene et al. 2002; Bowden et al. 2002; Iliadis and Maris 2007). In terms of research contents, the reasonable allocation of reservoir water resources (Teegavarapu and Simonovic 2002) have gradually evolved into the optimal allocation scheme of river basin water resources (Jowett 1997; Orr et al. 2007), the development and utilization of regional water resources (Jaarsma et al. 1999), the risk assessment of natural drought and waterlog disasters (Zhang et al. 2012), and the management in river basin water environment (Xiang et al. 2014). The research issues of water resource allocation have correspondingly transformed from a certain single objective into the uncertain and stochastic multi-objectives.

Water scarcity and water pollution increasingly plagued the world since the 1990s. The aims of the allocation of WPLE in integrated water-ecosystem-economy system have shifted from demand-decide-supply to the integrative allocation of water yield and water quality (Afzal et al. 1992; Lind and Davalos-Lind 2002) and from pursuing maximum economic benefits to pursuing maximum integrative benefits of economy, society, and ecology (Liu et al. 2010, 2012; Han et al. 2011; Nouiri 2014). The research on WPLE increasingly concerns the harmonious and sustainable development of eco-environment and socioeconomy. In terms of model building, researchers usually build eco-economy watershed models to analyze the allocation of WPLE. Among them, the Patuxent Landscape Model (PLM) in Maryland Patuxent River Watershed and the Everglades Landscape Model (ELM) in the Everglades of Florida are representative (Fang et al. 2007). However, the existing eco-economy models were usually built on separate ecological and economic systems. The integrative models that can simultaneously consider the coevolution of WPLE are lacking (Costanza and Gottlieb 1998).

As a typical inland river basin in arid Northwest China, the Heihe River Basin (HRB) exists amidst diverse human activities such as animal husbandry, agriculture, industry and ecology protection, etc. Therefore, it has become the ideal test site for water allocation under the combined effects of integrated water-ecosystem-economy system in inland river basins (Shi et al. 2015b). Water resources are the focus of research in HRB, are the link of water-ecosystem-economy system, and are the key limitation to the sustainable development of economy, society, and environment. The main question regarding the HRB water resource issue is how to coordinate the human/nature relationship to solve the current and future water resource decision-making in integrated water-ecosystem-economy system, so that the limited water resources can meet the needs of the sustainable development of the basin economy, social population, and eco-environment (Biswas 2004; Oki and Kanae 2006; Lim et al. 2010). Therefore, to strengthen the unified management of rational allocation of water resources in HRB, it is of great significance to promote optimal allocation scheme and efficient utilization of WPLE so as to improve the carrying capacity of water resources and facilitate regional sustainable development.

The water resources, ecology, and balance of water supply and demand are the main research foci in HRB (Fang et al. 2007; Song and Zhang 2015). However, less attention has been paid to the rational allocation of WPLE, particularly using an integrative model approach, especially in the Heihe River Basin of great significance. Therefore, this chapter aims to (1) define and forecast WPLE, (2) propose an optimal scheme to allocate WPLE, and (3) analyze the effects of the optimal water allocation scheme of WPLE in integrated water-ecosystem-economy system in Zhangye of HRB.

Forecast Framework of Water Consumption in Integrated Water-Ecosystem-Economy System

Definitions of Water Consumption in Production, Living, and Ecology

According to different uses, the water consumption in integrated water-ecosystem-economy system can be divided into production, living, and ecology water. Production water consumption refers to water used for agricultural irrigation and industrial production (Fig. 1). Living water includes water consumed by urban and rural human and livestock populations. According to the causes of ecological system formation, ecology water consumption is classified into natural and artificial ecology water consumption. Natural ecology water consumption refers to the water consumed by natural areas without artificial elements, including the water utilized for natural water bodies and vegetation. Artificial ecology water consumption refers to the water utilized by artificial methods, i.e., the water utilized to support the socioeconomic systems in artificial areas. Artificial ecology water consumption is directly or indirectly maintained by manpower. Artificial ecology water consumption also includes the water utilized for forests and grasslands and evaporation from

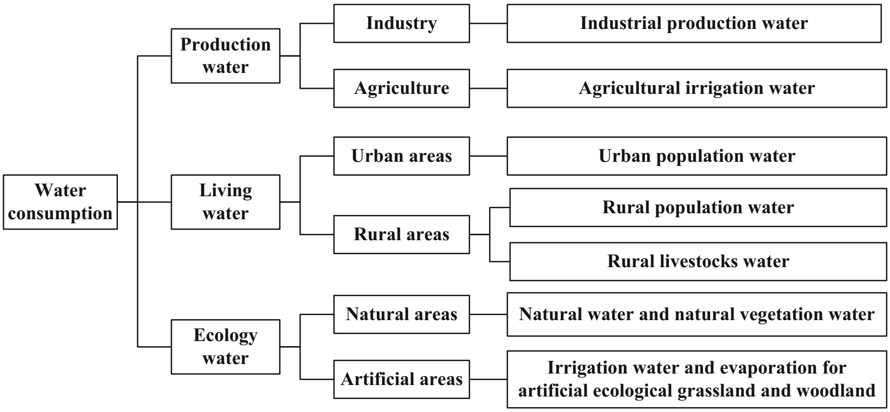

Fig. 1 The composition of water consumption in production, living, and ecology (Reprinted from Xu et al. 2016 with permission of Physics and Chemistry of the Earth)

reservoirs and ponds. Changes in ecology water consumption are influenced by technique progress factors and the areas of artificial ecological vegetation.

Study Area and Data Sources

Basic Information of Zhangye City

The Heihe River Basin is the second largest inland river basin in the arid and semiarid region of Northwest China, and it is in the core area of the ancient Silk Road and Eurasia land bridge. The Heihe River Basin is adjacent to the Qinghai-Tibet Plateau in the southwest, adjacent to the Shule River Basin in the west, adjacent to the Shiyang River Basin in the east, and adjacent to the Mongolian People's Republic in the north. The upper and middle reaches of the Heihe River Basin are separated by Yingluoxia, and the middle and lower reaches are separated by Zhengyixia. The upper reaches of the Heihe River Basin are the water conservation areas, which are the main areas of water resource production. The middle reaches are the main irrigated agricultural areas and are also the main areas of water consumption, consuming more than 85% of the total water consumption in the Heihe River Basin. The lower reaches are the main ecological protection area, which needs enough water resources to maintain the sustainable development of its fragile ecosystem. Therefore, the optimal water allocation scheme in integrated water-ecosystem-economy system rational allocation in the middle reaches of the Heihe River Basin is very important to protect and maintain the ecological environment in the lower reaches.

The agricultural production activities of the Heihe River Basin have a long history, and Zhangye City is the most developed agricultural area within this basin. Zhangye is located in the middle of the Hexi Corridor and the Heihe River Basin. The irrigated agriculture region of Zhangye is one of the top ten key bases for commercial food production in China. It is also the largest economic zone and the largest water consumption area in the Heihe River Basin (Fig. 2). Zhangye has a continental climate. In the winter, the weather is very dry and cold with little snow, while, in the spring, it is quite windy and sandy with little rainfall. The weather in the summer is hot with plenty of rainfall. The annual average temperature is 7.3 °C, with the lowest temperature being −28.7 °C and the extreme high temperature being 39.8 °C. The annual average precipitation in Zhangye is 130.4 mm (1971–2000 average), with a maximum and minimum value of 214.3 mm and 69.5 mm, respectively. The annual evaporation is 2002.5 mm (1971–2000 average), with a drought index of about 15. Zhangye is a typical arid area. The water consumption of Zhangye mainly includes the water consumption of agricultural and industrial production, urban and rural inhabitant, big and small livestock, and ecological irrigation.

Water Consumption of Zhangye in 2010

In 2010, the total water consumption in Zhangye was as high as 2.354 billion m^3 (Table 1). Among this number, the irrigation water was 2.022 billion m^3, and ecology water consumption was 224 million m^3, totally accounting for about

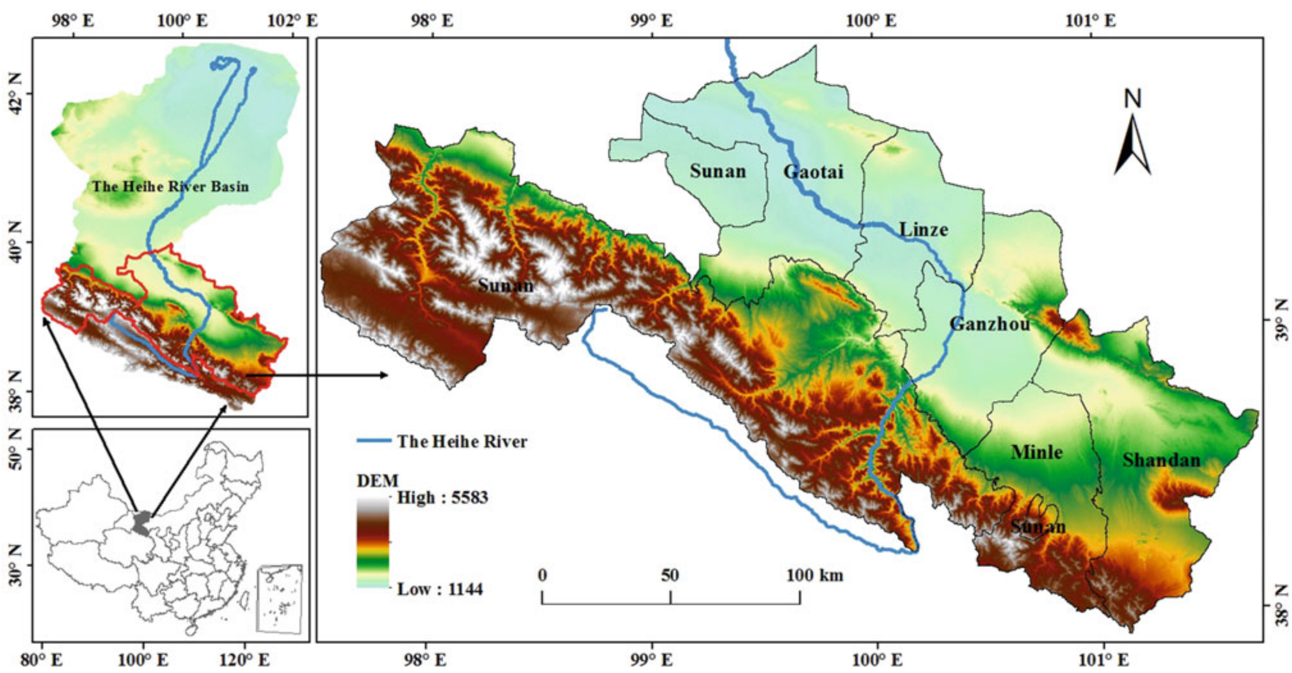

Fig. 2 The location of Zhangye (Reprinted from Xu et al. 2016 with permission of Physics and Chemistry of the Earth)

Table 1 The WPLE of different counties in Zhangye in 2010 (100 million m^3)

	Production water				Living water				Ecological water		
	Irrigation				Inhabitants		Livestock		Artificial areas		
Water supply	Paddy fields	Irrigated land	Vegetable farms	Industry	Urban	Rural	Large	Small	Woodlands	Grasslands	Natural areas
Ganzhou	0.015 0.06%	7.195 30.56%	1.145 4.86%	0.172 0.73%	0.194 0.82%	0.028 0.12%	0.015 0.06%	0.059 0.25%	0.062 0.26%	0.041 0.17%	0.129 0.55%
Gaotai	0.005 0.02%	2.463 10.46%	0.392 1.67%	0.040 0.17%	0.019 0.08%	0.030 0.13%	0.006 0.03%	0.025 0.11%	0.065 0.28%	0.043 0.18%	0.136 0.58%
Shandan	0.003 0.01%	1.571 6.67%	0.250 1.06%	0.059 0.25%	0.032 0.14%	0.035 0.15%	0.003 0.01%	0.013 0.06%	0.079 0.34%	0.052 0.22%	0.165 0.70%
Minle	0.006 0.03%	2.865 12.17%	0.456 1.94%	0.053 0.23%	0.019 0.08%	0.049 0.21%	0.005 0.02%	0.019 0.08%	0.054 0.23%	0.036 0.15%	0.112 0.48%
Linze	0.005 0.02%	2.553 10.84%	0.406 1.72%	0.051 0.22%	0.017 0.07%	0.029 0.12%	0.005 0.02%	0.021 0.09%	0.040 0.17%	0.027 0.11%	0.085 0.36%
Sunan	0.002 0.01%	0.766 3.25%	0.122 0.52%	0.058 0.25%	0.008 0.03%	0.006 0.03%	0.002 0.01%	0.006 0.03%	0.297 1.26%	0.197 0.84%	0.623 2.65%
Sum	0.036 0.15%	17.413 73.97%	2.771 11.77%	0.433 1.84%	0.289 1.23%	0.177 0.75%	0.036 0.15%	0.143 0.61%	0.597 2.54%	0.396 1.68%	1.250 5.31%

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95.42% of the water consumption. Industrial water consumption was 43 million m^3, accounting for 1.84%. The water consumption of urban living was about 29 million m^3, accounting for 1.23% of the total. The water consumption of rural living was about 18 million m^3, and the water consumption of livestock was 18 million m^3, accounting for 1.51% of the total.

Among different counties, Ganzhou had the highest water consumption, i.e., 905.5 million m^3, accounting for about 38.46% of the total. The water consumptions in Minle, Linze, and Gaotai were also high, with percentages of 15.61%, 13.70%, and 13.76%, respectively. In contrast, Shandan and Sunan consumed less water, with percentages of 9.61% and 8.87%, respectively. For agricultural irrigation water, the water consumed in Ganzhou reached 41.32% of the total because the irrigated land in Ganzhou accounted for 37.99% of Zhangye. The agricultural irrigation water consumed in Sunan and Shandan was as low as 4.4% and 9.02% of the total, respectively. The amount of industrial water consumption in Ganzhou reached 39.72% of the total due to the high GDP.

The urban population of Ganzhou accounted for 67% of Zhangye. Therefore, the living water consumption in Ganzhou accounted for 45.89% of the total in Zhangye, while the living water in Sunan only accounted for 3.41% of the total. The ecology water consumption in Sunan was as high as 49.8% of the total, while in Linze, it was as low as 6.78% of the total. The ecology water consumption in other counties was similar, i.e., about 10% of the total in each county. The high ecology water consumption in Sunan was mainly attributed to the high plantation area in artificial forests and grassland. In 2010, the artificial forests in Sunan accounted for 49.87% of the total in Zhangye.

Data Source

The population and GDP data were obtained from the Statistical Yearbook of Zhangye (The Statistical Bureau of Zhangye (2011)). The land use data, including the area of paddy fields, irrigated land, and vegetable farms, were sourced from the Bureau of Land Resources and Management of Zhangye. The water consumption of industry and agriculture in 2010 was sourced from the Annual Report of Farmland Irrigation in Zhangye obtained from the Water Supplies Bureau of Zhangye. The use coefficient of irrigation water was from the Report of Comprehensive Environmental Effect in Heihe River Basin (YREC 2012).

Forecasts of Water Consumption in Production, Living, and Ecology in 2020

The water consumption in production, living, and ecology (WPLE) can be forecasted by the water quota method. The water quota is the water consumption per calculating unit of each water consumption type. According to the definitions of WPLE, the water quota can be divided into the water consumption quota of agricultural irrigation, industry production, urban and rural inhabitants, big and small livestock, and ecological irrigation.

Forecast of Production Water Consumption

Production water consumption is divided into agricultural water consumption and industrial water consumption. The agricultural water consumption of Zhangye in 2010 can be directly obtained from statistical data. In 2020, it can be assessed according to the agricultural area and irrigation quota. The formula is as follows:

$$WCA_{t,i} = \frac{\sum_{i=1}^{n} \mathrm{Area}_{t,i} \times IN_{t,i}}{URIW_{t,i}} \tag{1}$$

where i is the category of agricultural crop, t is the year, $WCA_{t,i}$ is the water consumption of the i type of crop in year t, $Area_{t,i}$ is the agricultural area of the i type of crop in year t, $IN_{t,i}$ is the pure irrigation quota (irrigation water demand per unit area) of the i type of crop in year t (m^3/mu), and $URIW_{t,i}$ is the use coefficient of irrigation water (the ratio of irrigation water demand and actual irrigation water consumption) of i crop in year t, which ranges from 0 to 1.

With the development of techniques, the use coefficient of irrigation water continuously increases. In 2010, the use coefficient of irrigation water in Zhangye was as low as 0.48. Due to the popularization of water-saving technology and the implementation of comprehensive treatment projects in the Heihe River Basin, the use coefficient of irrigation water will continuously increase. According to the Report of Comprehensive Environmental Effects in the Heihe River Basin, the use coefficient of irrigation water in Heihe will reach 0.58 in 2020 (YREC 2012).

According to the statistical data, the water consumption of industry production in Zhangye in 2010 can be calculated. The consumption in 2020 can be assessed based on the water consumption quota of the industry value per 10,000 CNY and the ratio of water reuse (technological progress factor). The two variables reflect the water-saving effects influenced by the industrial scale and structure and the improvement of the technological process of production. The formula is as follows:

$$WCI_{t,i} = \frac{IV_{t,i} \times RR_{t,i}}{ICIP_{t,i}} \tag{2}$$

where i is the county, t is the year, $IV_{t,i}$ is the industrial value of i county in t year, $WCI_{t,i}$ is the water consumption of i county in year t, $ICIP_{t,i}$ is the water consumption quota of industrial value per 10,000 CNY of i county in year t, and $RR_{t,i}$ is the ratio of industrial water reuse.

According to the Report of Comprehensive Environmental Effects in the Heihe River Basin (YREC 2012), the ratio of industrial water reuse in the Heihe River Basin will increase from 72% in 2010 to 90% in 2020. The water consumption quota of industrial value per 10,000 CNY in Zhangye was 120 m^3 in 2010. This value will continuously decrease in the future due to the improvement of the industry structure and the ratio of industrial water reuse. According to the relevant research studies, together with the local actual conditions, the water consumption quota of industrial value per 10,000 CNY is predicted to be 10^3 m^3 in 2020.

Forecast of Living Water Consumption

Living water consumption is divided into urban living water consumption, rural living water consumption, and livestock water consumption. Urban and rural living water consumption in 2010 can be obtained from actual statistics. The water consumption of urban and rural inhabitants and livestock in 2020 can be predicted via the water quota method. Urban living water consumption includes water consumed by residents and the public infrastructure. The total living water consumed by urban residents in Zhangye was 28.9 million m^3 in 2010. The average water quota of urban living was 190 L/person/day in 2010. According to historical records, the water consumption quota of urban living in Zhangye was 142 L/person/day in 2005. Based on the regression model, the water consumption quota of urban living in Zhangye will increase to 250 L/person/day in 2020. The total water consumption of urban living in 2020 can then be forecasted based on the predicted urban population. The formula is as follows:

$$WCR_{t,i} = NR_{t,i} \times WCNR_{t,i} \tag{3}$$

where i is the user category, t is the year, $WCR_{t,i}$ is the total water consumption of the i category of users in year t, $NR_{t,i}$ is the total number of i category of users in year t, and $WCNR_{t,i}$ is the living water quota of i category of users in year t.

Rural living water consumption refers to water used by rural inhabitants. The total water consumption of rural inhabitants in Zhangye in 2010 was about 18 million m^3, with an average water consumption quota of 65 L/person/day. However, the water consumption quota in Zhangye was much lower than that of cities in the Yellow River Basin such as Xianyang, Xian, Luoyang, Zhengzhou, and Jinan. With the development of socioeconomic and living standards, the water consumption quota in both rural and urban areas in the Heihe River Basin would increase. The water consumption quota of rural people living in Zhangye in 2020 is forecasted based on the trend of the historical changes and the water stress. The predicted value is 120 L/person/day in 2020.

Water for feeding livestock is also one kind of living water consumption. In 2010, the total livestock water consumption was about 23 million m^3. The water consumption quotas for feeding large and small livestock were 35 and 15 L/animal/day, respectively, in 2010. We assumed that the water consumption quota would not change much in the future, as it is expected to be 40 and 20 L/animal/day for the large and small livestock in 2020, respectively. In this way, the total amount of water consumed by livestock can be calculated.

Forecast of Ecology Water Consumption

Since the related research on natural ecology water consumption is immature, we did not adopt any of the existing methods to assess natural ecology water consumption in

Zhangye. In consideration of the undeveloped industry, the natural ecological areas in Zhangye will not change much in the near future. Therefore, we assumed that the natural ecological areas would be unchanged from 2010 to 2020. The changes in ecology water consumption resulted from the changes in artificial ecological areas. The assessment of water consumption of artificial ecological areas is similar to that of agricultural water consumption. The formula is as follows:

$$WCC_{t,i} = \frac{EA_{t,i} \times EWC_{t,i}}{UIE_{t,i}} \tag{4}$$

where i is the category of artificial ecology vegetation, classified as artificial grassland and forests, t is the year, $WCC_{t,i}$ is the ecology water consumption of the i category of vegetation in year t, $EA_{t,i}$ is the total area of i category of ecological vegetation in year t, $EWC_{t,i}$ is the irrigation quota of i category of ecological vegetation in year t, and $UIE_{t,i}$ is the use coefficient of irrigation water for i category of ecological vegetation in year t.

In 2010, most of the water in the Ejina district was consumed by ecology on both shores of the Heihe River. Therefore, the ecology water consumption was equal to 322 million m^3 in 2010, i.e., subtracting the living and producing water in Ejina from the water that flowed into Ejina.

Optimal Water Allocation Scheme of WPLE in Integrated Water-Ecosystem-Economy System in Zhangye of HRB

Three Scenarios of WPLE

Conventional Development Scenario

In this scenario, the economic development in Zhangye in the future will continue based on historical development in terms of population, agriculture, industry, and the artificial ecological areas. A conventional development scenario (CDS) is a basic scenario that can be compared to other scenarios to find the best one.

Economy-Priority Development Scenario

In economy-priority development scenario (EPDS), the development speed of industry and agriculture will increase. In order to guarantee rapid development, more resources will be allocated to industry and agriculture. On the basis of ensuring living water consumption, the water allocated to ecology will decrease. Thus, growth in the artificial ecological areas will decrease. Under this scenario, the speed of the GDP increase is 1.5 times of that under CDS. The speed of industry structure adjustment is 1.3 times of the past. For the occupation of ecological areas due to economic development, the artificial forests and grasslands will decrease by 0.4% annually, while the population growth rate will increase by 0.3% annually. In addition, the urbanization speed will reach 1.2 times of the past. Under this scenario, technique progress becomes the key factor influencing water consumption. Due to the application of new techniques, in this scenario, the water consumption of industry value will decrease, which is contrary to the other scenarios.

Environment Sustainable Development Scenario

This environment sustainable development scenario (ESDS) enhances ecological conservation. Compared to the CDS, this scenario will decrease the speed of agriculture and industry development. The ecology water consumption in this scenario will increase by 0.4% to guarantee the sustainable development of the environment. On the basis of guaranteeing living water consumption, the water consumption for economic development will be reduced. The GDP growth dropped to 0.95 of that in the past. The industrial structure adjustment rate decreased to 10/11 of the past. The population growth rate slightly increased compared to the past.

The three scenarios have different features regarding water consumption. For the economy-priority development scenario (EPDS), the technique progresses faster than in the other scenarios, which decrease the water consumption of industrial value per unit. For the environment sustainable development scenario (ESDS), the growth of water consumption for artificial forests and grasslands will decrease. For the different foci under the three development scenarios, the water consumption coefficients of WPLE are not the same. The water consumption coefficients of every index under the three scenarios are listed in Table 2.

Optimal Allocation Model of WPLE

The optimal allocation of WPLE has many objectives, such as economic objective (output, profits, gross national product, and gross living product), social objective (social stability, quality of life, employment, and education), and environmental objective (minimizing water quality loss caused by water pollution, maximizing water environment benefits, maintaining the ecosystem balance, and improving the ecological system). Zhangye has shown water shortages, huge contradictions between the water supply and demand, fragile ecosystems, and a complicated water resource system. Therefore, this chapter, via the optimal allocation of WPLE, aimed to minimize the water shortage for the whole watershed and balance the water shortage in different districts.

Objective Function

In order to guarantee the positive cycle and continuous improvement of the ecological environment in the Heihe River Basin, the ecology water consumption in the lower reaches was set as a constraint condition. The water shortage of each sector in the middle reach should be reduced based on ensuring ecology water consumption in the lower reach. According to the concepts and goals of sustainable development, sustainable development should follow the criteria of maximizing benefits and being survivable, bearable, and sustainable. Therefore, we raised the objective function of water consumption allocation in Zhangye.

Table 2 The water use coefficients of WPLE in different water allocation scenarios

Water usage coefficient	Production water				Living water(L/person/day)				Ecological water(m^3/100,000 m^2)		
	Irrigation(m^3/acre)			Industry (m^3/10,000CNY)	Inhabitant		Livestock		Artificial areas		Natural areas
	Paddy fields	Irrigated land	Vegetable farms		Urban	Rural	Big	Small	Woodlands	Grasslands	
Scenario 1	18,405	10,845	10,395	110	240	120	50	35	4500	4500	1
Scenario 2	18,405	10,845	10,395	90	240	120	50	35	4500	4500	1
Scenario 3	18,405	10,845	10,395	110	240	120	50	35	4275	4275	1

Notes: Scenario 1 is the conventional development scenario; Scenario 2 is the economy-priority development scenario; and Scenario 3 is the environmental sustainable development scenario (Reprinted from Xu et al. 2016 with permission of Physics and Chemistry of the Earth)

1. Environmental objective: maximizing the demand of ecology water consumption

$$y_1 = \max\left\{\sum_{i=1}^{m} Q_i\right\} \tag{5}$$

2. Social objective: minimizing the differences in water shortages among different counties

$$y_2 = \min\left\{\max\left\{\frac{\sum_i \sum_j W_{i,j}^{\text{supply}}}{\sum_i \sum_j W_{i,j}^{\text{demand}}}\right\} - \min\left\{\frac{\sum_i \sum_j W_{i,j}^{\text{supply}}}{\sum_i \sum_j W_{i,j}^{\text{demand}}}\right\}\right\} \tag{6}$$

3. Economic objective: maximizing the economic benefits of the water supply

$$y_3 = \max\left\{\sum_{i=1}^{m} w_i^{ind} * W_i^{ind} + w_i^{agr} * W_i^{agr}\right\} \tag{7}$$

where y_1, y_2, y_3 are objective functions of environmental, social, and economic benefits, i is the number of counties, j is the index number of WPLE (i.e., production, or living, or ecology water) of each county, Q_i is the total water consumption in i county, $W_{i,j}^{\text{supply}}$ is the water supply amount of j index number in i county, $W_{i,j}^{\text{demand}}$ is the amount of water consumption of j index number in i county, w_i^{ind} is the coefficient of converting industrial water consumption to industry value in i county, w_i^{agr} is the coefficient of converting agriculture water consumption to agriculture value in i county, W_i^{ind} is the amount of industrial water consumption in i county, and W_i^{agr} is the amount of agricultural water consumption in i county.

Constraint Conditions

1. Minimum water supply reliability constraint

$$\beta_{y,m,u,k} \geq \min\left(\beta_{m,u,k}\right) \tag{8}$$

$$\beta_{y,m,u,k} = Sp_{y,m,u,k}/D_{y,m,u,k} \tag{9}$$

where $\beta_{y,m,u,k}$ is the water supply assurance rate of u computation unit in y year during m period of k type of users (%), $\min(\beta_{m,u,k})$ is the minimal water supply assurance rate for u computation unit in y year and k type of users, $Sp_{y,m,u,k}$ is the amount of water supply for u computation unit in y year during m period of k type of users(10,000 m^3), and $D_{y,m,u,k}$ is the amount of water consumption for u computation unit in y year during m period of k type of users(10,000 m^3).

2. Constraint in WPLE

$$\min\left(Wy_{m,j}\right) \leq Wg_{m,j} \leq \max\left(Wy_{m,j}\right) \tag{10}$$

$$\min\left(Wy_{m,j}\right) = \partial_j \max\left(Wy_{m,j}\right) \tag{11}$$

where j is the type of water consumption, i.e., living water consumption, production water consumption, and ecology water consumption (10 k m^3), and max ($Wy_{m,j}$) is the upper limit value of WPLE during m period. It is a predicted value for the amount of water stored (10 k m^3); min($Wy_{m,j}$) is the lower limit value of WPLE during m period (10 k m^3); and ∂ is the basic water consumption coefficient.

3. Nonnegative constraint

$$\sum_i \sum_j W_{i,j}^{\text{supply}} > 0 \tag{12}$$

where i is the number of counties, j is the number of WPLE, and $W_{i,j}^{\text{supply}}$ is the lower limit of water supply for j indicator in i county. Every value of indicators should be larger than 0.

Genetic Algorithm

The genetic algorithm is adopted to build the optimal allocation model in WPLE. First, a random initial population was selected and encoded according to certain rules such as binary encoding. Then, the objective function was used to calculate the fitness value of each individual. The groups that suited the objective function were selected, and the groups with smaller individual fitness were removed (Fig. 3). Then, genetic cross operation and mutation operations were performed among the rest of the individuals to create new groups. The loops were circulated, i.e., select-crossover-mutation, until a termination condition was met (Fig. 3). In this chapter, Matlab was used to model the multi-objective planning of the genetic algorithm. The parameters were set as follows: population size was 100, mutation probability was 0.7, and crossover probability was 0.8. The default iteration number was 100 times the number of modeling variables, i.e., 6600 times.

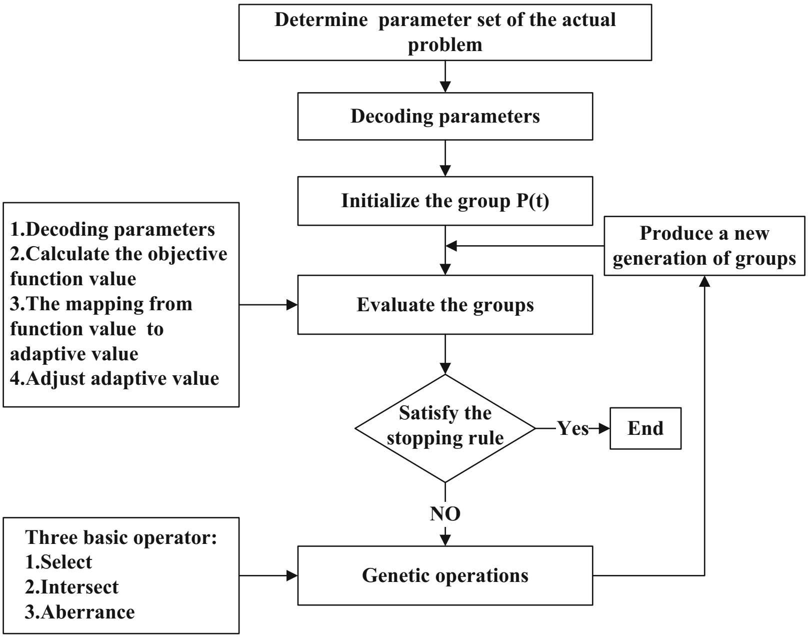

Fig. 3 Technical route of the genetic algorithm (Reprinted from Xu et al. 2016 with permission of Physics and Chemistry of the Earth)

Scenario-Based Water Allocation Scheme of WPLE in Zhangye in 2020

Optimal Allocation of WPLE in Zhangye in 2020 Under the Conventional Development Scenario

Based on the historical socioeconomic data from 2003 to 2010 and the parameters set under the three scenarios, after optimal allocation, the WPLE in 2020 was calculated based on the three scenarios. Under CDS, the WPLE are 176.1 million m^3, 10.6 million m^3, and 48.7 million m^3, and the proportions of WPLE are 74.80%, 4.50%, and 20.70%, respectively (Table 3). Compared with the WPLE in 2010, the proportions of production water consumption decreased, while the proportion of ecology water consumption significantly increased. In addition, the living water also slightly increased.

Compared with the water consumption in 2010, the production water consumption in 2020 under CDS decreased by 14.72%. The decrease in the production water consumption was mainly due to the reduction in irrigated land. The water consumption of industrial production increased by 419.4%. Due to the impacts of population growth, the living water consumption will significantly increase under the CDS. The ecology water consumption for artificial forests, artificial grasslands, and natural areas will increase by 160.3%, 144.70%, and 88.08%, respectively.

Table 3 Water optimal deployment in Zhangye under the conventional trend development scenario (100 million m^3)

	Production water				Living water				Ecological water		
	Irrigation				Inhabitants		Livestock		Artificial areas		
Water supply	Paddy fields	Irrigated land	Vegetable farms	Industry	Urban	Rural	Large	Small	Woodlands	Grasslands	Natural areas
Ganzhou	0.026 0.11%	5.591 23.75%	0.963 4.09%	0.824 3.50%	0.386 1.64%	0.040 0.17%	0.062 0.26%	0.022 0.09%	0.134 0.57%	0.104 0.44%	0.220 0.93%
Gaotai	0.005 0.02%	1.973 8.38%	0.452 1.92%	0.295 1.25%	0.040 0.17%	0.048 0.20%	0.027 0.11%	0.010 0.04%	0.146 0.62%	0.131 0.56%	0.239 1.02%
Shandan	0.005 0.02%	1.100 4.67%	0.140 0.59%	0.316 1.34%	0.064 0.27%	0.056 0.24%	0.012 0.05%	0.005 0.02%	0.239 1.02%	0.114 0.48%	0.333 1.41%
Minle	0.004 0.02%	1.495 6.35%	0.270 1.15%	0.241 1.02%	0.040 0.17%	0.073 0.31%	0.019 0.08%	0.008 0.03%	0.163 0.69%	0.108 0.46%	0.214 0.91%
Linze	0.006 0.03%	2.096 8.90%	0.322 1.37%	0.296 1.26%	0.035 0.15%	0.046 0.20%	0.022 0.09%	0.009 0.04%	0.094 0.40%	0.082 0.35%	0.143 0.61%
Sunan	0.010 0.04%	0.768 3.26%	0.137 0.58%	0.277 1.18%	0.016 0.07%	0.008 0.03%	0.007 0.03%	0.003 0.01%	0.778 3.30%	0.430 1.83%	1.202 5.11%
Sum	0.056 0.24%	13.023 55.31%	2.284 9.70%	2.249 9.55%	0.581 2.47%	0.271 1.15%	0.149 0.63%	0.057 0.24%	1.554 6.60%	0.969 4.12%	2.351 9.99%

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In different districts, the proportion of water consumption in Ganzhou and Minle will decrease by 2.91% and 4.42%, respectively, while, in Sunan, it will increase by 6.58% due to the substantial increase in ecology water consumption.

Optimal Allocation of WPLE in Zhangye in 2020 Under the Economy-Priority Development Scenario

Under the EPDS, accelerated economic growth will increase the industrial and agricultural value and the population growth. However, ecological areas will be constricted due to rapid economic growth. Consequently, ecological grassland and forest areas will decrease. The WPLE under this scenario would be 179.3 million m^3, 12.4 million m^3, and 43.7 million m^3, accounting for 76.16%, 5.27%, and 18.57%, respectively (Table 4). Compared to the CDS, the proportion of production water consumption is slightly greater due to the increase in industry water consumption. Nevertheless, the proportion of ecology water consumption increased under the EODS, which means that the increase of production water consumption will mainly reduce the living water consumption but will not significantly influence the ecology water consumption. Compared to the WPLE in 2010, the production water consumption in 2020 significantly increased.

Compared to the CDS, the water consumption in the paddy fields would slightly increase by 21.43%, while the water consumption for irrigated land and vegetable farms would decrease by 1.04% and 6.13%, respectively.

The water consumption of industrial production under the EPDS would significantly increase by 25.74% more than that under the CDS. Due to the influence of urbanization and population growth, the water consumption of urban living would increase by 10.84%, while the water consumption of rural living would decrease by 1.85% more than under the CDS. The water consumption of large and small livestock significantly increased by 61.07% and 59.65%, respectively. Compared to the CDS, the ecology water consumption of artificial forests, grasslands, and natural areas would decrease by 8.3%, 12.38%, and 10.76%, respectively. The water consumption distribution in various counties under the EPDS is similar to the CDS.

Optimal Allocation of WPLE in Zhangye in 2020 Under the Environment Sustainable Development Scenario

Under the ESDS, economic development will slow due to the deceleration in industrial production growth and urbanization. Due to the conservation of the ecosystem, the area of ecological forests and grasslands will increase. The population will slightly grow due to the improvement of the ecological environment, but the rate of growth will be quite similar to that under the CDS.

Under this scenario, the WPLE in Zhangye were 176.5 million m^3, 10.6 million m^3, and 48.3 million m^3, and the proportions of WPLE were 74.99%, 4.51%, and 20.50%, respectively (Table 5). Compared to the other two scenarios, the proportion of production water consumption was larger than in the CDS but smaller than in the EPDS. The living water consumption was the same as production water consumption, i.e., higher than in the CDS and lower in the EPDS. The proportion of ecology

Table 4 Water optimal allocation in Zhangye under the economic priority development scenario (100 million m^3)

	Production water				Living water				Ecological water		
	Irrigation				Inhabitants		Livestock		Artificial areas		
Water supply	Paddy fields	Irrigated land	Vegetable farms	Industry	Urban	Rural	Large	Small	Woodlands	Grasslands	Natural areas
Ganzhou	0.026 0.11%	5.394 22.91%	0.798 3.39%	1.105 4.69%	0.428 1.82%	0.042 0.18%	0.102 0.43%	0.037 0.16%	0.178 0.76%	0.085 0.36%	0.207 0.88%
Gaotai	0.008 0.03%	1.969 8.36%	0.449 1.91%	0.320 1.36%	0.043 0.18%	0.044 0.19%	0.044 0.19%	0.016 0.07%	0.139 0.59%	0.095 0.40%	0.221 0.94%
Shandan	0.007 0.03%	1.161 4.93%	0.130 0.55%	0.412 1.75%	0.074 0.31%	0.053 0.23%	0.022 0.09%	0.008 0.03%	0.168 0.71%	0.111 0.47%	0.261 1.11%
Minle	0.004 0.02%	1.525 6.48%	0.264 1.12%	0.277 1.18%	0.043 0.18%	0.075 0.32%	0.029 0.12%	0.012 0.05%	0.161 0.68%	0.076 0.32%	0.215 0.91%
Linze	0.009 0.04%	1.950 8.28%	0.310 1.32%	0.343 1.46%	0.038 0.16%	0.043 0.18%	0.033 0.14%	0.014 0.06%	0.122 0.52%	0.059 0.25%	0.189 0.80%
Sunan	0.014 0.06%	0.888 3.77%	0.193 0.82%	0.371 1.58%	0.018 0.08%	0.009 0.04%	0.010 0.04%	0.004 0.02%	0.657 2.79%	0.423 1.80%	1.005 4.27%
Sum	0.068 0.29%	12.887 54.75%	2.144 9.11%	2.828 12.01%	0.644 2.74%	0.266 1.13%	0.240 1.02%	0.091 0.39%	1.425 6.05%	0.849 3.61%	2.098 8.91%

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Table 5 Water optimal allocation in Zhangye under the environment sustainable development scenario (100 million m^3)

Water supply	Production water				Living water				Ecological water		
	Irrigation			Industry	Inhabitants		Livestock		Artificial areas		Natural areas
	Paddy fields	Irrigated land	Vegetable farms		Urban	Rural	Large	Small	Woodlands	Grasslands	
Ganzhou	0.020 0.08%	5.467 23.22%	0.775 3.29%	0.973 4.13%	0.392 1.67%	0.046 0.20%	0.058 0.25%	0.021 0.09%	0.186 0.79%	0.089 0.38%	0.291 1.24%
Gaotai	0.006 0.03%	2.120 9.01%	0.339 1.44%	0.286 1.21%	0.039 0.17%	0.050 0.21%	0.023 0.10%	0.010 0.04%	0.152 0.65%	0.133 0.56%	0.242 1.03%
Shandan	0.007 0.03%	1.141 4.85%	0.132 0.56%	0.339 1.44%	0.064 0.27%	0.054 0.23%	0.012 0.05%	0.005 0.02%	0.200 0.85%	0.117 0.50%	0.295 1.25%
Minle	0.003 0.01%	1.534 6.52%	0.383 1.63%	0.204 0.87%	0.040 0.17%	0.078 0.33%	0.017 0.07%	0.007 0.03%	0.124 0.53%	0.083 0.35%	0.205 0.87%
Linze	0.007 0.03%	2.069 8.79%	0.333 1.41%	0.240 1.02%	0.035 0.15%	0.048 0.20%	0.020 0.08%	0.008 0.03%	0.126 0.54%	0.084 0.36%	0.194 0.82%
Sunan	0.014 0.06%	0.790 3.36%	0.143 0.61%	0.327 1.39%	0.016 0.07%	0.010 0.04%	0.006 0.03%	0.002 0.01%	0.770 3.27%	0.461 1.96%	1.075 4.57%
Sum	0.057 0.24%	13.121 55.74%	2.105 8.94%	2.369 10.06%	0.586 2.49%	0.286 1.21%	0.136 0.58%	0.053 0.23%	1.558 6.62%	0.967 4.11%	2.302 9.78%

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water consumption under this scenario was similar to that of the CDS. The water consumption of different districts and counties was similar to that of the other two scenarios.

The WPLE under ESDS is similar to that under CDS while significantly different from that under EPDS. The water consumption in paddy fields, irrigated land, and vegetable farms will be 16.18% less, 1.82% more, and 1.82% less than the ones under EPDS, respectively. The industrial water consumption will reduce significantly by 16.23%. The water consumed by large and small livestock will reduce by 43.33% and 41.76%, respectively. The water consumption of urban living will decrease by 9%, while the water consumption for rural living will increase by 7.52%. The water consumed by artificial forests, grasslands, and natural areas will increase by 9.33%, 13.90%, and 9.72%, respectively.

Effects and Policy Implications of the Optimal Water Allocation Scheme of WPLE in Zhangye

Effects of the Optimal Water Allocation Scheme of WPLE

On the basis of maximizing ecology water consumption and the benefits of water consumption, after the optimal allocation of WPLE, the proportion of production water consumption in 2020 will significantly decrease compared with that in 2010 under all the scenarios, ranging from 11% to 14%, while the water consumption for industrial production will increase. The reduction of production water consumption in Zhangye in the future results mainly from the decrease in water consumption for agricultural production. Therefore, in order to adapt to the new situation that the agricultural production water consumption reduce in the future, it is imperative to restrict the expansion speed of the agricultural oasis, carry out the adjustment of agricultural planting structure, and develop water-saving crops in Zhangye.

Under the three scenarios, living and ecology water consumption increase. The continued increase of living water consumption is used to sustain the growing population and economy, and the increase of ecology water consumption will promote the sustainable development of ecological environment in Zhangye in the future. As the future production water consumption will decrease while other two consumption of WPLE will increase, the conflicts in WPLE in Zhangye are mainly attributed to the contradictions of production water consumption with living and ecology water consumption, in particular with ecology water consumption. The contradiction of industry and agriculture development with ecological protection will be an entrenched problem in Zhangye. After the optimal water allocation scheme of WPLE under the three scenarios in integrated water-ecosystem-economy system, the ecological benefits have received the same attention like the economic benefits, and the future economy will develop on the basis of the protection of the ecological environment.

The competition for water resource consumption in Zhangye exists not only among the WPLE but also inside the WPLE. Under the EPDS, both the urban population and industry will experience rapid development. Living water consumption will increase due to the fast-growing urban population. Industrial development will inevitably consume a great deal of water, which will influence the water consumption for agricultural production. Although, under the EPDS, the production water consumption in Zhangye only increased by 1.79% compared to that under the CDS, the water consumption for industrial production increased by 25.74%. In addition, the water consumption for agricultural production decreased by 1.72%.

Policy Implications for the Optimal Water Allocation Scheme of WPLE

The optimal allocation of WPLE is a key issue influencing regional sustainable development. Environmental, social, and economic objectives were set in our study to achieve the optimal allocation of WPLE in 2020. However, the contradictions among the WPLE in integrated water-ecosystem-economy system are inevitable. Any increase in one component of production, living, and ecology water consumption could lead to a decrease in the other two types. In addition, the total amount of water resources in a region is generally maintained in a range with slight changes. Thus, some policies are needed to be implemented for the followed objectives: maximizing the demand of ecology water consumption, minimizing the differences in water shortages among different counties, and maximizing the economic benefits of the water supply.

Zhangye is located in an arid and semiarid area with a fragile ecosystem. The stability of the ecosystem is crucial to guarantee the sustainable development of industrial and agricultural production. Therefore, the policies of ecological civilization construction, e.g., grain-for-green and artificial forest construction, need to be strengthened to protect the regional ecosystem development, especially in the water shortage region with the fragile ecological environment. The water consumption in integrated water-ecosystem-economy system should give priority to ensuring the development of ecological environment, namely, ecology water consumption needs to increase, while living water consumption and production water consumption should be reduced.

With the growth of economy and population in integrated water-ecosystem-economy system, the water resource consumption of Zhangye in the future will face greater challenges than ever. However, the living water consumption of Zhangye in the future will inevitably increase along with the continuous growth of population and urbanization, and what we can do is reduce the quota of living water to make its unit water consumption lower. In order to guarantee the ecology water consumption in the future, the population growth should be slowed down, and water-saving technology of living water needs to be extensively applied.

The main contradiction of WPLE is the competition between ecology water consumption and production water consumption. Therefore, production water consumption must be reduced in order to ensure that ecology water consumption is sufficient to maintain the sustainable development of ecosystem. However, the agricultural producing water accounts for more than 85% of the total production water consumption of Zhangye. Thus, production water consumption, especially agricultural producing water consumption, should be decreased. In order to reduce agricultural producing water consumption, it is necessary to curb the expansion of the agricultural oasis, adjust the agricultural planting structure, and develop water-saving crops (Liu et al. 2016). Furthermore, the improvement of the efficiency of both agricultural and industrial water use is necessary to first ensure the demand of ecology water consumption and to optimally allocate water consumption.

Summary

In recent years, with global change and the rapid development of social economy, water resources in many countries are facing the serious problems such as water scarcity and water pollution, especially in China, where water resources per capita are only one quarter of world's average. The contradiction between supply and demand, water environment pollution, and water ecosystem degradation has seriously affected the sustainable development of China's economy and society. The Heihe River is the second largest inland river in the arid and semiarid region of Northwest China, which is the cornerstone of the sustainable development of the ecosystem, economy, and society in the Heihe River Basin. Water resources, and its scarcity especially, is one of the key factors that restrict the development of the Heihe River Basin. Zhangye City is the most important irrigated agriculture region in the middle of the Heihe River Basin, for which water consumption accounts for more than 85% of the total basin water consumption. It is crucial to study the optimal allocation of water resources in integrated water-ecosystem-economy system of Zhangye and to achieve the harmonious and sustainable development of ecosystem, economy, and society.

According to the different uses of the water resources, the water consumption in integrated water-ecosystem-economy system of Zhangye can be classified into production, living, and ecology categories. We proposed the definitions of water consumption in production, living, and ecology (WPLE). According to the irrigation quota method, we provided a forecast framework of WPLE and designed three different development scenarios, i.e., conventional development scenario (CDS), environment sustainable development scenario (EPDS), and environment sustainable development scenario (ESDS). Based on the development objectives of socioeconomic-ecological benefit maximization (survivable, bearing capacity, and sustainable), the water optimal allocation model of Zhangye is built and utilized to assess the changes in WPLE under three scenarios. After defining and forecasting WPLE, we performed the optimal allocation of WPLE under three scenarios based on the method of genetic algorithms. However, there were a few insufficiencies in our study. First, the natural ecological areas in Zhangye from 2010 to 2020 were assumed to be unchanged due to the lack of a defendable method of forecasting changes in natural ecological areas. Therefore, the changes in ecology water consumption are only based on the changes in artificial ecological areas. In addition, due to the lack of related data of WPLE in Zhangye, except for 2010, the validity of the method was not verified. Moreover, the predictions of future land use changes are not presented in space. It would be better to predict both spatial and quantitative land use changes via land use change models or methods.

In 2010, the total water consumption in Zhangye was as high as 2.354 billion m^3. Among this number, the water consumptions in production, living, and ecology were 206.5 million m^3, 6.5 million m^3, and 22.4 million m^3, respectively, and the proportions of WPLE were 87.73%, 2.74%, and 87.73%, respectively. Production water occupies the largest proportion of water consumption. Production water is mainly used for agricultural irrigation, which accounts for 97.90% of the total consumption of production water. In the future, under the constraint of constant total water consumption, the WPLE under the CDS are 176.1 million m^3, 10.6 million m^3, and 48.7 million m^3, accounting for 74.80%, 4.50%, and 20.70% of the total consumption, respectively. The WPLE under the EPDS are 179.3 million m^3, 12.4 million m^3, and 43.7 million m^3, accounting for 76.16%, 5.27%, and 18.57% of the total consumption, respectively. The WPLE under the ESDS are 176.5 million m^3, 10.6 million m^3, and 48.3 million m^3, accounting for 74.99%, 4.51%, and 20.50% of the total consumption, respectively. Production water consumption will significantly decrease, while living and ecology water consumption will increase during 2010–2020.

The WPLE under those three scenarios were optimally allocated based on the sustainable development of society, economy, and ecology, while the water consumption in 2010 was not based on these multiple objectives. To achieve the maximization of social, economic, and ecological benefits in the integrated water-ecosystem-economy system of Zhangye, necessary measures, i.e., adjusting agricultural and industrial structure, controlling the rapid development of population and economy, and protecting the ecological environment, need to be implemented. Under the CDS, population, agriculture, industry, and the artificial ecological areas will continue based on historical development. Water resources will be optimally allocated to production, living, and ecology for the maximal benefits of society, economy, and ecology. Thus, production water consumption needs to reduce, and living and ecology water consumption needs to increase from 2010 to 2020. Compared with the CDS, more water resources will be allocated to industry and agriculture in order to guarantee rapid development under the EPDS. To ensure enough living water consumption for growing population, ecology water consumption of the EPDS will decrease. Under the ESDS, the ecology water consumption will increase to guarantee the sustainable development of the environment, and the water consumption for economic development will be reduced compared with the CDS. In different districts of Zhangye, Ganzhou's economy is the most developed, and its water consumption is the biggest. The rapid economic development of Zhangye will aggravate the unequal distribution of water resources among counties, which is not conducive to regional sustainable development. The ESDS pays more attention to the principle of fairness in the development of the counties and adapts to the sustainable development of Zhangye. Moreover, the WPLE of ESDS takes ecological conservation as its primary objective and maintains reasonable economic development, which is more convenient to achieve the joint and harmonious development of society, economy, and ecology in integrated water-ecosystem-economy system. Thus, the water allocation of WPLE under the ESDS is the best scheme for the economic, social, and environmental multi-objective.

Due to the economic development of Zhangye City which is relatively backward in China, the overall level of social and economic could increase in short time by accelerating the economic development, but the ecological environment in Zhangye region was very fragile. Sustainable development of ecosystem is the foundation of sustainable socio-economic development. Thus, economic development should be based on the premise of healthy ecology if we are to achieve the sustainability in Zhangye. The optimal allocation of WPLE in the future year, 2020, will be achieved under conditions of maximizing ecology water consumption and the benefits of water consumption. The establishment of the optimal allocation model in WPLE is valuable to suggest certain policies that will help to promote the optimal allocation of regional water resources and improve the bearing capacity of water resources. To achieve the optimal allocation of WPLE in integrated water-ecosystem-economy system, it is necessary to protect the ecological environment, adjust agricultural and industrial structure, improve the use efficiency of both agricultural and industrial water consumption, curb agricultural oasis expansion, and develop water-saving crops in Zhangye. Through the rational allocation of WPLE, economic development can be maintained at a reasonable pace, and a more stable ecosystem will be crucial to guarantee sustainable development of both industrial and agricultural production.

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Hydrological Ecosystem Services for Integrated Water Resources Management

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Contents

Introduction 362
Driving Mechanism of LUCC 364
  Natural Factors of LUCC 364
  Socioeconomic Factors of LUCC 365
Effects of LUCC on Regional Hydrological Ecosystem Services 366
  Hydrological Ecosystem Services 366
  Evaluation and Zoning of Aquatic Ecosystem Services 366
  Effects of LUCC on Regional Hydrological Ecosystem Services 378
Effects of Regional Hydrological Ecosystem Services on Human Well-Being 380
  Positive Effect of the Changes of Regional Hydrological Ecosystem Services on Human Well-Being 381
  Negative Effect of the Changes of Regional Hydrological Ecosystem Services on Human Well-Being 381

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Preservation of Regional Hydrological Ecosystem Services for IWRM 382
  Ecological Civilization Construction and Preservation of Regional Hydrological Ecosystem Services 382
  Urbanization and Protection of Hydrological Ecosystem Services 383
  Ecological Function Regionalization and Optimization of the Integrated Water Resources Management 383
Conclusion and Discussion 384
  Conclusions 384
  Discussion 385
References 385

Abstract

This chapter provides valuable information for integrated water resources management through evaluating the research on the interaction mechanism among land use changes, regional hydrological ecosystem services, and human well-being. Firstly, the driving mechanism of land use and land cover changes is introduced in this chapter. Secondly, the overview of the interaction mechanism among land use and land cover changes, regional hydrological ecosystem services, and human well-being is given. Based on the meta-analysis, land use changes have a profound influence on regional hydrological ecosystem services, and the variation of hydrological ecosystems could benefit or impair human well-being. Taking Wuhan City as an example, the ecological and ecological services of the river basin were analyzed synthetically, and the ecological environment sensitivity and ecological service function of Wuhan were measured respectively, in accordance with the requirements of creating national ecological city, on the basis of ecological function zoning at the provincial level, making an ecological function regionalization in Wuhan area according to the Ecological functional partition specification. Finally, two suggestions are emphasized for policy makers for the future integrated water resources management: (1) Proper land use makes for the water resource management; (2) Blindly pursuing the provisioning services weakens other services of hydrological ecosystems.

Keywords

Land use · Regional hydrological ecosystem services · Integrated water resources management · Ecosystem services · Ecological function zoning

Introduction

There is growing concern that water crisis caused by human activities is severely threatening human survival and impairing the law of nature (Bakker 2012). It poses challenges on policy makers for developing scientific and proper plans for preserving water resources or saving water use and leads to the recognition that the management of water resources requires a holistic approach. Integrated Water Resources Management (IWRM), an empirical concept built up from the on-the-ground experience of practitioners, is now the dominant paradigm for relieving the water-related issues. The UN provided the most-quoted definition (1992): a process to promote the coordinated development and management of water, land, and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems. Therefore, IWRM can be enhanced through water resource modeling and land use planning. With the exploration on the interconnections between Land Use and Land Cover Changes (LUCC) and regional hydrological ecosystem services or water–land coupling system, the solutions for improving water environment are no longer limited to study water itself, and the research on the interaction mechanism of LUCC and hydrological ecosystem services could offer another accessible path for integrated water resources management.

The dynamics of LUCC and their resulting consequences are one of the central themes of global change research. With the development of theory and methodology of the dynamics of land system change and the establishment of the Global Land Project (Jiyuan et al. 2014), researchers have increasingly realized the close relationships among natural environmental evolution, terrestrial ecosystem processes, human production activities, and the dynamics of LUCC (Deng et al. 2014). LUCC considered as an important driving force for the hydrological ecosystem change, enormously alters the structure of the earth surface system as well as its material and energy flows. In the past decades, aside from the study on the process and driving mechanism of LUCC at different spatial scales, the investigation upon the externality of LUCC, especially the effects of land use changes on regional hydrological ecosystem services, was another hotspot, due to the awareness that water is an increasingly scarce yet essential resource for sustainable development. As the enhanced land use intensity and growing land cover diversity dramatically modify the biogeochemical circulation, hydrological process, and landscape of the earth surface, these variations affect the status, characteristics, and functions of the regional hydrological ecosystem (Deng et al. 2013a).

The Millennium Ecosystem Assessment (MA) synthesizes and analyzes the theory and methodology of ecosystem services framework, and makes plenty of efforts to illustrate its widespread importance and strengthens recognition and knowledge of societal dependence on ecosystems (Smith et al. 2013). Hydrological ecosystem services are just one category of diverse services providing tremendous beneficial interests for people. As human well-being varies with change in ecosystem services as reported by Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Service (IPBES) in twenty-first century, hydrological ecosystem services involving freshwater supply, spiritual uses, and flood damages have both negative and positive impacts on human well-being. Thus, the IWRM is required to govern the consequences induced by alteration of hydrological ecosystem services for optimizing the human benefits. Of course, there is a large amount of evidences to clarify the internal and external mechanism of the changes of hydrological ecosystem services for integrated water resources management (Gascoigne et al. 2011).

This paper gives the answers of the following questions in tandem with an investigation on the interaction among LUCC, regional hydrological ecosystem services and human well-being. What is the driving mechanism of dynamics of LUCC in terms of natural conditions and socio-economy? How does the LUCC act on regional hydrological ecosystem services? What are the impacts of regional hydrological ecosystem services on human well-being? And how does the IWRM do to improve the human well-being based on the effects of LUCC upon hydrological ecosystem services? Then the remainder will introduce the IWRM through land use regulating in the context of research on the impacts of LUCC on hydrological ecosystem services. Last but not least, conclusions and expectations of relevant study on LUCC and regional hydrological ecosystem services and IWRM will be given.

Driving Mechanism of LUCC

The analysis on driving forces of LUCC is one of the vital contents for LUCC research, their relationship is often quantified by combining use conceptual model and mathematical model, introducing mathematical statistics methods and adopting the historical and current LUCC data (Deng et al. 2013b). The drivers of LUCC are usually divided into two major categories: natural factors and socioeconomic factors. Huang et al. (2007) made multiple efforts to identify the natural elements of LUCC. Natural factors often refer to natural and environmental characteristics, climate change, soil condition, vegetation succession, periodic interference, and other natural processes (Lin et al. 2014) made achievements on socioeconomic elements. As the report of International Geosphere-Biosphere Program (IGBP) and International Human Dimensions Program on Global Environmental Change (IHDP) stated (Qian et al. 2013), socioeconomic elements include demographic change, poverty status, technological progress, economic growth, political and economic structure, and core value of the society. However, the main driving force remains uncertain due to the variation of regional characteristics.

Natural Factors of LUCC

First and foremost, the differences of natural conditions determine regional heterogeneity of the LUCC in spatial and temporal, containing the heterogeneity of land suitability, natural structure of LUCC and natural condition of land system (Li et al. 2013). In the long run, the physical elements provide basic condition for LUCC, especially geology, geomorphology and soil. Except for the human activities, organism and water resource are the components of the land and also drive the natural dynamics of land through the phenomena of surface erosion, transportation and deposition acting on the formation of the land. In the natural system, climate change is usually considered as the main driver of LUCC, and their relationship is complex. Recently, the popular method is to assess the effects of future climate change on LUCC by using an economic model based on exogenous environment variables. The fourth assessment report released by Intergovernmental Panel on Climate Change (IPCC) in 2007 presented that climate change induced by human activities would bring adverse effects on society, economy and environment, even alter the way of land using, in light of the prediction for the changes of global temperature, sea level and snow cover in the next 100 years by different models. According to the results of the simulation and prediction for LUCC in different climate scenarios, land use types vary with climate change in different typical regions, such as the urbanization region and the afforestation region.

Socioeconomic Factors of LUCC

Socioeconomic factors of LUCC are land demand, land investment, urbanization, land use intensity, land ownership, land privatization, population, technology, economic growth, policy, core value of the society, etc. The relevant research established index system for LUCC and constructed LUCC model considering the coupling characteristics of LUCC model and other global environmental change models to simulate and predict the dynamics of LUCC. With the advances of global urbanization, growth of population, and boom of agricultural activity and industrialization, artificial influences cannot be ignored. Based on the future socio-economic development conditions and national policies of China, Deng Xiangzheng set up three scenarios, namely Usual scenario, Rapid Economic Growth scenario, and Cooperate Environmental Sustainability scenario, to simulate the spatial structure of LUCC in 2005–2010 taking natural factors and socioeconomic factors into account by adopting Global Change Assessment Model (GCAM), and utilized Dynamics of Land System (DLS) to analyze the future land use change in spatial and temporal in China(Xiangzheng Deng 2008). Several international case studies also revealed an intricate relationship between population and LUCC (Lin et al. 2014), which implies that it is not linear dependence due to the large regional differences and temporal variation. Thus, it is necessary to comprehensively understand the driving mechanism of LUCC in global range and carry on the research by conducting the case studies for comparative analysis.

Due to heterogeneity of the way and the consequences of these factors acting on LUCC, we treat all these factors as a whole to simplify their sophisticated relationships, and reveal the processes and the evolution of inherent forces of LUCC via the research on structure, function and the material/energy flows of LUCC (Wu et al. 2015). Therefore, the research on driving mechanism of LUCC increasingly involved the integrated apply of natural and social sciences.

Effects of LUCC on Regional Hydrological Ecosystem Services

Hydrological Ecosystem Services

Human has access to direct and indirect streams of benefits generated by hydrological ecosystem services, the final outputs of ecosystem functions or processes, in the following main categories. They are organized into following broad categories:

Hydrological provisioning services, often referred to the services by using the term "watershed services" emphasizing the utilization of the concept in the set of integrated water resources management (Smith et al. 2006), are deemed as one of the bundle of essential services like air quality, carbon dioxide sequestration, and soil generation provided by the ecosystems which are interrelated in dynamic and complex ways. The hydrological ecosystem efficiently acts on flow regulation and filtration, crucial aspects of which involve the control of mean surface runoff, peak or flood flows, base or dry season flow, and erosion and sediment load, as well as recharge of groundwater and soil moisture. These services maintain water quality, as well as mangroves, estuaries, and coastal zone processes. Also, they control the level of groundwater tables that may have adverse effects on agriculture and have benefited on water storage. Apart from these provisioning and regulating services, those that maintain natural flow and disturbance regimes as drivers of ecosystem evolutions which support aquatic ecosystem resilience refer to hydrological supporting services. Besides, some services could also support cultural values, for instance aesthetic qualities could support tourism and recreational uses. Peterson et al. (2002) stated that with the increasing number of buildings along the Northern Highlands Lake District of Wisconsin during the past 30 years, exploitation of lake contributed to coastal economic growth and strengthened the lake's cultural services. In contrast, the changes of vegetation coverage along the lake aggravated subsidence, deteriorated fish habitats and fishing industry, which directly weakened a bundle of provisioning services. In addition, the regulating services decline with the worsening water quality.

The above findings indicate that balanced growth among hydrological ecosystem services is optimum, or other services will degrade if human blindly pursue the provisioning services. Moreover, it will endanger the benefits of the contemporary and next generations. Therefore, all kinds of ecosystem services make for human life, and it is sustainable to keep balance of each ecosystem services.

Evaluation and Zoning of Aquatic Ecosystem Services

To explore the impacts of LUCC on regional hydrological ecosystem services, firstly we should evaluate the regional hydrological ecosystem services. According to the structure and function of the regional ecosystem, the evaluation factors such as the importance of water conservation, soil conservation, and nutrient conservation, which could reflect the evaluation factors of regional ecosystem production, life and restoration characteristics, are selected to build the evaluation index system of the importance of ecosystem services, divide each ecosystem service into different levels and assignments according to the importance, clear spatial distribution, and then use the expert scoring method to give indicator weight, space calculation overlay, on the regional integration evaluation.

Evaluation of Aquatic Ecosystem Services

(1) Importance Evaluation of Water Conservation Function. The evaluation is based on the contribution of the water conservation function of the evaluation area to the water resources of the whole basin and the role of the runoff regulation. The ecological importance of water conservation in regional ecosystem depends on the extent of regional dependence on water resources and flood regulation. Therefore, it can be evaluated according to the geographical position of the evaluation area in the regional urban river basin, and the contribution to the whole basin water resources. The importance of water security and flood regulation under different climate types can be divided into four categories (Table 1) that are important, medium important, unimportant, and insignificant.

Taking Wuhan City as an example, in order to highlight the importance of water conservation in the region, and combining with relevant experts' opinions, it is necessary to join the lake and reservoir water source catchment area to evaluate the importance of ecosystem water conservation service function. Various water conservation forests, water conservation buffer on both sides of the river as a reference, and ultimately the use of Table 2 grading approach to the importance of water conservation in Wuhan City to evaluate the classification.

The grading results are shown in the Fig. 1 below:

Table 1 Grading table of ecosystem water conservation importance

Type	Arid	Semiarid	Humid	Semihumid
Urban drinking water source area	Vital	Vital	Vital	Vital
Agricultural irrigation water	Vital	Vital	Important	Unimportant
Flood conditioning storage areas	Unimportant	Unimportant	Important	Vital

Table 2 Ecosystem conservation in Wuhan City

Affect the target	Importance Type, Range		Importance
River	Trunk river (urban water, flood storage)	Both sides of the river 1 km	Vital
		Both sides of the river 2 km	Important
		Both sides of the river 3 km	More important
	Two rivers (water, flood storage)	Both sides of the river 500 m	Vital
		Both sides of the river 1 km	Important
		Both sides of the river 1.5 km	More important
Lakes, reservoirs water source protection (water, flood storage)			Vital
Agricultural areas and other areas			General important

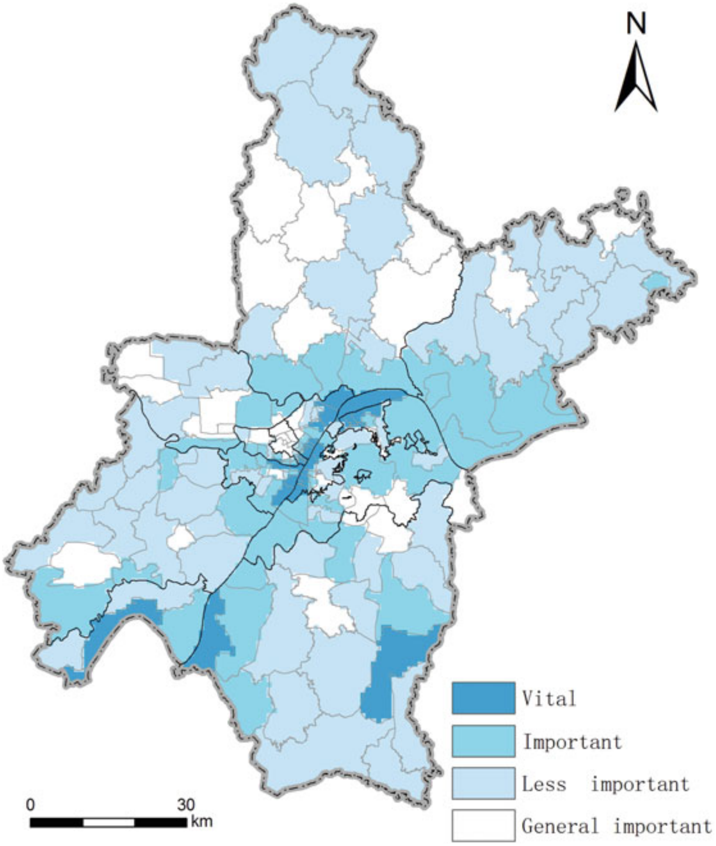

Fig. 1 The importance of water conservation in Wuhan city

The vital area of water conservation is located at 1 km along the Yangtze River and around Liangzi Lake and other important lakes. The important area of water conservation is from the 2 km buffer zone along the Yangtze River and related lake wetland. The area with important water conservation area is 4442 km^2, Accounting for 51.8% of the total area. The remaining agricultural areas and other areas were evaluated as important areas of water conservation due to their less contribution to regional water conservation.

(2) The importance of soil conservation services. Soil conservation is one of the important regulating services provided by ecosystems, and plays an irreplaceable role in regional erosion control and ecological security maintenance. Forest and grassland ecosystems have a very significant soil conservation function. Forest and grassland soil conservation function is mainly reflected in the forest and grassland vegetation interception of rainfall. It also reduces the kinetic energy of raindrops and litter layer storage function of regulating surface runoff to prevent soil splash erosion, surface erosion function (Huang et al. 2015). The importance of soil conservation is based on the sensitivity analysis of soil erosion, the analysis of local soil erosion on the

downstream river and water hazards. Based on the analysis of the spatial distribution of soil erosion sensitivity, considering the distribution of the city and its impact on the water environment of rivers and lakes, the harm degree of soil conservation to the downstream rivers and water resources was analyzed, and the administrative boundaries were taken into account. The importance is divided into four levels, respectively, very important, important, more important, and generally important.

The soil conservation function plays an important role in biodiversity conservation, soil resource protection and ecological security in Wuhan. Evaluation of the importance of soil conservation in Wuhan City and the evaluation criteria of water sensitivity and soil erosion sensitivity were classified according to the grading criteria of importance (Table 3). Taking Wuhan river distribution map and soil erosion sensitivity map as index layer, and then GIS software was used to superpose the layers. Finally, the distribution map of importance of soil conservation in Wuhan was obtained through comprehensive evaluation and grading.

The partition results are shown in the Fig. 2 below:

The area of soil conservation in Wuhan is 368 km^2, accounting for 4.3% of the total area. The soil conservation is very important because of the high sensitivity of soil erosion. The area of important soil conservation is 1138 km^2, accounting for 13.3% of the total area. Soil conservation of more important area is 3129 km^2, accounting for 36.5% of the total area. In other areas, the area is 3938 km^2, accounting for 45.9% of the total area, due to the less susceptible to water or soil erosion.

(3) Evaluation of Importance of Maintaining Function of Nutrient Substance. Nutrient maintenance is one of the important ecological service functions of ecosystem. Soil plays a key role in organic matter reduction and nutrient cycling. Different types of microorganisms in the soil reduce the specific compounds to the simplest inorganic compounds. The reduction of organic matter to form simple inorganic matter is ultimately returned to the plant as nutrients. The degradation of organic matter and nutrient cycling are two aspects of the same process. Soil plays an important role in the cycling of N, C, S, P, and other nutrient elements. The change of carbon and nitrogen cycle in ecosystem will change the concentration of greenhouse gases in the atmosphere and cause the global climate change. In addition, the loss of carbon and nitrogen may cause the eutrophication of water body. Maintaining the balance of nutrients in ecosystems is of great importance to human society.

Table 3 Classification of soil conservation importance

Affect the water body	Susceptibility of soil erosion				
	Insensitive	Mildly sensitive	Moderate sensitivity	Highly sensitive	Extremely sensitive
1–2 rivers and urban water quality	General important	Highly important	Vital	Vital	Vital
3 rivers	General important	Medium importance	Highly important	Highly important	Vital
4–5 rivers	General important	General important	Medium importance	Highly important	Highly important

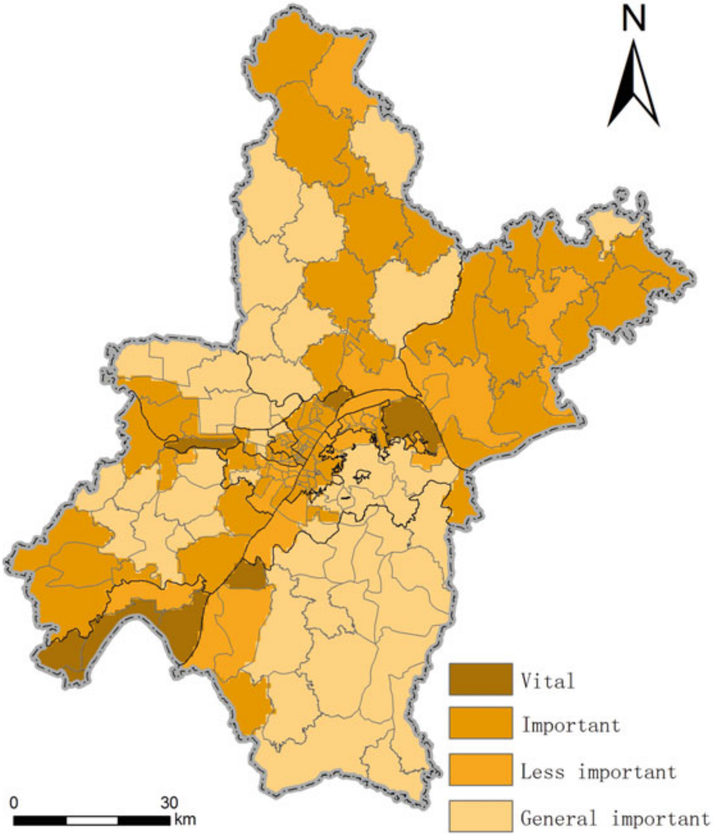

Fig. 2 The hierarchical map of soil conservation in Wuhan

The assessment of the importance of nutrient maintenance in Wuhan was mainly based on urban water sources, wetland parks, and lakes at all levels, and evaluated the eutrophication results and severity according to the loss of nitrogen and phosphorus in the catchment area. According to the evaluation index and the importance grade in Table 4, the importance distribution map of the regional nutrient material was obtained by GIS software, and its distribution was evaluated.

The evaluation results are shown in Fig. 3:

The vital area for nutrient maintenance is 485 km^2, accounting for 5.7% of the total area, mainly in the Junshan street, Daji street, Zhuankou street, East Lake Scenic Area, the Canglong Island office of Economic Development Zone, and Anshan Office. These streets have very important nutrient-retaining functions due to the distribution of the National Wetland Parks such as the Houguan Lake Wetland Park, the Anshan Wetland Park, the Canglong Island Wetland Park, and the East Lake Wetland Park. The Baiquan Office, Suohe Town, Wulongquan Street, Fasi Street, and Mulan Township are important areas for nutrient maintenance, covering

Table 4 Evaluation indexes of importance of maintaining nutrients and their importance

Indicator	Importance level rating	Assignment
Urban water sources, national wetland parks, National protected species livestock and wetlands	Vital	7
Large reservoirs, provincial wetland parks, Provincial species of habitat of lakes and wetlands	Pole important	5
Medium – sized reservoirs, municipal wetland parks, municipal species habitat of lake wetlands	Important	3
Small reservoirs, general lake wetlands	General important	1

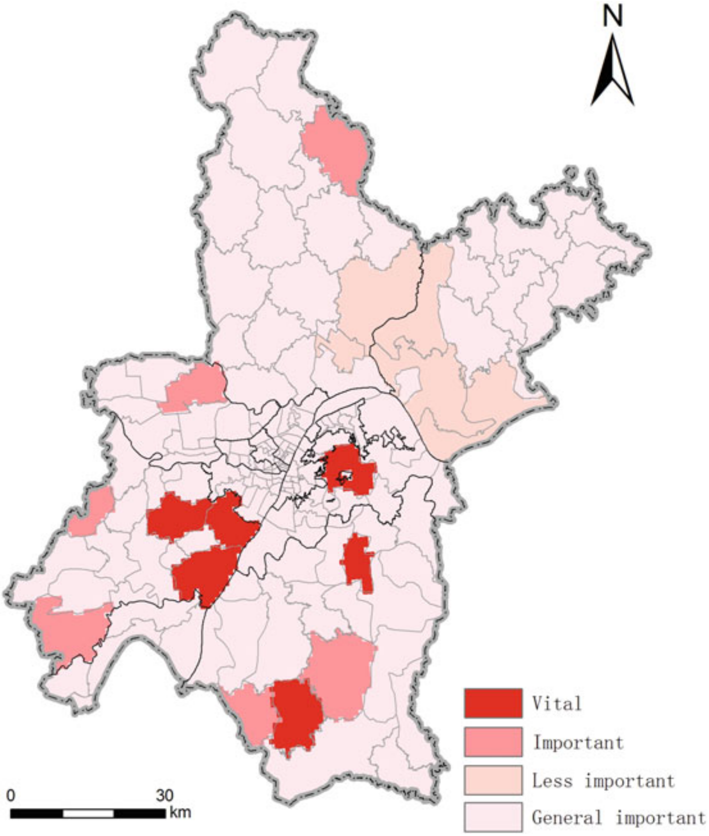

Fig. 3 Wuhan City nutrition to maintain the importance of grading map

an area of 698 km^2, accounting for 8.1% of the total area. In these areas lie provincial wetland parks, for instance Dugong Lake Wetland Park, Suozi River Wetland Park, Zhuyanghai Wetland Park, and other lake wetland. The areas with less important nutrient maintenance are mainly Liuzhi Street, Sanliqiao Street, Cangfu Street, Yangluo Street, and Shuangliu Street, and their total area is 801km^2, accounting for 9.3% of the total area. The main reason for the maintenance of nutrients in these areas is mainly due to the presence of Cao Lake, Zhangdu Lake, and Wu Lake. Due to the fact that the rest of the area is rarely distributed with lake wetlands, it is estimated that the total area where nutrients are generally important is 6594 km^2.

Water Ecological Function Zoning Method

Water ecological function zoning is to extract the differences between the hierarchical structure and spatial characteristics of watershed ecosystems, and provide support for the differential management of water ecological system and the management of water quality objectives, so as to realize the water ecological health services. We can use the graph overlay method and leading mark method to divide the region in the process of water ecological function regionalization, and then adopt the cluster analysis method to adjust the result and to ensure the integrity of the ecosystem types and processes in the region, and take into account the consistency of the types of ecological services.

1. Space superposition method

The top-down method, which is a universal law focusing on regional differentiation, analyzes the similarities and differences of regions from superior to subordinate according to the relative consistency and regional conjugated, Class division method.

Spatial superposition method is a commonly used top-down qualitative method. It is a method of extracting spatial implicit information through geographic information system, and implementing spatial superposition of various elements including terrain, soil, landform, and vegetation. Overlay analysis will overlay the various data layers representing different topics, with the boundaries of coincidence or the average position as the boundaries of the new partition to form a new data level that combines the attributes of the original two or more layers. The overlay analysis generates new spatial relationships, but also the input of multiple data-level attributes linked to generate a new attribute relationship. The main steps of the spatial superposition method are: first, the single factor distribution map is processed by grid, and then the raster map with the attribute value is superimposed by the raster Calculator in the ArcGIS spatial analysis module to get the superimposed comprehensive index, and then reclassify the attribute values of all the raster to obtain the final superposition map of the comprehensive factors. Finally, based on the actual situation of the study area, the preliminary partition results are adjusted and modified, and finally the partition results are determined. Spatial superposition method has the advantages of being a simple method and providing intuitionistic results.

2. Cluster analysis

Bottom-up approach is based on similarity principle, from the smallest part of the region, through clustering integration and other related operations, with the principle of regional conjugation and relative consistency, we merge them into high-level units.

Cluster analysis is a typical bottom-up quantitative method. It is one kind of multivariate statistical analysis method which classifies the samples or indexes according to the similarity of things and the characteristics of things themselves. The basic idea is that there is a similarity between the samples or indexes. The main process of clustering analysis is to find out the statistic that can measure the similarity between the sample and the index according to the multiple observation indexes of the sample. On the basis of these statistics, some similar samples are aggregated into one class. The main process of clustering analysis is to find out the statistical magnitude of similar situation between samples or indicators according to the several observing targets of the sample, and put the samples with larger similarity into the same class, put the closely related samples into a small taxonomic unit, and put the not closely related samples into another small taxonomic unit, until all the samples are aggregated, and finally divide the different types, form a small-to-large classification system. Double-constrained clustering is a kind of clustering analysis, which refers to the clustering form in spatial domain and attribute domain at the same time. The double-constrained clustering method is to discover geography. Spatial objects are clustered, extended and changed in spatial attributes or attribute combinations, and the related concepts of double constrained clustering include spatial continuity and attribute distance within classes. In order to partition the ecological functions of Wuhan City, we need to consider the attribute value of clustering index, the spatial distance of each partition unit, attribute weight, and distance weight. We conduct cluster analysis on study area by taking ecological environment status quo, ecological regulation and socio-economic evaluation as indicators. The double-constrained clustering is to discover the spatial aggregation, distribution, and variation of nonspatial attributes, which is embodied in spatial continuity and attribute cohesion. When dividing ecological function zone, similar characteristics and spatial vicinity should be taken into account. Therefore, due to the introduction of double-constrained clustering method, the study of ecological function zoning become more scientific.

3. Leading sign method

Dominant mark method, also known as dominant factor method, on the basis of the comprehensive analysis of factors' combination and interaction, identify the element type (or dominant factor) with symbolic significance. Ecological function zoning by this approach usually carries relative validity and legitimation. The division of the boundaries of this approach usually has a relatively clear meaning. It should be noted that each level of regional units have their own differentiation leading factors, but reflecting the dominant factor is not only a major sign but often a set of interrelated signs and indicators. Therefore, in the use of dominant sign method for partitioning, in addition to the main indicators, it should also be considered the relevant indicators to correct the boundaries. As a result of the simple partition method, it may result in the uncertainty of the results, and even lead to erroneous conclusions, at this time, with the leading sign method will enhance the scientific and correct results.

According to the ecological function zoning in Hubei Province, Wuhan belongs to the wetland ecological zone (first-level zone) and lake ecological sub-zone (second-level zone) in the middle reaches of the Yangtze River. In accordance with the requirements of establishing a state-level eco-city and the “Technical Specifications for Ecological Functional Zoning (exposure draft)” issued by the MEP (Ministry of Environmental Protection), on the basis of the zoning of ecological functions at the provincial level, the zoning of ecological functions in the urban area of Wuhan shall be conducted.

Wuhan is divided into 11 ecological function areas, including the main city of Habitat security functional area, Metro Habitat security functional area, water – Taoist River water conservation function area, Caidian West Lake water conservation function area, House River water conservation and biological Diversity functional area, Meiyuan ni-Mulan water conservation and biodiversity functional area, Liangzi Lake water conservation and biodiversity functional area, Shenhu biodiversity functional area, Zhangduhu biodiversity functional area, Qinglongshan soil Conservation and biodiversity functional areas, as well as the Jiu-shan Mountain soil conservation and biodiversity functional areas.

1. Habitat security functional areas

Regional characteristics. Wuhan City has a total of two Habitat protection function area, which are the main city of Habitat security functional area and the Metro Habitat security functional areas. The Habitat protection function area is located in Wuhan city center, covering the most seven administrative regions of Jiangan District, Jianghan District, Qiaokou District, Hanyang District, Wuchang District, Castle Peak, and Hongshan District, including Dazhi Street, Chang Green streets, Wuhan Central Business District, Yellow Crane Tower streets, and other 93 streets; Metro Group Habitat security features include the new Island, Huangpi, East Lake, Caidian, Jiangxia, and other administrative regions of the region, including Caidian Economic Development Zone Offices, Longquan Street, Yangluo Street, and Qijiawan Street, a total of 39 streets. The total area of 3787.39 km^2 accounts for 44.2% of the land area of Wuhan City. The main functions of the Habitat Protection Functional Zone include maintaining the regional ecological security, balancing the contradiction between human settlements and economic development, and ensuring the urban ecological culture and human health environment. The main function of new Habitat Safeguards Functional Area is to guide the balanced population distribution and alleviate the population pressure in the central city. At the same time, with the aid of the four major industrial sectors such as “Grand Optical Valley, Grand Automotive Industrial Zone, Grand Airport and Grand Port,” the regional economic strength will be enhanced.

Main ecological problems of the functional area. The expansion of urban is not limited, cities and towns expansion is accelerating, the environmental protection facilities are lagging behind, the ecological carrying capacity is seriously overloaded, the ecological function is low, therefore, the environmental pollution is increased, the urban ecological function is reduced and the quality of living environment is decreased.

Protection and construction direction. The type of functional areas in Wuhan City is the focus of future development and optimization of the region. In the process of development and optimization, it is necessary to strengthen urban ecological construction, improve the proportion of ecological land use, improve the quality of air and water environment, control the emission intensity of major pollutants like sulfur dioxide and nitrogen oxides, reduce noise pollution and improve the ecological environment quality, to create a livable place to improve the public's satisfaction with environmental quality. In accordance with the requirements of the main functional zoning, land use planning, and urban and rural construction planning, it is necessary to adjust and optimize the service and focus on nurturing and improving service functions and focus on the development of financial services like finance and trade, administration, science and education, information consultation, tourism and leisure, becoming the modern service center in the central region. For the purpose of rational distribution of regional population and labor productivity needs optimal allocation of regional of development resources. Optimize the layout of urban land use, promote intensive sustainable development of urban, establish the green living sustainable houses, and improve land utilization efficiency. In accordance with the principle of "priority in the environment, population evacuation, traffic guidance, and relative occupancy," relocated residential areas in relatively good natural areas by means of bus lines and rapid rail transit, so as to establish a relatively balanced spatial structure of residence, employment and service system, and guide the main urban population to the external evacuation, forming a reasonable distribution and supporting the perfect residential land space pattern. At the same time, the new residential area requires a piece of development, protection of residential reasonable spacing, increase public green space, reserve sufficient parking spaces, and configure the education, health, sports, culture, commercial, and other public facilities simultaneously. Increase the transformation of urban villages and shantytowns, and promote "city village" to the urban community changes. We should make full use of the rich landscape resources of Wuhan, strengthen the urban landscape construction, improve the environment of the residential area, construct small-scale scenic spot, construct the core tourist area with sightseeing and business exhibition, emphasize the coordination between urban artificial ecology and natural ecology development, employ rational allocation of public green space, and improve the city recreational leisure function.

2. Water conservation function area

Regional characteristics. Wuhan has two water conservation functional areas, one of which is Ju River-Taoist River water conservation function area, which is located in the northeast of Xinzhou District, including the Taoist River Scenic Area, Old Street sub-district, Xugu town, etc. Another one is Caidian West Lake water conservation Function area, located in the northwest area of Caidian District, including the Tonghu sub-district, Junshan sub-district, etc. The total functional area are 732.96 km^2, accounting for 8.56% of the land area of Wuhan City. Jushui is the main water source of Xinzhou District, and Caidian West Lake is the drinking water source of Caidian District Suohe town, having an important water conservation and storage function.

Main ecological problems of this type of functional areas. The functional areas are affected by the rural nonpoint source pollution. The water resources in the water-Tao-Guan River area are not enough, and the aquatic ecosystem is fragile and the function of water conservation is declining with time.

Protection and construction direction. The establishment of water conservation and wetland protection zones is used to restrict or prohibit all kinds of economic and social activities and modes of production that are not conducive to protecting water source conservation functions of ecosystems. Control and curb water pollution, reduce water resources load, prohibit the development of industries that lead to water pollution, and carry out the construction of ecological clean watershed; expansion of surface vegetation cover, taking biological measures to carry out soil and water conservation work, to ensure that the regional ecological balance. Strict policy on cultivated land protection was carried out to control the loss of arable land, to stabilize the area of garden land, pasture land, and other agricultural lands, to carry out soil pollution control and restoration, and to strive to improve comprehensive production capacity and utilization efficiency, and to carry out afforestation and increase forest land area. Strengthening afforestation, greening, road greening, Binjiang greening and embankment afforestation construction, increasing barren hills and wasteland afforestation, inefficient forest transformation and abandoned quarry vegetation restoration efforts were carried out to improve the green coverage.

3. Water conservation and biological diversity functional areas

General situation of regional characteristics. Wuhan City was divided into three water conservation and biodiversity functional areas, including FuHe water conservation and biodiversity functional areas in the northeastern Dongxihu, Jiangan district in the northwest and southwest parts of the Huangpi district, including evergreen garden district management committee, such as gold and silver lake streets, BaiQuan office 14 streets; Meiyuanni-Mulan water conservation and biodiversity area is located in the northwest Huangpi District, including 9 sub-districts, such as Caijiazha, Wangjiahe, Mulan Mountain scenic spot; Liangzi lake water conservation and biodiversity area is located in the south of Jiangxia district, including lake see streets, see streets, economic development zone in Liangzi Lake scenic area office and other seven street, three functional areas consists of a total area of 2601.85 km^2, accounting for 30.36% of the land area in Wuhan city. Main functions include soil water storage, increasing rainfall and fog, water conservation, ensuring rich surface vegetation, and protecting the biological diversity.

Main ecological problems of this type of functional areas. The overexploitation of human activities leads to vegetation loss, soil and water loss, wetland shrinkage, ecological environment destruction; rural nonpoint source pollution leads to fragile aquatic ecosystem; influenced by water, chloride causes serious ammonia nitrogen pollution of FuHe.

Protection and construction. Coordinate the relationship between land use and ecological construction, implement the construction and restoration project of water system network, reduce soil erosion by strengthening the protection of vegetation coverage, and optimize the watershed management. It is needed to establish and perfect relevant laws and regulations and special supervision mechanism, to improve the pollution investigation dynamics behavior; to ensure the original regional ecological integrity, and maintain the ecological balance, tourism development projects which may damage the environment in relevant waters are strictly prohibited. Actively implementing ecological forest network construction, relying on the regional natural landscape resources, to actively promote artificial afforestation, afforestation, with nature reserves, forest park ecological green space construction as the key point, through the lakeside green, forest green, highway greening, farmland forest tries greening, increase the forest coverage rate, constructing the landscape ecological network system. The focus was on strengthening the Dabie Mountains ecological construction and management, which is in northern Huangpi district: Implement the protection and restoration of Liangzi Lake and large reservoirs and other wetlands, construct the urban ecological barrier and give full play to the functions of aesthetics, education and culture of wetlands. Planning and construction of protected parks, a reasonable arrangement of scenic spots, ecotourism areas supporting facilities. On the basis of protecting the existing human resources and the natural environment such as landscape greening, it is an ideal place to provide leisure travel and promote ecological culture, make the public feel the harmony between mankind and nature.

4. Biodiversity functional area

Regional characteristics. Wuhan is divided into two biodiversity functional areas. The Chenhu Biodiversity Functional Area is located in the southern part of Caidian District, including three districts of Xiaosi Township, Xiangkou Street, and Dengnan Street. The Bodi Biodiversity Functional Area is located in the southern part of Xinzhou District, including the Willow Street, Lake Street, and Wang set streets 3 streets, with a total area of 638.53 km^2, accounting for 7.45% area of Wuhan City land. There is a provincial nature reserve – Chenhu wetland nature reserve, municipal wetland nature reserve – Zhangduhu wetland nature reserve, and so on. The main function of this function area is to maintain wetland ecological environment balance and ensure the biological diversity.

Main ecological problems of this type of functional areas. The excessive use of land resources and biological resources caused by the expansion of human activities, and the invasion of alien species, leading to the degradation of biological resources, biodiversity is seriously threatened; Chen Lake area is also affected by river basin water, wetland ecosystems are under threat.

Protection and construction direction. Carrying out surveys and monitoring of biodiversity resources, then assess the status of biodiversity conservation and the causes of the threat. Strengthening the construction and management of nature reserves, coordinating the contradiction between ecological protection and economic construction, controlling the size of beach development, and prohibiting the development and construction in the nature reserve area; strengthening the control of alien species invasions, prohibiting the introduction of alien species in the biodiversity conservation functional areas; implementing the National Biodiversity Conservation Project, and improving the construction of nature reserves system based on the important functional areas of biodiversity.

5. Soil conservation and biological diversity functional areas

Regional characteristics. Wuhan has two soil conservation and biodiversity functional areas, with a total area of 808.41 square kilometers, accounting for 9.43% of the land area in Wuhan City. One of which is Qinglongshan Soil Conservation and Biodiversity Functional Area, located in the northwest of Jiangxia District, including 4 sub-districts, such as the Jinkou, Zhengdian. Another one is Jiuzhen Mountain Soil Conservation and Biodiversity Functional Area, located in the northeast of Caidian District and Hannan District, including the Junshan sub-district, Shamao sub-district, etc. With a total area of 808.41 km^2, accounting for 9.43% of the land area in Wuhan City. There are Qinglongshan Forest Park and Jiushan Mountain Forest Park. The forest coverage is higher and the surface vegetation is abundant. It plays an important role in protecting biodiversity. Its main function is to maintain soil and maintain the balance of ecosystem and provide the city with Ecological security barrier.

Main ecological problems of this type of functional areas. Human development activities lead to the degradation of surface vegetation, soil and water loss, the potential threat of rocky desertification, increased soil erosion sensitivity, threatening the diversity of species resources development.

Protection and construction direction. Protection of national and provincial nature reserves, scenic spots and forest parks, and other ecological barrier land needs. Prohibit any land use activities that do not meet the leading function, actively implement the construction of ecological forest network, and build an ecological network system integrating landscape. Soil and water conservation projects in areas where soil erosion is serious and may cause serious harm to local or downstream areas are to be treated with emphasis. Strengthening the protection and restoration of ecosystems in the region, and rationally arranging the land for supporting facilities in scenic spots and ecotourism areas. Protect the habitat of natural ecosystems and important species and prevent the ecological construction from changing it.

Effects of LUCC on Regional Hydrological Ecosystem Services

In order to promote socioeconomic development, humans change the ways of land use, and management methods are needed to improve the living standard, which also alters regional hydrological ecosystem services to some extent. LUCC often leads to the variation of regional hydrological ecosystem services, which on the one hand reflected the hydrological characteristic of land surface as the changes of some physical attributes of the regional land surface involving roughness, albedo, and soil moisture can trigger the climate change. On the other hand, hydrological ecosystem services change can veer from the earth's surface water circulation and then alter the water exchange between land surface and the atmosphere, between soil and plant (Lin and Lin 2015).

From a macroscopic view, there is a close relationship between structures and functions of hydrological ecosystems among material, energy value, and information transformation between human and land. From the microscopic view, the natural components of the hydrological ecosystem and their interactions also can profoundly impact the distribution of regional land resources as well as its development and utilization mode. Specifically, the effects of land use on hydrological ecosystem services embody in three aspects. First, there is a difference between the main hydrological ecosystem services produced by different land use types. Secondly, land use pattern change has a significant impact on the hydrological ecosystem services. Thirdly, the effect of LUCC on hydrological ecosystem services differs with the varying land use intensity (Bolund and Hunhammar 1999). And the effect can be positive or negative. Therefore, it is urged to enhance the understanding of the hydrological ecosystems for human by the research of developing the theoretical framework and mathematical model containing the assessment of hydrological ecosystem services and natural capital value (Deng et al. 2010).

(1) Effect of LUCC on the hydrological provisioning services. The hydrological ecosystem continuously provides sufficient clean water for the human society, which serves as the basis of human survival. A study in African did by the UN Food and Agriculture Organization (FAO) found that agricultural production activities significantly interfered with the water conservation and nutrient balance of soil during 1982–1984, and the consequences were more serious in some countries as the soil nutrients and soil water were almost exhausted (Smaling and Fresco 1993). Another case study of the Rouge River Basin in southwest Michigan in USA showed that the land use changes, especially the industrialization, completed the heavy metal pollutant and organic chemicals to be discharged into underground. The shallow aquifers and the water of Rouge River were contaminated (Murray and Rogers 1999). The surplus of nitrogen and phosphorus from agricultural production bring about water quality deterioration, oxygen depletion, death of fish, algae bloom, and epidemic of waterborne diseases (Bennett et al. 2001; Townsend et al. 2003). The transformation of land use types responded to the changes of hydrological provisioning services.

(2) Effect of LUCC on the hydrological regulating services. The regulating services of hydrological ecosystem include water conservation, flood control, and water purification. The dynamics of vegetation type, area and quantity induced by LUCC break the regional balance of water resource and hamper the reaction capacity for environmental change controlled by the main vegetation structure. The research on urbanization indicates that rural land is greatly reduced because

of urbanization construction. According to the obvious correlation between mainly water-quality index and land-use type, it shows that land use change resulted from urbanization greatly influences water resources supply and demand balance (Shi et al. 2015).

(3) Effect of LUCC on the hydrological supporting services. The hydrological supporting services involve the maintenance of natural flow and disturbance regimes which support aquatic ecosystem resilience. Each hydrological ecosystem service corresponds to different land use type. On the one hand, LUCC can alter the physiochemical characteristics on land surface and change the hydrological ecosystem, thus influencing the regional hydrological cycle as well as the whole biochemical process. On the other hand, the hydrological ecosystem supports LUCC with soil water balance. One research on the wetland around the Trichonis Lake in Greece shows that climate slightly influences the changes of wetland, while LUCC plays the leading role in the wetland change (Dimitriou and Zacharias 2010).

(4) Influence of LUCC on the water-related cultural services. The water-related cultural services mainly include the spiritual and religious values, recreation and ecotourism, aesthetic value, incentive function, education function, social function, cultural inheritance, cultural diversity, and knowledge system. Some of them are tangible and visually identifiable, while others are invisible and expressed by human activities (Pleasant et al. 2014). The research in Malagasy reveals that there is a correlation between the ecosystem service and the cultural heritage value caused by the mobility of local fisher men. The relevant analysis can offer preserving measures for the local cultural heritage. The cultural services of ecosystem can be improved by proper land use planning like the construction of school and park.

Effects of Regional Hydrological Ecosystem Services on Human Well-Being

Human survival and sustainable development depend on the freshwater provisioned by hydrological ecosystem services. And it is varying due to the fact that it is encompassed by a fluctuating external environment, which implies that changes of hydrological ecosystem services could be for or against human well-being. However, Mcconnell (2002) proposed that the overall impacts of ecosystem services on human well-being cannot be determined by the research in one region or modeling through using short-term data. Identically, Daw et al. (2011) concluded that people benefited from ecosystem services was constrained by the family size, education level, poverty, vulnerability, and social relations. These findings are appropriate for hydrological ecosystem services also. Therefore, the study on regional hydrological ecosystem services instead of hydrological ecosystem services could offer more useful information for integrated water resources management.

Positive Effect of the Changes of Regional Hydrological Ecosystem Services on Human Well-Being

Humans receive abundant benefits from natural environment in the form of goods and services (Delgado et al. 2013). Hydrological ecosystem services, derived from ecosystem services, involve provisioning services (e.g., water supply, power production and irrigation), regulating services (e.g., water purification and erosion control), water-related cultural services (e.g., aesthetic appreciation and spiritual uses), and water-related supporting services (e.g., provision of water for plant growth, create habitats for aquatic organisms). The positive effects of regional hydrological ecosystem services on human well-being are demonstrated from four aspects. Firstly, water supply considered as a provisioning service, both its quality and quantity are bound up with agricultural advance, economic development, and human health. In the last 50 years, the amount of global water use has been tripled (Bennear and Olmstead 2008). The FAO distinguishes freshwater consumption from the following aspects. According to the global average data, approximately 70% of water use is for agriculture, 20% for industrial and 10% for domestic purposes, including households, municipalities, commercial establishments, and public services. Secondly, regulating services which are provided by regional hydrological ecosystem services are amongst the most essential for the sustainability of resource use. In Lake Victoria, Simonit and Perrings (2011) calculated the value of regulating services-nutrient buffering functions of wetland to improve the ecosystem service compensation scheme, indicated that the total cost of the payments for nutrient buffering services is 3.86 M dollars per year. Jenkins et al. (2010) emphasized the significance of the regulating services of wetland in the Mississippi Alluvial Valley for advising the government to take conservation practices on wetland ecosystem services (Faulkner et al. 2011). Thirdly, cultural services involved not only the visual enjoyment provided by the hydrological landscape, but also elevating the utility of humans. Vemuri and Costanza (2006) stated that there was a positive correlation between service value of ecosystem per person and life satisfaction including hydrological ecosystem services. Fourthly, Vörösmarty et al. (1998) concluded that terrestrial water cycle is of critical importance to a wide array of earth system processes.

Negative Effect of the Changes of Regional Hydrological Ecosystem Services on Human Well-Being

That human gain from hydrological ecosystem services is growing in a non-linear way. It implies that people will mutually develop with hydrological ecosystem if they obtain benefits in a proper range, or the hydrological ecosystem will be damaged if they blindly input labor and capitals. In verse, human well-being will be impaired by these damages (Eggen and Suter 2007). Through other study, Foley et al. (2005) proposed that the development of agriculture was at the expense of sacrificing natural ecosystems.

Assessment report of MA program in 2005 declared that 60% of the world's ecosystem services have been degraded, especially the services for providing fish, freshwater, and cultural services of spiritual and aesthetic value (Kamp et al. 2003). By contrast, the decline of hydrological ecosystem interferes with the balance of other ecosystems and negatively affects the human well-being. Sannwald et al. (2006) concluded that water scarcity and land degradation interacted with each other, forming a vicious circle. Tisdell (2001) also stated that water scarcity affected the natural flow, and thus IWRM has to take water supply for natural flow into account. In summary, the decline of provisioning services of hydrological ecosystem is also one of the drivers of the degradation of other ecosystems.

Human well-being varies with the decline of hydrological supporting services which especially has a negative effect on the biodiversity conservation. The research on the relationship between vegetation dynamics and landscape pattern of desert oasis reveals that the disappearance of scrub meadow, mire vegetation, and riparian forest leads to the decline of hydrological supporting services, and in turn influences biodiversity and causes landscape to be deserted. Besides, Young and Potter (2002) proposed that the changes of water flow owing to estuarine sandbar strongly influenced the species and density of estuarine organisms based on the research on the normally closed Wellstead Estuary on the south coast of Western Australia.

Regulating services of hydrological ecosystem reflect in the aspects of water and soil conservation and water purification. These services decline along with the decreasing of flood land or wetland, which leads to the degradation of purification capacity and surface water quality, thus influences residential water. Renard and Ferreira (1993) stated that sediment in rivers and reservoirs and soil erosion influenced and decided surface water quality. Besides, hydrological cultural services act on the spiritual welfare of humans. In another study, Liu et al. (2005) analyzed the changes of hydrological ecosystem services and found that the increasing area of reservoir pond in Sangong river basin improves flood control ability and enhances the provision services for production and living, but weakens aesthetic.

Preservation of Regional Hydrological Ecosystem Services for IWRM

Ecological Civilization Construction and Preservation of Regional Hydrological Ecosystem Services

Based on the above analysis, promoting the land use pattern creates a new thought for preserving regional hydrological ecosystem services and give more information for IWRM. With the concept of ecological civilization construction put forward, government invested a lot to build ecological programs by improving the way of land use for sustaining the law of the nature. For examples, The Grain for Green project covering the whole China makes for incorporating hill-slope hydrology and adjusting regional runoff (Band et al. 1993), and the programs like Natural Forest Protection Project, the construction of Three-North Shelterbelt project, ecological protection zone playing the same role in hydrology. In addition, the program returning cultivated land to lakes benefits the water supply for regional hydrological ecosystem services. However, ecological measures sometimes incur more threatening hydrological problems when they are not matched well with regional hydrological ecosystem. As we all know, while water hyacinth has been proved as a biosorbent to remove heavy metals or plant nutrients from polluted water for water purification (Ibrahim et al. 2012), it is also one of the world's worst aquatic weeds causing severe bio-invasion.

Urbanization and Protection of Hydrological Ecosystem Services

A series of research works show that hydrological ecosystem services relate closely with urbanization, which may have a positive or negative impact on hydrological ecosystem services. Urbanization incurs a series of eco-hydrological problems, such as pumping groundwater exceedingly, land sinking cracking, rain flood disaster, and the serious pollution of surface water. Urbanization strongly interfere the environment security. To some extent, it deteriorates the water environment, and hurts sustainability of urban civilization. In African, urbanization has reduced rainfall and the degree of harmony between ecosystem and urbanization. The development of urbanization is related to population migration, and large-scale agricultural population migration and land reform lead to hydrological ecosystem changes. However, some research shows that urbanization also has a positive impact on hydrological ecosystem services. Deng et al. have stated that urbanization promoted the water use and land use intensity (Deng et al. 2015). The proper pace of urbanization is the premise for ecosystem services' protection, sustainable economic advances and improvement of living standard. Therefore, it is vital for ecological safety to formulate reasonable land use policy and protect the ecological land (Jin et al. 2014).

Ecological Function Regionalization and Optimization of the Integrated Water Resources Management

Spatial zoning is extensively applied in the field of geography with the development of theory and methodology of geography, and scholars have already made some achievements in application, such as agricultural zoning (Marin 2007), woodland partition (Zollner et al. 2005), ecological zoning, and water resource partition (Shitikov et al. 2007). Regional spatial function zoning is an approach to analyze spatial geographical heterogeneity on a microscopic scale, aiming at making full use of the natural geographical system and preserving attributes of different regional functions, while ecological function regionalization identifies effectively different ecosystem services. Thus, it can refer to a technique to study the core hydrological ecosystem services and their differential features and also they can be regulated to achieve the goal of gaining human well-being and optimizing the IWRM. As LUCC changes the function and structure of hydrological ecosystem, people can optimize the way of land use to create a virtuous circle of society–ecosystem–economy (Watanabe and Ortega 2014). In the middle of the Heihe River Basin of China, Shi et al. (2014) have analyzed the changes of hydrological ecosystem services through ecological function regionalization using System for Identifying and Zoning Ecosystem Services (SIZES). The results show that with the decrease of forest land, grassland and wetland and the increase of urban construction land use, the climate changes obviously and the supply and regulation ability of hydro-ecosystem are affected. Therefore, regionalization of ecosystem functions can help identify major ecological issues and establish management systems that support the development of services for hydro-ecosystem services, so as to achieve the objective of integrated management of water resources, optimization of hydro-ecosystem functions and enhancement of human well-being.

Conclusion and Discussion

Conclusions

The process of land use change is complex and uncertain as its driving mechanism presents entirely disparate in different scales. With population growth, economic development, and urbanization, proper land use pattern for sustainable development has attracted the concern of ecologists, economists, and management scientists. Combining research on land use changes and ecosystem services offers luxuriant evidences for settling regional environmental issues. The above analysis proved that land use changes thoroughly influence the regional hydrological ecosystem services through altering physical characters of earth's surface and water cycle processes.

Subsequently, the changes of the regional hydrological ecosystem services may positively or negatively act on human well-being considering their regional features. But to what extent do the regional hydrological ecosystem services influence human well-being is not clear and more research is needed. Notably, there are few quantitative analyses while most of relevant research works concentrate on the descriptive analysis. Therefore, this is still a potential field of modeling and statistical methods for quantifying their impacts based on further understanding of the interaction of regional hydrological ecosystem service and human well-being.

However, the regional hydrological ecosystem services are highly sensitive to the changes of themselves. For the provisioning services, regulating services, cultural services, and supporting services, we have always modified the supply of regional hydrological ecosystem services to enhance the delivery or production of a particular good or service. But the inappropriate distribution of the four services results in the strengthening of the provisioning services, whereas the other three are weakened, and in turn cause the overall decline of human well-being.

Discussion

While a large number of current studies emphasized the direct effects of human activities on hydrological ecosystem services, the analysis upon indirect effects induced by land use changes has still potential for further research. The review proceeds from disclosing the driving mechanism of LUCC and separately describes how the four kinds of services of hydrology vary with LUCC, which clearly illustrates the processes of the generation of the indirect impacts. Therefore, further research is required to assess the indirect impacts in each sector in the context of land use change, and the concept of these indirect effects into the development of society–economy–ecology for clarifying the process among LUCC, regional hydrological ecosystem services and human well-being, and integrated water resources management.

There is a complex and dynamic process of interaction between LUCC, regional hydrological ecosystem services and human well-being. With the balance of the system as a whole, competition among the four service functions of the hydrological ecosystem undermines human health, as opposed to their synergy. Just like people blindly pursue more services from the hydrological ecosystem while ignoring human significance, resulting in an improper distribution of these services and reducing the overall effectiveness of the regional hydro-ecosystem services. Therefore, humans should have a global and long-term perspective in the process of receiving goods and services from hydrological ecosystem services.

Human well-being and social system are inseparable, and corresponding management system should support the coordinated development of land use, regional hydrological ecosystem services, and human welfare. IWRM offers solutions to the water crisis in linking water to other vital resources and viewing the whole water cycle together with human interventions as the basis for sustainable water management. The research on the effects of land use changes on regional hydrological ecosystem services is in accordance with the purpose of the IWRM, affording valuable information for optimizing the IWRM. In the future, we require in-depth research on three aspects. First of all, we should focus on the quantitative relation between regional hydrological ecosystem services and human well-being. Secondly, it is important to analyze the mechanism about IWRM under the different background of land use policy. Thirdly, it is necessary to study comprehensive function regionalization of regional water resources.

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Decision Support System for Integrated and Adaptive Water Governance

Zhongyuan Li, Qian Zhang, Feng Wu, and Pei Wang

Contents

Introduction 388
System Design and Implementation 390
  Decision-Making Process 390
  System Architecture 391
  Tools and Technologies Used 392
  Model 394
  Model Integration 398
  Validation of the Water Economic Model Result 399
Application of IAGWR-DSS 401
  Case Study Area 401
  Data Used 403
  Scenario Designs for Impacts of Industrial Transformation on Water Consumption 404
  Results Analysis 407
Discussion and Conclusions 414
References 416

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Abstract

Water resource management has attracted increasing attention, as water has become increasingly regarded as one of the most critical resources in the world's sustainable development, especially in arid areas such as Northwest China. This is the result of a lack of effective administration and management of water resources. In this study, a decision support system for integrated and adaptive governance of water resources (IAGWR-DSS) was designed and developed to support integrated water resource management in river basins. IAGWR-DSS is based on integration of a geographical information system platform (ArcGIS Engine 10.2), a database platform (Microsoft Access), and a plug-in development framework. Some economic models and land use models have been integrated into IAGWR-DSS, such as computable general equilibrium (CGE) models. Four parts are included in IAGWR-DSS: (1) a basic information subsystem including the fundamental geographic information, landform, soil type, land use, hydrology, meteorology, spatiotemporal relations of the social economy, and water attributes of the basin; (2) a scenario simulation environment for the CGE model; (3) a data management subsystem to update the water consumption data, land change data, and socioeconomic data in the database; and (4) a decision support subsystem to visualize and map the results of the simulation and generate a decision report for decision makers. This study focused on the second largest inland river basin in China – the Heihe River Basin, located in an arid area – as an example to illustrate the proposed decision support system prototype for integrated water resource management, coupling the socioeconomic system and the hydrological cycling process. The key tasks of the decision support system for integrated water resource management in the Heihe River Basin are to rationally allocate water resources between the upper, middle, and lower reaches (the spatial dimension) and also between the industrial, living, and ecological sectors (the structure dimension). The change in the regional water resources and arable land can be observed visually, intuitively, and rapidly. The developed DSS is very useful to deal with complex water resource management problems in river basins.

Keywords

Decision support system · Integrated water resource management · Adaptive governance of water resources · System · Model · Database · River Basin

Introduction

With global climate change, sustained population and socioeconomic growth, rapid urbanization, and transition of water resource exploitation, the conflict between the supply of and demand for freshwater resources is increasingly prominent, and the health of water environments and ecological systems is becoming worse and worse, which seriously threatens humans' survival, environment, and food security (Hanjra and Qureshi 2010; Jenerette and Larsen 2006). Worldwide, more than 1.2 billion people living in river basins are facing a shortage of water resources (Karimi et al. 2013; Molden 2007), and now this shortage has become a key limiting factor in social and economic development and environmental protection in these areas (Fedoroff et al. 2010; Oki and Kanae 2006). With contemporary social and economic development and the emergence of this ecological crisis, the need for people to live in harmony with water has become a theme for the development of river basins. The challenges in the management of river water resources are how to protect the water environments and ecological systems that humans and other creatures depend on for their existence, and how to improve the sustainability of basin water resource utilization (Petit and Baron 2009).

Basins are the natural unit for developing a strategy to cope with the shortage of water resources (Simons et al. 2015), which has often been abstracted with regard to the social and ecological aspects of complex systems, so establishing integrated basin water resource management systems is one of the important directions in international water resource management. Meanwhile, decision support systems for the management of basin water resources provide technological support and are powerful tools for sustainable basin water resource development, environmental management, and planning (Anderson and Iyaduri 2003; Giusti and Marsili-Libelli 2015; Pollard and du Toit 2008).

More and more researchers have realized that parallel eco-hydrological and socioeconomic water cycling models have limited comprehensive understanding of water circulation and water use because there are interactive feedbacks between eco-hydrological and socioeconomic water cycling processes (models), and the relations between them are not one-way direct impacts or responses. Nevertheless, the mechanisms and spatiotemporal scales of the two streams of models are distinctly different. The majority of socioeconomic models are spatially discrete, relying on administrative boundaries and yearly or monthly statistical data. However, widely used eco-hydrological models are spatially continuous and explicit at the pixel level, and they rely on hourly monitoring data. Consequently, how to integrate the two streams of models and distinctly express the interactive relations between the physical and socioeconomic factors in the upper, middle, and lower reaches is a prominent scientific challenge for coupling human–natural system research (Deng et al. 2017). To date, the need for seamless integration of these two categories of model has been underexamined, and there are few existing successful case studies.

Importantly, without considering eco-hydrological and socioeconomic water cycling simultaneously, any analysis of water circulation will result in partial and potentially misleading conclusions and will ultimately fail to effectively guide sustainable water resource management. To fill the knowledge gaps in model integration, we first summarize the pixel-level geophysical variables and water resource parameters according to administrative units. We then integrate these geophysical and socioeconomic variables into multiregional and dynamic computable general equilibrium (CGE) models (Calzadilla et al. 2008; Jiang et al. 2014; Wu et al. 2015) with the aid of land functional parcel identification and resource (water and land)–embedded input–output tables.

Since decision support systems are widely used in integrated water resource management, the nations of the world have applied them to their own national conditions to carry out a large amount of research (Abramson et al. 2014; Aydin et al. 2015; Chen et al. 2010; Cliburn et al. 2002; Droubi et al. 2008; Ge et al. 2013; Georgakakos 2004; Giupponi 2007; Junier and Mostert 2014; Ling et al. 2014; Lorz et al. 2013; Lang and Gleick 2008; Pallottino et al. 2005; Simons et al. 2015; Zhang et al. 2010), which can provide experience for building an integrated basin water resource management decision support system for reference. However, a basin system is dynamic, changeable, nonequilibrious, open dissipative, and unstructured or semistructured in terms of the dual processes of the natural water cycle and the socioeconomic water cycle, and the existing models and systems inevitably cannot meet the current demand for comprehensive water resource management. In addition, the current research on the integration lacks simulation of a spatially explicit analysis of social and economic systems of water resource utilization, with simulation of the social water cycle and a comprehensive and dynamic design and simulation scenario for social and economic development on a river basin scale. What is more, the models for integration are not adequate, lacking the ability to fully express the relations between the natural and socioeconomic systems, and it is hard to create reasonable forecasts and response options taking into account the dramatic changes that may occur in the climate, water resources, and ways of using water.

In order to support the basin's sustainable development, establishing a watershed integration model combining "natural processes" and "social learning," this paper uses a water–socioeconomic model as a basis to design a framework, structure, and function for a decision support system for integrated and adaptive governance of water resources (IAGWR-DSS) to implement a model coupling the socioeconomic system and eco-hydrological processes. Using a database with high-precision and real-time updates, taking into account climate change, land use changes, basin planning, socioeconomic development, and other scenarios that affect basin water resources, this can not only realize the processes of a socioeconomic and eco-hydrology model based on analysis of simulations but also forecast the evolution of the river basin's water–ecology–social economy coupled systems. What is more, it can improve the precision, reliability, and practicability of the system to solve common problems in the system, using natural geographic data and a combination of social and economic data and different scales of the model, so that it can provide comprehensive decision-making knowledge and technology support for basin water resource management.

System Design and Implementation

Decision-Making Process

The main idea of IAGWR-DSS is a full meta-analysis of basin water resource integrated management of all types of user needs; it brings together a wide range of integrated management of river basin water resources and the wisdom of experts in related fields of scientific research, using computers, software engineering, networking, geographic information systems, remote sensing, and other advanced technologies. It integrates related data on water resource management to provide accurate, convenient, fast, and rich water resources for all types of users, with an integrated watershed management model algorithm and data services. The decision support system for the integrated watershed management framework includes five important parts: users, models, data, scenario simulations, and an interactive user interface (UI). Users can, according to their needs, drive the model by simulating different scenarios of data processing, with output simulation and calculation of results with a visual display at the UI, for decision support to the user. In the whole process, users can propose various models; propose algorithms for the problems and needs of the decision making in a timely manner, in consultation with experts, according to problems and demand issues; constantly refine and improve model algorithms; and create models and algorithms to improve applicability, efficiency, and accuracy, thus forming a virtuous circle of users, models, simulation, data, and decision support, and ultimately providing reliable decision support programs. The design of the decision support system for integrated water resource management of the watershed is shown in Fig. 1.

System Architecture

IAGWR-DSS is a user-friendly, interactive, GIS-based decision support system, which consists of socioeconomic models for sustainable development and management of natural resources and human behavior on a watershed basis. Various data analysis and process techniques have been integrated into development of IAGWR-DSS to handle the models and various data sets. In addition, an integrated socioeconomic simulation model and Dynamics of Land System (DLS) model have been integrated and developed with UIs to support scenario simulation and analysis for water resource management and watershed decision-making processes.

Three-layer architecture is used in the system design, including the UI, application layer (AL), and data layer (DL). Every layer corresponds to a different functionality and role. A concept structure diagram of IAGWR-DSS is shown in Fig. 2.

The DL includes multisource (satellite, GPS, ground, site, report, paper, and statistical yearbook) data sets on the watershed, such as socioeconomic data, water resource data, hydrological data, meteorological data, soil property data, crop data, land use data, vegetation data, ground observation data, etc. The AL is implemented using ArcGIS Engine and .Net Framework, which is a powerful and flexible technology for building the model-running and visualization environment. This provides a user-friendly platform for various modeling environments and data management, processing, analysis, and results visualization functionality. The UI consists of different scenario simulation, parameter configuration, and results display interfaces for models. It also provides various data manifestations (data sheets, charts, graphs, and maps) to help users understand the simulation results of watershed water resource management more efficiently.

Fig. 1 Design philosophy for a decision support system for integrated and adaptive governance of water resources (IAGWR-DSS)

Tools and Technologies Used

- *ArcGIS Engine:* ArcGIS Engine (10.2) is a collection of GIS components and developer resources that can be embedded, allowing addition of dynamic mapping and GIS capabilities to existing applications or building of new custom mapping applications. Developers use ArcGIS Engine to deploy GIS data, maps, and geo-processing scripts in desktop or mobile applications using application programming interfaces (APIs) for COM, .NET, Java, and C++.
- *.NET Framework:* .NET Framework (4.0) is a software framework developed by Microsoft and runs primarily on Microsoft Windows. It includes a large class library, known as the Framework Class Library (FCL), and provides language

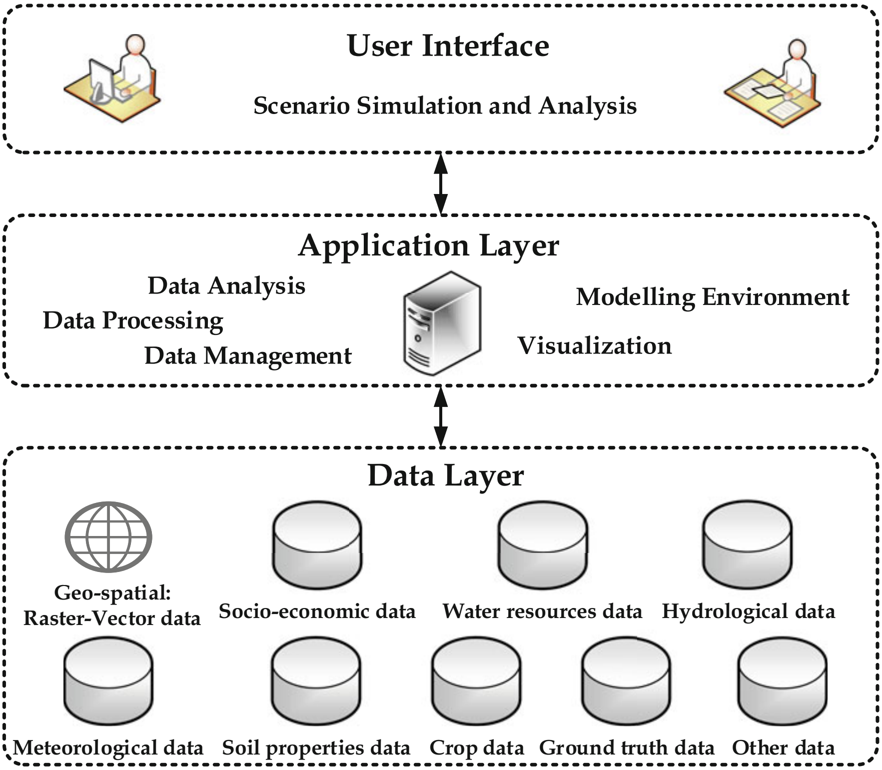


Fig. 2 System architecture of the decision support system for integrated and adaptive governance of water resources (IAGWR-DSS)

interoperability (each language can use code written in other languages) across several programming languages.

- *Microsoft Access:* Microsoft Access is a database management system (DBMS) from Microsoft. It combines the relational Microsoft Jet Database Engine with a graphic UI and software development tools. It is a member of the Microsoft Office suite of applications, included in the Professional and higher editions, or sold separately.
- *Personal Geo-Database:* Personal Geo-Database is a Microsoft Access database with a set of tables defined by Esri for holding geo-database metadata, and with geometry for features held in a BLOB column in a custom format (essentially shapefile geometry fragments). This driver accesses the Personal Geo-Database via ODBC but does not depend on any Esri middle-ware.

IAGWR-DSS is implemented by visual C# based on the ArcGIS Engine 10.2 for .Net 4.0; nonspatial data can be stored in Microsoft Access directly, and geospatial data can be stored and managed in the Personal Geo-Database via the ArcGIS Engine API. Fig. 3 shows the general UI of the system.

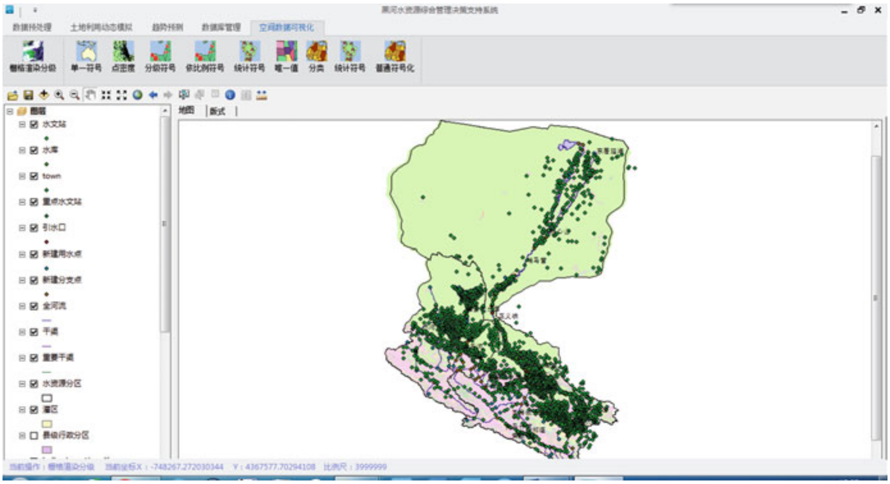


Fig. 3 User interface (UI) of the system

Model

Water resources and socioeconomics are an inseparably integrated system; they rely on each other and influence each other. Water is the foremost productive material in both the economic system and the necessities of life. The conversion, use, protection, and health of water resources have been impacted directly by the economic system's mode of production.

As an important part of this complex and giant system, water resources have a direct impact on the scale and stability of the economic system. The utilization of water resources in socioeconomics has made unceasing progress with the development of human beings' knowledge, production technology level, and social consciousness. Therefore, it is necessary to depict the transfer process of water resources in the socioeconomic system and build subject behavior model equations for socioeconomics, simulating water flow in production, circulation, allocation, and use in the socioeconomic system.

A CGE model has the advantage of depicting the macroscopic behavior of the socioeconomic system. It is a useful tool for analyzing water prices, water rights, water resource allocation, and the water market, and it is an effective means for analyzing and forecasting water demand with changes in the socioeconomic system. This section focuses on the framework and definition of an integrated model, named the Water Economic Model (WEM), which embeds the water and land resources and the key theory of ecological–hydrological process scenario simulation. The WEM links the key parameters in ecological–hydrological processes and the socioeconomic system, which influence water resource management. The productivity level is influenced by ecological–hydrological processes via the quantity and quality of water resource factor input into the productive process. Changes in the allocation ratio of surface and underground water and land change ecological–hydrological processes by influencing the cyclic process of surface water and underground water in the water and land resource combination of the socioeconomic system. Water resources are affected by socioeconomic subject behavior through land use.

On the basis of the CGE model, the socioeconomic system model decomposes the investment of surface water, underground water, and other water, and increases the price-influencing mechanism for surface water and underground water to analyze the consumption utility of the socioeconomic system. The subjects of the production will allocate the investment combination of the initial factors on the basis of consumption utility. Allocation of water resources can be carried out in the socioeconomic system via market mechanisms such as water prices, water rights, and so on. Therefore, the behavior of the socioeconomic system is affected by the water and land resources via the processes of production, consumption, and taxation.

The basic principles of the WEM production module are (1) to allow industrial producers a variety of different types of products at the same time while (2) considering many primary factors in production input such as land, labor, capital, etc., and (3) retain controllability of multiple input–output production modes by a series of separability assumptions.

The decision making of all of the model's production departments is based on production technology principles of cost minimization and stable returns to scale. Multilevel nested functions, named the Leontief function and constant elasticity of substitution (CES), are adopted to describe the framework of the production module. There are different alternative or complementary relationships between inputs into the same nested structure. The Leontief function is used to describe the gross output, which is affected by the combined commodity of intermediate inputs, the combination of the primary elements and other costs, and a fixed ratio of inputs.

$$COM_{c,i} = acom_{c,i} \times XP \tag{1}$$

$$PRIM_i = aprim_i \times XP_i \tag{2}$$

$$OCT_i = aoct_i \times XP_i \tag{3}$$

$$PX_i = \sum_{c \in COM} acom_{c,i} \times PCOM_{c,i} + aprim_i \times PPRIM_i + aoct_i \times POCT_i \tag{4}$$

Each intermediate input can be divided into the combination of a domestic commodity and an imported commodity. The combination between these two products is decided according to the elasticity of substitution and is described by the CES function.

$$DCOM_{c,i} = sdc_{c,i} \cdot \left[\frac{PCOM_{c,i}}{PDCOM_{c,i}}\right]^{\sigma com_c} \tag{5}$$

$$ICOM_{c,i} = \ sic_{c,i} \cdot \left[\frac{PCOM_{c,i}}{PICOM_{c,i}}\right]^{\sigma com_c} \tag{6}$$

$$PCOM_{c,i} = \left[sdc_{c,i} \cdot PDCOM_{c,i}^{1-\sigma com_c} + sic_{c,i} \cdot PICOM_{c,i}^{1-\sigma com_c}\right]^{\frac{1}{1-\sigma com_c}} \tag{7}$$

The combination of land (LND), capital (CAP), and labor (LAB) is expressed by the CES function.

$$LND_i = slnd_i \cdot \left[\frac{PPRIM_i}{PLND_i}\right]^{\sigma prim_i} \tag{8}$$

$$LAB_i = slab_i \cdot \left[\frac{PPRIM_i}{PLAB_i}\right]^{\sigma prim_i} \tag{9}$$

$$CAP_i = scap_i \cdot \left[\frac{PPRIM_i}{PCAP_i}\right]^{\sigma prim_i} \tag{10}$$

$$PPRIM_i = \left[slnd_i \cdot PLND_i^{1-\sigma prim_i} + slab_i \cdot PLAB_i^{1-\sigma prim_i} + scap_i \cdot PCAP^{1-\sigma prim_i}\right]^{\frac{1}{1-\sigma prim_i}} \tag{11}$$

The combination of different types of labors (LABO) is also described by the CES function.

$$LABO_{o,i} = slabo_{o,i} \cdot \left[\frac{PLAB_i}{PLABO_i}\right]^{\sigma lab_i} \tag{12}$$

$$PLABO_i = \left[\sum_{o \in OCC} slab_{o,i} \cdot PLABO_{o,i}^{1-\sigma lab_i}\right]^{\frac{1}{1-\sigma lab_i}} \tag{13}$$

A household puts part of its income from capital, land, labor, corporate profits, and deposit interest into productive consumption, and puts another part into investment.

In order to assess the contributions of and impacts on economic development and requirements for change in land–water resources in Zhangye City, this study improved the CGE model on the basis of international mainstream research on the relationship between land–water resources and socioeconomic systems. There are not enough land–water resources in Zhangye; the water resource has become the main restricting factor in the development of the local economy. Therefore, it is reasonable to put the land–water resources into the CGE model as production factors. The combination between different types of water resources can be described by the CES function. Water resources are the key limiting factor in the planting structure, development scale, and economic distribution in Zhangye. The Leontief function can express the relationship between land and water resources.

$$SWT_i = sswt_i \cdot \left[\frac{PRWT_i}{PSWT_i}\right]^{\sigma rwt_i} \tag{14}$$

$$UWT_i = suwt_i \cdot \left[\frac{PRWT_i}{PUWT_i}\right]^{\sigma rwt_i} \tag{15}$$

$$OWT_i = sowt_i \cdot \left[\frac{PRWT_i}{POWT_i}\right]^{\sigma rwt_i} \tag{16}$$

$$PRWT_i = \left[srwt_i \cdot PSWT_i^{1-\sigma rwt_i} + suwt_i \cdot PUWT_i^{1-\sigma rwt_i} + sowt_i \cdot POWT^{1-\sigma rwt_i}\right]^{\frac{1}{1-\sigma rwt_i}} \tag{17}$$

$$RWT_i = arwt_i \times LWT_i \tag{18}$$

$$LND_i = alnd_i \times LWT_i \tag{19}$$

$$PLWT_i = arwt_i \times PRWT_i + alnd_i \times PLND_i \tag{20}$$

A static model only depicts a period of economic system subject behavior; all of the endogenous variables just have characteristics of this period. The future climate change scenarios have been predicted until at least 2030; therefore it is necessary to analyze long-term, dynamic, and different years' changes in the endogenous variables of economic agents.

Investment, consumption, and exportation are the three major driving forces of economics. This study researches the dynamic extension mechanism using the WEM. Investment is the main variable for carrying out long-term forecasting of the model in recursive dynamic extensions year after year. The forecasting system contains three kinds of mechanism: (1) the stock–flow relationship of investment and capital; (2) the positive relationship between investment and profit/rate of return; and (3) the relationship between wage growth and employment. The model assumes that domestic production and importation are driving forces of the next round of economic development in investment demand.

The initial capital value for each time interval in the WEM is the economic capital situation at the end of the previous year and the start of the current year. The capital at the beginning of the year, which affects subsequent production, is the sum of the capital stock at the beginning of the previous year and the new capital from the previous year. The growth rate of the capital at the beginning and end of the year is determined by the capital supply curve. Investment is decided by the expected rate of return on capital. The expected rate of return can be convergent with the actual rate of return through a local adjustment mechanism. A recursive dynamic model year by year means that every result of the model stands for the change in the current and next years. The dynamic accumulation mechanism of capital is dynamic recursion according to the benefit of industry sectors. Investors can consider the population increase in the dynamic model for a long time, predict the future employment trend, and change the employment rate according to dynamic adjustment of salaries. Wages will rise if the employment is above the trend level at the end of the term. Therefore, employment and real wages go in opposite directions; this mechanism leads to employment being adjusted according to the trend.

$$\frac{W_{t+1} - W_t}{W_t} = \gamma \left[\frac{L_t}{T_t} - 1 \right] + \gamma \left[\frac{L_{t+1}}{T_{t+1}} - \frac{L_t}{T_t} \right] \tag{21}$$

Model Integration

Water use efficiency and management are correlated with land use and cover changes (LUCCs), population distribution, industrial structure, economic development, climate changes, and environmental governance (Deng et al. 2015). The CGE model is integrated into IAGWR-DSS; brief descriptions of the model are given below.

The CGE model is an effective tool to reallocate the primary factors across sectors for different industrial transformation scenarios. It is widely used to evaluate the impact of external shocks on water utilization efficiency at different scales, especially the impacts of socioeconomic policies on water flow across sectors (Wu et al. 2014). Most studies of the CGE model have mainly focused on the effects of shifting water rights and water allocation across sectors, regulation of surface and groundwater resources, and water resource management (Çirpici 2009; Horridge and Wittwer 2008).

This water CGE model is an extended standard CGE model, so it usually includes the components of the factor market, consumption market, production market, government market, trade flow, and commodity exchanges as an intermediate input–output process. Commodities are produced by all firms in a sector that present both market demand for consumption and market supply of production. Thereby, the regional economic structure can be aggregated by a series of production functions to represent a practical and specific economic scale, and water may also be considered as a factor in production. The consumption market is formed by all households, which represents all family earnings and purchases. Their incomes are divided into two parts: one part comes from all-factor income and the other part comes from their salaries. For money flows in a well-constructed circulation, household purchases connect the factor market and commodity market. Water commodities purchased in the product market may not include all water use for all production processes in every sector (Wu et al. 2014). The conceptual water flow in a CGE model is presented in Fig. 4.

The CGE model was used to determine the future water demand and to optimize and assess the water allocation in the forecasted urbanization scenarios. In the model, the circular flow of the economy and water were represented by a set of financial transactions. The value of water changes substantially with time and space. The production and consumption functions were used to represent the economic activities of primary, secondary, and tertiary industries. In the nested structure of production function, land and water were considered as part of the primary factors. The CGE model is modified to embed water, and the economic activities of primary,

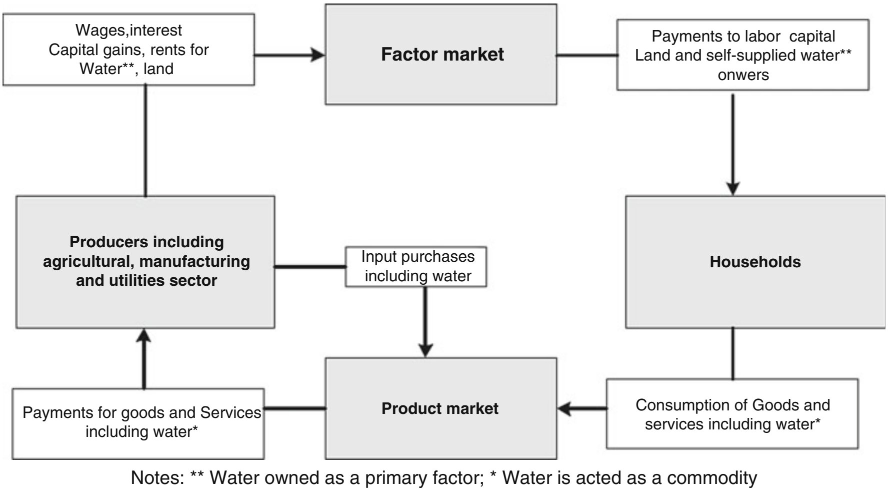


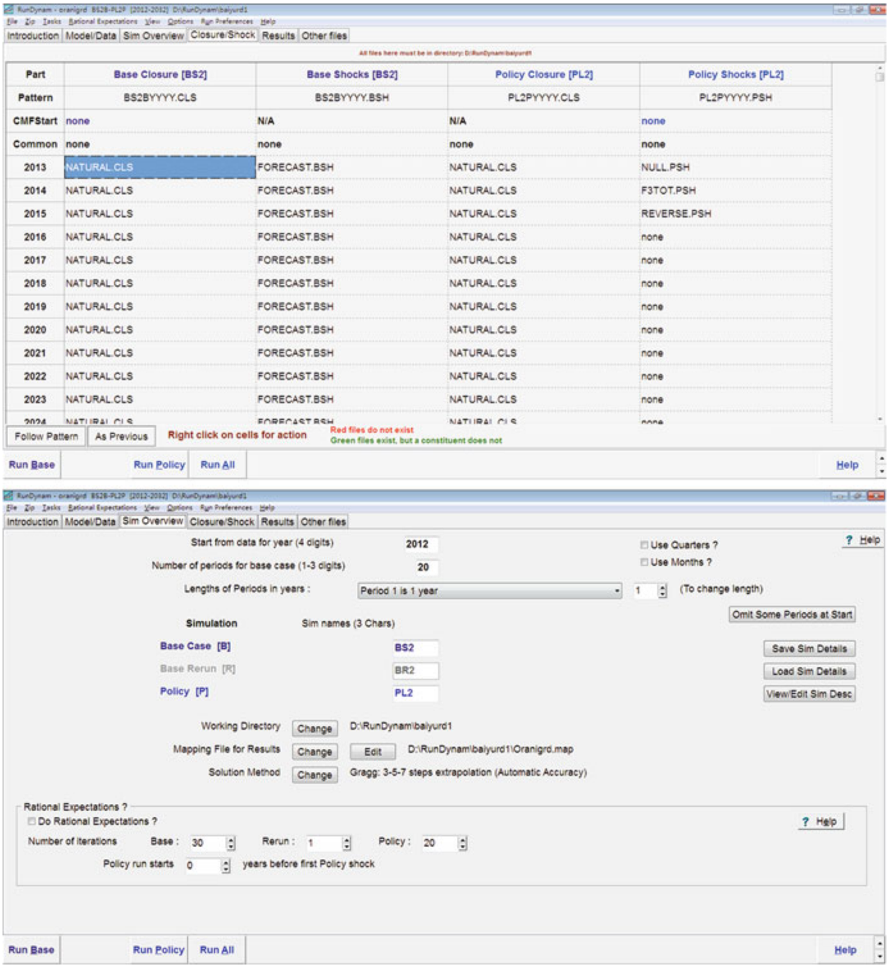
Fig. 4 Framework of economic activities embedding water resources in the computable general equilibrium (CGE) model (Reprinted from Wu et al. (2014) with permission of Sustainability)

secondary, and tertiary industries are included in the water-embedded CGE model with the production and consumption functions. A detailed description of production function and the variables of input–output are reported in Wu et al. (2014).

The Global Trade Analysis Project – Water (GTAP-W) model is a very famous model based on the Global Trade Analysis Project (GTAP) model for water use in agriculture (Calzadilla et al. 2011), which was implemented using GEMPACK software (Hertel 1996). In the GTAP-W model, the original land endowment has been split into pasture land, rain-fed land, irrigable land, and irrigated land. Irrigation water is nested into a value-added part, which implies substitution possibilities with irrigable land and all other factors of production. By combining irrigated land and its water supply, production factors are set into a value-added nest through a CES function. The nest structure of GTAP-W is relatively simpler but more flexible (Wu et al. 2014). The model's parameter-setting UI is shown in Fig. 5.

Validation of the Water Economic Model Result

The closure of the WEM sets the endogenous variables and exogenous variables, and mathematically, it means to explain "the necessity of providing the model with the same number of equalities and endogenous variables." Generally, an equation set is closed in order to resolve this set (Fig. 6). However, as for a multidimensional economic theory model, the closure rules are more complicated. Thus, closure rules should be correctly set to produce more appropriate results. The four closure rules in the CGE models include neoclassical closure, Keynes's closure, Kaldor's closure, and Johnson's closure, one of which is selected by the WEM according to the simulated scenario.



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Part	Base Closure [BS2]	Base Shocks [BS2]	Policy Closure [PL2]	Policy Shocks [PL2]
Pattern	BS2BYYYY.CLS	BS2BYYYY.BSH	PL2PYYYY.CLS	PL2PYYYY.PSH
CMFStart	none	N/A	N/A	none
Common	none	none	none	none
2013	NATURAL.CLS	FORECAST.BSH	NATURAL.CLS	NULL.PSH
2014	NATURAL.CLS	FORECAST.BSH	NATURAL.CLS	F3TOT.PSH
2015	NATURAL.CLS	FORECAST.BSH	NATURAL.CLS	REVERSE.PSH
2016	NATURAL.CLS	FORECAST.BSH	NATURAL.CLS	none
2017	NATURAL.CLS	FORECAST.BSH	NATURAL.CLS	none
2018	NATURAL.CLS	FORECAST.BSH	NATURAL.CLS	none
2019	NATURAL.CLS	FORECAST.BSH	NATURAL.CLS	none
2020	NATURAL.CLS	FORECAST.BSH	NATURAL.CLS	none
2021	NATURAL.CLS	FORECAST.BSH	NATURAL.CLS	none
2022	NATURAL.CLS	FORECAST.BSH	NATURAL.CLS	none
2023	NATURAL.CLS	FORECAST.BSH	NATURAL.CLS	none
2024	NATURAL.CLS	FORECAST.BSH	NATURAL.CLS	none

Right click on cells for action

Red files do not exist

Green files exist, but a constituent does not

Start from data for year (4 digits) 2012

Number of periods for base case (1-3 digits) 20

☐ Use Quarters ?

☐ Use Months ?

Lengths of Periods in years : Period 1 is 1 year 1 (To change length)

Simulation	Sim names (3 Chars)
Base Case [B]	BS2
Base Rerun [R]	BR2
Policy [P]	PL2

Working Directory D:\RunDynam\baiyurd1

Mapping File for Results D:\RunDynam\baiyurd1\Oranigrd.map

Solution Method Gragg: 3-5-7 steps extrapolation (Automatic Accuracy)

Rational Expectations ?

☐ Do Rational Expectations ?

Number of iterations Base : 30 Rerun : 1 Policy : 20

Policy run starts 0 years before first Policy shock

Fig. 5 Parameter-setting user interface (UI) of the computable general equilibrium (CGE) model

Neoclassical closure is long term, while Keynes's and Johnson's closures are short term, so the four closure rules are not contradictory. The appropriate closure rule should be selected according to the objective of the modeling. Admittedly, the operation result is determined by the use of the specific macroscopic closure rules. Moreover, for either neoclassical closure or Johnson's closure, the output is fully determined by the production function. Since the elements are appointed and completely used, the real wage rate and wage yield are identified by the marginal labor productivity and income surplus. As for Keynes's closure, the output, employment, and relative price are obtained jointly by the demand and supply. Kaldor's closure is relatively simple, as it considers full employment (Wu et al. 2017).

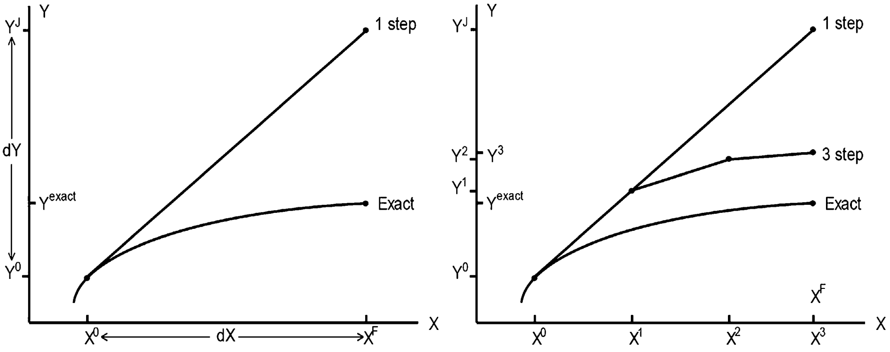

Fig. 6 Water Economic Model (WEM) methods for solving linear model error (Reprinted from Wu et al. (2017) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

Application of IAGWR-DSS

Case Study Area

The Heihe River Basin is located in an arid/semiarid region (90–102°E, 37°50’–42°40’N), which includes part of Qilian County in Qinghai Province, some counties and cities in Gansu Province, and part of Ejina Banner in the Alxa League of Inner Mongolia (Li et al. 2001; Deng et al. 2015). The total basin area is 0.24 million km^2, and the average altitude of the basin is over 1200 m. The major river of the basin is the Heihe River, with a total length of 821 km, composed of three major reaches: upstream, middle, and downstream. Our study area includes the upstream and middle reaches of the river (Fig. 7). The upstream reach, which is the water source area, is located in the southern Qilian Mountains. This region is characterized by remarkable vertical zonality; the elevation ranges from 5290 m in the high-mountain zone to 2000 m in the low-mountain or hill zone. This results in a steep gradient in mean annual precipitation, which decreases from about 500 mm to 250 mm as the elevation decreases. The middle reach is located between the Qilian Mountains and the deserts. The elevation in this part of the basin ranges from 2000 m to 1340 m, and the mean annual precipitation decreases from 250 mm to $<$100 mm, respectively. Water scarcity is therefore mainly created by the topographic characteristics of the Heihe River Basin.

The upstream and midstream are divided according to differences in water production and use, and cover areas of 11,200 and 25,600 km^2, respectively. The natural conditions and economic characteristics are spatially differentiated in regular ways. The population, economy, and industry are mostly concentrated around the midstream oases. The midstream covers the Gansu Corridor irrigation agriculture belt, with widely distributed oases, and provides the majority of commodity grains and vegetables for Northwest China. The major water consumers in the industry sectors are electric power, food production, and mineral mining. The water demand for economic development has been an annual

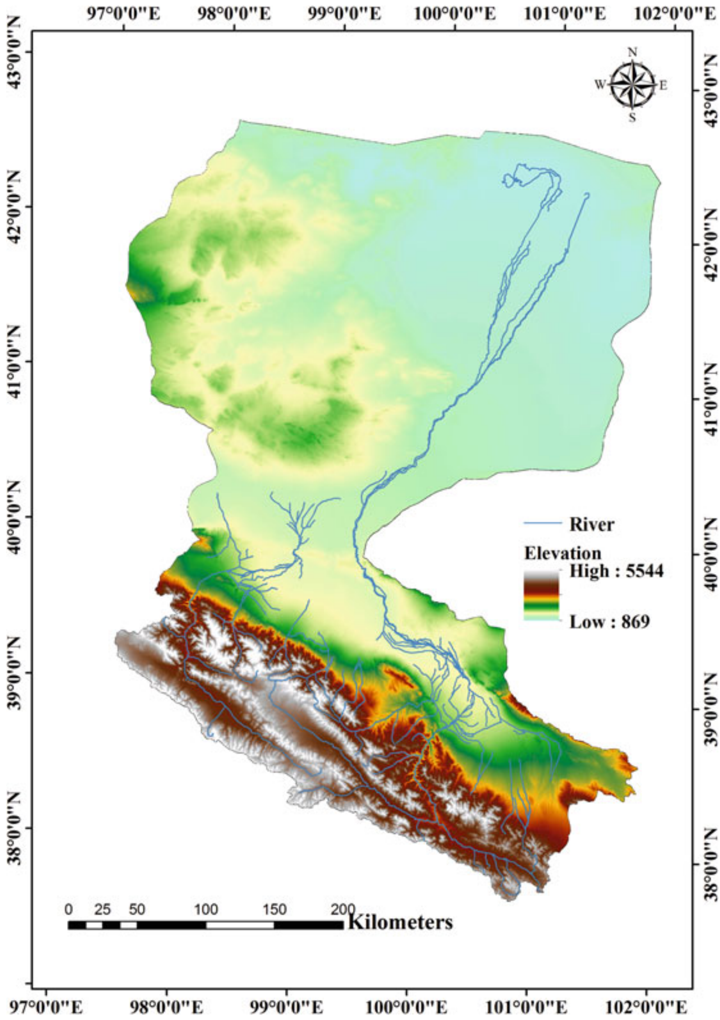

Fig. 7 Location of the study area

average water volume of 2.4 billion m^3 in recent years: 1.9 billion m^3 for agriculture and 0.5 billion m^3 for daily life, industrial use, and ecological use. The water use efficiency values are 400 and 90 m^3/CNY 10,000 in agricultural added value and industrial added value, respectively. During eco-city construction, about 5000 m^3 water was transferred through the transformation from agricultural to nonagricultural status, so as to maintain wetland construction and ecological tourism. The tourism production value in the basin was CNY 6 billion, which greatly improved water productivity in the service industry (Wu et al. 2017).

Data Used

The corresponding data are the social and economic indicator data on the city (county) scale; those used in the models are provided by the Cold and Arid Regions Sciences Data Center in Lanzhou (http://westdc.westgis.ac.cn).

The core data of the WEM is in the input–output table. We first complied an extended multiregional input–output table in 2012, with land and water in the basin and one unit outside the basin (Table 1). The multiregional input–output table was worked out on the basis of single-region input–output tables and can provide basic input parameters for the WEM (Okadera et al. 2006; Jonathan 2011; Zhang and

Table 1 Parameter descriptions

Parameter	Description
XP_i	Total output of department i
$acom_{c,\ i}$	Share of intermediate input products C in the manufacturing process of department i
$aprim_i$	Share of primary factors in the manufacturing process of department i
$aoct_i$	Share of other inputs in the manufacturing process of department i
$COM_{c,\ i}$	Total number of intermediate input products C in the manufacturing process of department i
$PRIM_i$	All primary factors in the manufacturing process of department i
OCT_i	All other inputs in the manufacturing process of department i
PX_i	Price of total output in department i
$PCOM_{c,\ i}$	Price of intermediate input products C in department i
$PPRIM_i$	Price of primary factor combinations in department i
$POCT_i$	Price of other input combinations in department i
$PDCOM_{c,\ i}$	Price of domestic commodities C of intermediate input in department i
$PICOM_{c,\ i}$	Price of imported commodities C of intermediate input in department i
$DCOM_{c,\ i}$	Number of domestic commodities C of intermediate input in department i
$ICOM_{c,\ i}$	Number of imported commodities C of intermediate input in department i
$sdc_{c,\ i}$	Share parameters of domestic commodities C of intermediate input in department i
$sic_{c,\ i}$	Share parameters of imported commodities C of intermediate input in department i
σcom_c	Elasticity of substitution of domestic commodities of intermediate input in department i
$\sigma prim_i$	Elasticity of substitution of primary factor combinations in department i
$PLND_i$	Price of land resource input in department i
$PLAB_i$	Price of labor input in department i
$PCAP_{\mathrm{i}}$	Price of capital input in department i
$slnd_i$	Share parameters of land resources in department i
$slab_i$	Share parameters of labor force in department i
$scap_i$	Share parameters of capital in department i
σlab_i	Elasticity of substitution of different labor types in department i
$slabo_{o,\ i}$	Share parameters of labor type o in department i
$PLABO_{\mathrm{i}}$	Price of labor type o in department i

Anadon 2014). As there is no published county-level input–output table from statistical departments in the Heihe River Basin, we first complied the county-level input–output table embedding land and water in 2012. The table comprises 48 sectors, including 42 sectors in accordance with the national input–output table and seven subsectors disaggregated from the agricultural sector. During the compiling of the county-level table, we added accounts for water and land resources and calculated their values. For agricultural land, we used the sowing area from the county-level statistical yearbook (2012) as land use data and average land use rent of CNY 7500/ha as the price. For nonagricultural land, we calculated land use area by interpreting remote sensing images into 41 nonagricultural sectors and used the local remise price of land as the price. We also used a water consumption coefficient and sowing area to evaluate the agricultural water demand, and collected the enterprises' information from the water resources survey to evaluate the water use in industry sectors. With regard to water prices, surface water was CNY 0.01/m^3, while groundwater was CNY 0.15/m^3. We accounted for the values of water and land in different sectors and embedded them into the input–output table. On the basis of the county-level input–output table, we compiled the multiregional input–output table in the Heihe River Basin. We collected the sector-level trade flow data based on the surveys from statistical departments reporting the inflow and outflow of each county separately. Then we constructed an interregional trade flow matrix with both sector and county dimensions, using the best-known gravity model of Leontief et al. (1963), which had achieved popularity and success in calibrating trade flows because of its mathematical simplicity, its intuitive nature, and the reliability of its empirical results (Meng et al. 2013; Zhang et al. 2013). For calibration of the augmented gravity model, each sector needed a known trade matrix of dominant/representative commodities. For sectors such as the service sector, we had no qualified sample data on dominant/representative commodities. We adopted the simple data pooling method of Hulu and Hewings (1993) to get the initial trade flow matrix. Considering the equilibrium relationships between counties, we applied the RAS technique to ensure agreement with sum constraints, as well to minimize the number of necessary changes for getting the respective values of row and column sums (Lenzen et al. 2012; Guo et al. 2014). The multiregional input–output table could be created after linking and calibrating the input–output tables in the Heihe River Basin (Tables 2 and 3).

Scenario Designs for Impacts of Industrial Transformation on Water Consumption

The main water source for Zhangye is the Heihe River, and water consumption is closely related to the category and development of industries. In Zhangye, the output values for all industries, except for other agriculture, continued to increase during 2003–2008 (Table 4). The output values for secondary industry increased significantly by 39.78% during 2003–2005 and by 88.43% during 2005–2008, followed by those for tertiary industry, which increased by 24.59% and 39.07%, respectively,

Table 2 Parameter descriptions

Parameter	Description
SWT_i	Surface water capacity of primary factors in department i
UWT_i	Underground water capacity of primary factors in department i
OWT_i	Other water capacity of primary factors in department i
$PRWT_i$	Water price of primary factors in department i
σrwt_i	Elasticity of substitution of different water resource inputs in department i
$sswt_i$	Ratio of surface water to total water input of primary factors in department i
$suwt_i$	Ratio of underground water to total water input of primary factors in department i
$sowt_i$	Ratio of other water to total water input of primary factors in department i
$PLWT_i$	Price of water–land combination in department i
$arwt_i$	Ratio of water in water–land combination in department i
$alnd_i$	Ratio of land in water–land combination in department i
LWT_i	Number of water–land combinations in department i

Table 3 Variable descriptions

Variable	Description
KGRj,t	Growth rate of capital stock in the current period
Kj,t	Current capital of industry sector j
Dt	Current allowance for depreciation
It	Current investment
E	Expected rate of return
R	Bank rate
INFt	Current inflation rate
Rt + 1	PK/PI
Wt	Current real wage
T	Employment trend
Lt	Actual employment

during the same periods. However, the output values for animal husbandry and the construction industry increased by 30% and 35%, respectively, during 2003–2005, whereas their growth rates during 2005–2008 were only 7% and 10%, respectively. Water consumption increases with output growth, especially in the planting industry. The increases in the rates of water consumption were 30% during 2003–2005 and 7% during 2005–2008. At the same time, the marginal revenue of water in tertiary industry rose from 1.22 during 2003–2005 to 5.43 during 2005–2008. The abrupt decreased growth rate of water consumption between the two periods, even as the irrigation water supply from precipitation held stable in Zhangye, can be explained by two factors. First, in pursuit of rapid economic development, higher output of crops at a lower level of water consumption may occur. Second, improvement in water use technology led to lower water consumption (Wu et al. 2014).

In this model, water is the primary factor in the agricultural sectors and the intermediate input in the industrial sectors; therefore, water is embedded in the economic flow. The assumption that the data are obtained from an economy in

Table 4 Changes in output, water consumption, and marginal water revenue from 2003 to 2008

	2003		2003–2005			2005–2008		
Sector	I: output (CNY billion)[a]	II: water consumption ($\times 10^8$ m^3)	III: output change (CNY billion)[a]	IV: water consumption change ($\times 10^8$ m^3)	V: marginal water revenue (CNY/m^3)[a]	VI: output change (CNY billion)[a]	VII: water consumption change ($\times 10^8$ m^3)	VIII: marginal water revenue (CNY/m^3)[a]
Planting	22.4	15.49	0.13	0.3	0.43	0.22	0.07	3.14
Animal husbandry	7.76	0.23	0.3	−0.25	−1.20	0.07	0.13	0.54
Other agriculture	1.17	2	−0.24	−0.27	0.89	0.08	0.23	0.35
Industry	17.44	0.39	0.4	0.22	1.82	0.88	−0.1	−8.80
Construction	9.08	0.05	0.35	0.11	3.18	0.1	0.12	0.83
Services	31.06	0.34	0.22	0.18	1.22	0.38	0.07	5.43

[a] In 2008 values

some type of equilibrium is the primary condition for all CGE models. In the baseline simulation, the model operates in a reverse fashion with gross domestic product (GDP), production, consumption, and international trade being exogenous, and the corresponding technical and preference change variables being endogenous. In the baseline simulation, the model operates according to changes in GDP, consumption, investment, and other observed variables during a historical period, and then it calculates the necessary changes in technology and preferences. Calibration is the procedure commonly used for parameter specification, which was carried out with the data from 2003 to 2008 based on the input–output table in 2002; the model is completed when the parameters have been calibrated and we are ready to evaluate the effects of three scenarios of water consumption. We followed the static calibration procedure to compute the baseline after determining the parameter values, applying the CGE model until all parameter values were correctly specified.

In this study, we designed three scenarios to analyze the impacts of industrial transformation on water consumption with a modified CGE model, which provides a scientific basis for water resource management. In the three scenarios, we separately assumed that the output value for secondary industry increased by 5% during 2003–2008 (scenario 1), the output value of the planting industry decreased by 5% in 2003–2008 (scenario 2), and the output value of the tertiary industry increased by 5% in 2003–2008 (scenario 3). The three scenarios represent industrial transformation, and the simulation results can show the influence of industrial transformation on water consumption, which can provide a scientific basis for water resource management.

Results Analysis

Water Balance of the Water–Economy–Society Integrated System

Water use in the water–economy–society integrated system of the Heihe River Basin in 2012 is shown in Fig. 8. The results reveal that the total water use in the economic system in 2012 was about 4505 million m^3, including direct production water use of 4460 million m^3 and direct domestic water use of 45 million m^3. According to the consumption of real water and virtual water, the economic system consumed 5520 million m^3, while the social system consumed 4460 million m^3, including surface water of almost 2973 million m^3 and groundwater of 1532 million m^3.

According to the relevant literature and the regional development plans, we clarified the predictions for population, investments, consumption, and economic growth by 2030 in the midstream (Table 2). We simulated the trend of economic development, built the baseline scenario (with no adoption of any economic water-saving policy/measure or economic sector development policy), and analyzed the water demand from the economic systems in this baseline scenario. The long-term closure dominated by employment growth was set on the basis of the dynamic WEM according to the future economic development prediction indicators.

According to the parameters in Table 5 and in the baseline scenario, we first adjusted the forecast parameters so as to make the simulated results in 2013 and 2014

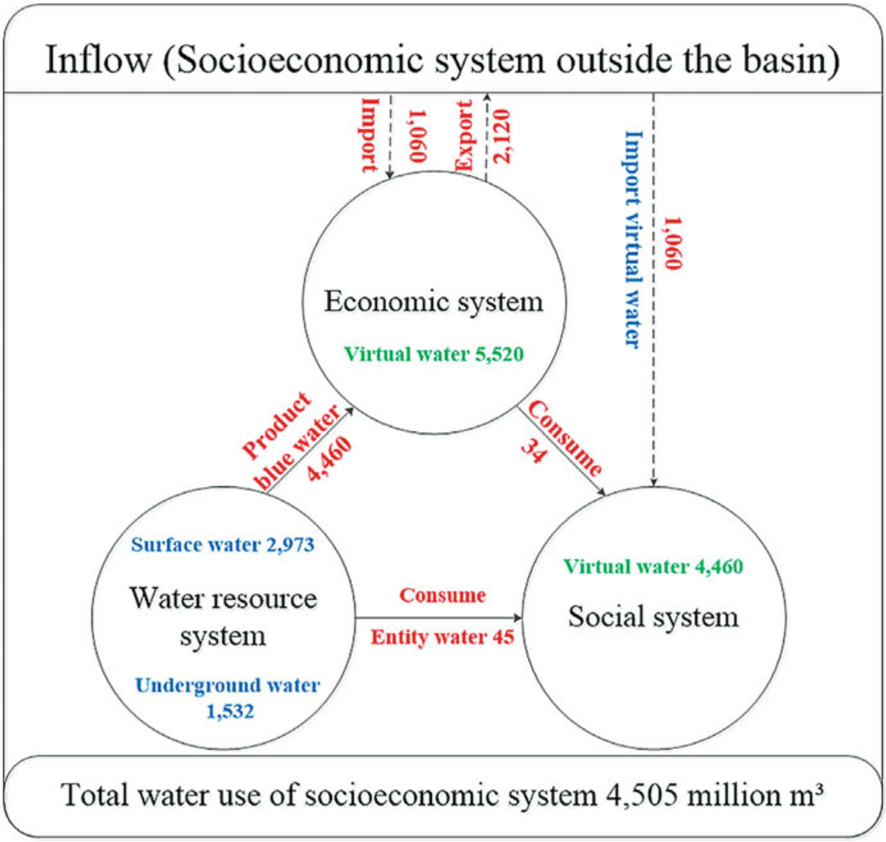

Fig. 8 Water balance of the water–economy–society integrated system in 2012 (Reprinted from Wu et al. (2017) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

Table 5 Predictions of economic development (Reprinted from Wu et al. (2017) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

Parameter	Accession rate (%)	Technology progress (%)	Average resident consumption growth rate (%)	Average investment growth rate (%)
2000–2012	0.23	6.8	12	28.33
Predicted value	0.30	4	5.8	18

consistent with the corresponding statistics. After that, the baseline forecast was expanded to 2030. The growth rate of GDP would gradually smooth down and decline from 5.4% in 2014 to 2.1% in 2030, so the GDP in 2030 was predicted to be CNY 75 billion.

With regard to the water demand in the economic system, it was assumed that the phenomenon of water consumption exceeding the available water resource amount would occur in 2017. The total water demand in the economic system would rise from 21.9 × 10^8 m^3 in 2012 to 39.15 × 10^8 m^3 in 2030, and the water demand would exceed the available water resource quantity in the midstream (26.5 × 10^8 m^3) as early as 2017. Thus, in order to maintain the appropriate agricultural scale and to guarantee rapid economic growth by actively developing the secondary and tertiary sectors, the midstream would have to cope with the very severe stress of a water shortage. According to the current economic laws and water use efficiency, the demand for the water resource would nearly double by 2030, which would be unachievable. It was predicted that the economic water consumption in the midstream would be maximized to 39.88 × 10^8 m^3 by 2029. Along with the inflection in the uptrend of industrial structure growth, the changing trend of economic total water consumption would also inflect. The total water consumption by the economic systems would start to decline by 2029 (Fig. 9). Thus, as for the simulated rules alone, the industrial structures would significantly affect the total water consumption in the economic systems. From the point of industrial output growth, the output growth in the primary sector would be very high until 2020, while the output growth from the secondary sector would be maximized, whereas the output growth in the tertiary sector would become the largest by 2026. The output growth rates gradually separated the secondary and tertiary sectors (Fig. 9). Before 2025, the midstream would still enjoy rapid growth; the output growth rates of different sectors would grow at a rate of above 5% per year. The simulated results further validated the conclusion about the necessity of industrial transformation in the midstream, aimed at sustainable economic development. The development objectives of novel urbanization would bring the driving force and opportunity into the renewal of sector transformation during the economic development in the future.

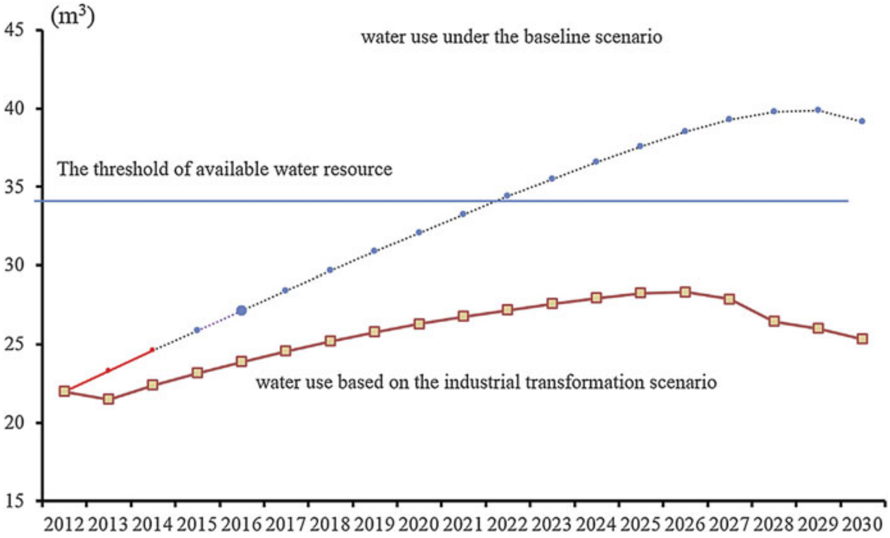

Fig. 9 Water demand of the economic system in the baseline and industrial transformation scenarios (Reprinted from Wu et al. (2017) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

Urbanization has enlarged the runoff volumes in the main streams of the Heihe River and reduced the recharge of groundwater in the urbanized areas, though the trend was not significant. According to the urbanization plans in Gansu Province, the focus area is the Gansu Corridor in the midstream of the Heihe River Basin. Urbanization would increase the runoff entering from ground surfaces in the midstream, but also the demand for water. Simulation in the WEM showed that the change in resident consumption propensity caused by urbanization would affect the production and consumption in the economic system, and the allocation of water–land resource elements in this sector. On the basis of the static WEM, we simulated the effects of urbanization (rising from 36% to 60%) on the water demand of the economic systems (Wu et al. 2015). The results showed that exportation declined by 0.12%, while importation increased by 0.22%. Calculations with the income approach showed that the contribution rates of the labor force and direct tax increased by 0.05% and 0.04%, respectively. However, among all elements, only the contribution rate of the labor force increased, by 0.07%. The reasons were that the rise of urbanization rate leaded to the general enhancement of worker quality, so did the marginal labor productivity and the income efficiency. Moreover, the rise in the urbanization rate led to general enhancements of worker quality, marginal labor productivity, and income efficiency. From the aspect of the sectors, the increase in the urbanization rate led to an improvement in the capacity for agricultural consumption, so the product consumption amount in the agricultural sectors increased by over 7.10%. The increase in the urbanization rate also promoted demand in the energy and resource sectors. For instance, the demands for coal mining and for oil and natural gas exploitation increased by 7.10%. Meanwhile, the product demands supplied by water, electricity, and natural gas increased by over 2.7%. The supply demands for the service sectors such as architecture, wholesale and retail, and restaurants were promoted. Conversely, the product demand from the nonresident consumption sectors declined. Moreover, the increments in the residential consumption level and the consumer price index promoted the elevation of land rents. In particular, it had an effect on the sectors of water conservancy, the environment, and public facility management of to 9.83%, followed by the sector of water production and supply (3.45%) (Table 6). Finally, with regard to the water resource depletion driven by household-consumed products, the water resource depletions rose in most sectors but also declined slightly in some sectors. The percentages of water resource depletions were very little, but the concrete figures were large, so the pressure on the water resource demand was still very large. With regard to the agriculture sector alone, although the percentage of water resource consumption could not exceed 0.50%, the concrete amount was very large. It was indicated that the resulting variation in the water resource was very severe. Thus, the demand for the water resource caused by the urbanization-driven consumption demand from the entire agricultural sector increased by 3.88×10^6 m^3. The comprehensive analysis indicated that the demand for domestic water and industrial water increased by 1.57×10^7 m^3 because of urbanization.

Table 6 Simulation results for household consumption and resource consumption with urbanization

Product	Household consumption	Land rent	Water consumption
Wheat	7.11	0.21	0.09
Maize	7.11	0.29	0.12
Oil plants	7.11	0.56	0.31
Cotton	7.1	0.15	0.06
Fruit	7.11	0.44	0.19
Vegetables	7.11	0.89	0.38
Other farming	7.11	0.75	0.43
Coal mining and dressing	7.12	0.76	0.31
Petroleum and natural gas extraction	7.1	0	0.14
Metal mining	4.69	0.1	0.05
Nonmetallic minerals and other mining	−1.4	0.19	0.11
Food manufacturing and tobacco processing	−1.78	0.21	0.06
Textile products	−1.39	0	0.04
Textile, leather, and feather products	−2.52	0	−0.24
Timber processing and furniture manufacturing	−1.38	0.51	0.07
Printing, paper stationery, and sporting goods manufacturing	−1.38	0.27	0.12
Petroleum processing, coking, and nuclear fuel processing	−1.39	0.01	0.12
Chemical products	−1.39	0.04	0.11
Nonmetallic mineral products	−5.65	−0.28	0
Metal smelting, rolling, and processing	−5.75	0.4	0.08
Metal products	−1.38	0.2	0.06
General and special equipment manufacturing	2.86	0.13	0.09
Transportation equipment manufacturing	−3.77	0	0.06
Electrical machinery and equipment manufacturing	−4.01	0	0.1
Communication, computer, and other electronic equipment manufacturing	−5.74	0	−0.82
Instrumentation and office machinery manufacturing	−5.74	0	−0.08
Handicrafts and other manufacturing	−5.7	0	−0.63
Scrap waste	−5.75	0	0.11
Electricity and heat production and supply	2.75	1.45	0.2
Gas production and supply	2.83	0	0.52
Water production and supply	2.76	3.45	0.15
Construction	2.82	0.12	0.1
Transportation and warehousing (including postal services)	−1.4	0.22	0.08
Main business	1.83	0.08	0.1
Information transmission, computer services, and software	2.64	1.37	0.22

(*continued*)

Table 6 (continued)

Product	Household consumption	Land rent	Water consumption
Wholesale and retail trade	2.82	0.01	0.1
Hotel and catering services	2.82	1.61	0.76
Finance	−2.23	−1.91	−0.47
Realty business	−0.47	−6.22	−0.28
Leasing and business services	−2.44	−0.31	−0.03
Research and experimental development	−2.54	0.3	0.16
Integrated technological services	−2.54	0.64	0.34
Water conservancy and environmental and public facilities management	−2.54	9.83	0.38
Services to households and other services	−2.34	−1.78	−0.63
Education	−5.51	−3.41	−1.11
Health, social security, and social welfare	−5.57	−4.92	−1.96
Culture, sports, and entertainment	−5.42	−2.87	−0.93
Public management and social organization	−5.75	0.03	0.13

Impacts of Industrial Transformation on Water Consumption

It is challenging but necessary to boost economic development through the efficient use of water resources. The simulation results show that the output value of all sectors increased in scenario 1 when the output value of secondary industry increased by 5% (Fig. 10a). However, the proportion of water consumption in secondary industry increased, while those of farming, animal husbandry, and the service sector decreased, and that of other agriculture remained stable (Fig. 10b). The analysis suggests that the output value of other sectors was driven by the industrial technical change. The food industry is the major secondary industry in Zhangye; therefore, development of secondary industry may advance primary and tertiary industries by raising prices. Specifically, GDP increased by 2.6% and total water consumption was reduced by 0.13%, indicating that the farming industry is the largest water-consuming sector in the region. In the second scenario, the outputs of almost every industry sector decreased, but the change in water consumption was different. The change in water consumption in secondary industry was contrary to that of the output value. In the last scenario, the development of tertiary industry would promote secondary industry, but the effect on agriculture was not significant. However, the water consumption of the planting industry decreased by 2.5%; therefore, it would be beneficial to promote the expansion of secondary industry and tertiary industry with lower water use intensity while advancing the development of the planting industry and other agricultural sectors.

A reduction in water consumption per unit of GDP can be achieved through promotion of technical change in the three scenarios. The industrial transformation of planting plays a key role in improving water use efficiency to achieve the goal of reducing water consumption. In scenario 1, when the output value of secondary industry increased by 5%, the annual GDP increased by 0.80%, while the water

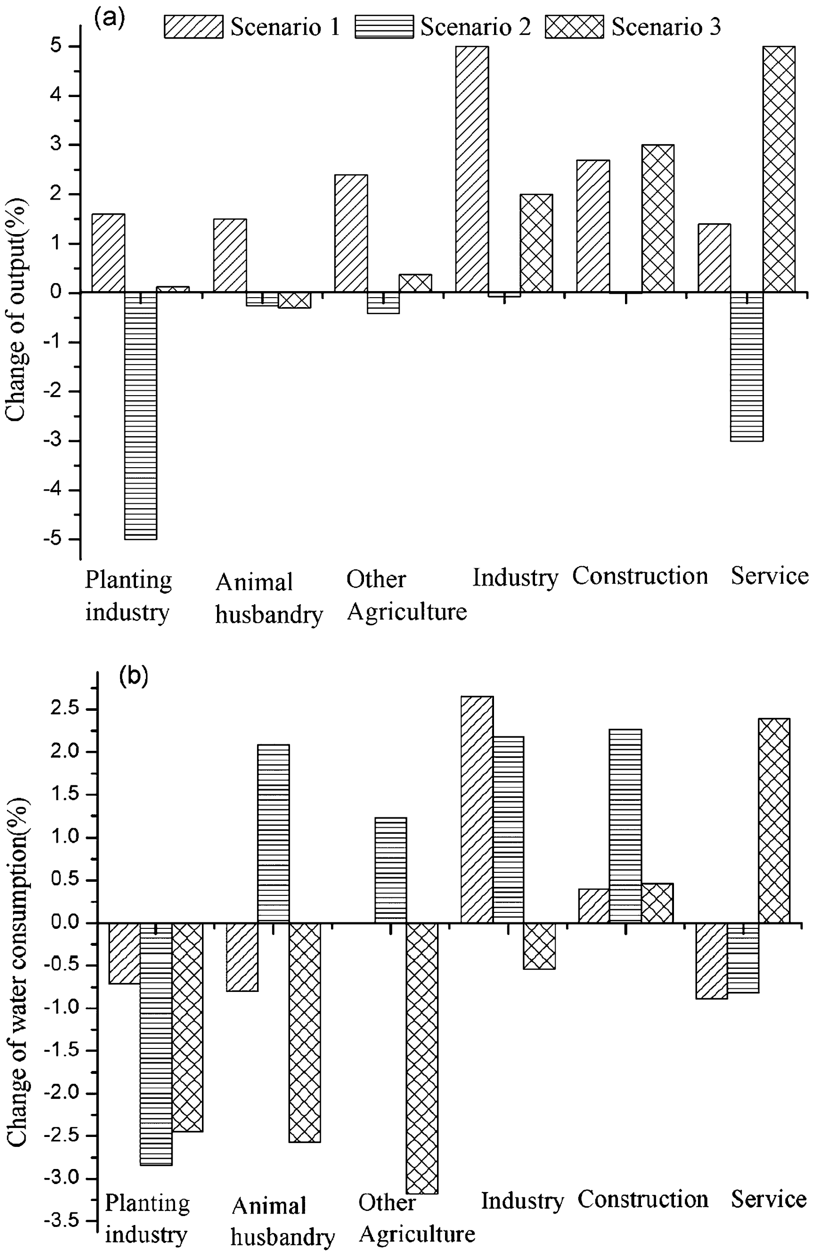

Fig. 10 Effects of industrial transformation on (**a**) output values and (**b**) water consumption in different scenarios (Reprinted from Wu et al. (2014) with permission of Sustainability)

consumption per unit of GDP decreased from 80 m^3/CNY 10,000 in the baseline scenario to 65 m^3/CNY 10,000 in scenario 1. In scenario 3, the water consumption per unit of GDP decreased by 25% as the annual GDP increased by 0.50% (Table 6). This indicates that secondary industries play an essential role in pushing economic development, while development of tertiary industries can greatly raise water use efficiency in Zhangye. The food industry in the secondary industries can push the development of primary industry, which is also closely related to the development of tertiary industry. Therefore, the development of tertiary industries can drive the complete industrial chain in Zhangye's economic system. The proportion of industries with high water consumption in Zhangye is very large, which can cause serious environmental issues, so the development of these industries goes against the goal of sustainable development. Therefore, the municipal government and relevant institutions in this environmentally fragile region should cooperate to promote coordinated development of both economic and ecological systems. For example, high-water-consuming industries with a high direct water use coefficient should be limited to some extent in the future. Overall, according to the simulation results in the three scenarios, we suggested that the third scenario should be adopted for water resource management reform (Table 7).

Discussion and Conclusions

This study demonstrates the design and development of IAGWR-DSS, a decision support system prototype for integrated river basin water resource management. IAGWR-DSS provides a reference solution for integrating the models, data, knowledge, and experts into one system and one database. IAGWR-DSS took the Heihe River Basin as an example; integrated the CGE and DLS models; collected socioeconomic data, fundamental geographic information data, natural geographic data, and ecological environmental data; and outputted some results of scenario simulation under the constraint of the water resource management redline.

This study constructed a decision-making tool for water resource supply-and-demand scenario regulation and analysis, which serves the selection of a water resource–adaptive approach to the watershed socioeconomic system. In addition, this study also analyzed the relation of the mutual feed between the watershed water

Table 7 Comparison of different scenarios' effects on economic development and water consumption (Reprinted from Wu et al. (2014) with permission of Sustainability)

	Annual GDP growth rate during 2003–2008 (%)	Water consumption per unit of GDP (m^3/CNY 10,000)
Baseline	14.40	80
Scenario 1	13.80	72
Scenario 2	15.20	65
Scenario 3	14.90	60

GDP gross domestic product

resource and the socioeconomic system, gave some examples to explain that how the ecological -hydrological processes affect the socioeconomic system.

We investigated the patterns and routes of eco-hydrological processes affecting the water demand of the economic systems in the midstream of the Heihe River Basin, and explored the potential route of the economic systems' response to eco-hydrological change in the midstream. The key parameters for the model integration simulation were obtained, and thereby the WEM was developed on the basis of an extended multiregional input–output table with land and water resources. We revealed the coupling mechanisms between natural water cycles and economic water cycles in the midstream and upstream of the Heihe River Basin. On the basis of the WEM, we simulated the water demand of the economic system in the scenario where the urbanization rate would increase to 60% by 2030. We found that the midstream urbanization scenario entailed a 12% increase in the economic water demand, which highlighted the water supply-and-demand contradiction in the midstream area.

To resolve the conflicts between water supply and demand in the midstream and to guarantee economic stability and sustainable development, we hope the decision makers of Heihe River Basin can reconfiguration the water resources of midstream and downstream, thereby balancing the water demand of the economic system in the midstream. Moreover, new water resource reallocation methods should be found to improve the single-unit water productivity and promote stable and healthy economic growth, which are critical to guarantee sustainable regional development.

We found that the direct water consumption coefficients of the planting sector and other agricultural divisions are much higher than those of other sectors, and changes in the corresponding output values have significant effects on the total water consumption. However, the marginal revenue of water use in the tertiary sector is the highest among all sectors. Then we evaluated the changes in water consumption caused by industrial transformation, using the CGE model in three scenarios designed with industries' technical changes in mind. The simulation results indicated that the water-saving benefit from industrial structure transformation is significant when the output value of secondary industry and tertiary industry increases but the percentage of the planting sector in the total output value decreases. Enhancing water use efficiency through industrial transformation will be an effective way to meet water needs in the face of severe water scarcity in this typically arid region of Northwest China. The simulation suggested that encouraging the development of tertiary industry is a sustainable trade-off scheme for raising water use efficiency, and moderating the development of the planting sector is also an important way to improve water use efficiency in the whole river basin.

The decision support system implements integration, query, analysis, and sharing of data. It can offer a scientific basis, support data, and analysis results for decision makers but cannot help decision makers make decisions. IAGWR-DSS is a prototype and still under development. Some functions are under development to enable interaction with data and comparison of scenarios. A simple Android version of IAGWR-DSS will be provided in the future, which will be very convenient for use by decision makers.

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Index

A
Advanced Research WRF (ARW), 105
Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), 78
Agricultural growth, 152, 161, 166, 175
Agricultural irrigation, 186
Agricultural water requirement (AWR), 185
  mapping spatiotemporal surface, 187–191
  spatiotemporal surface of, 191–199
  water balance theory for, 191
Agricultural water use efficiency, 169–176
Artificial ecology water consumption, 337
Artificial intelligence, 36, 39, 54

B
Blundell-Bond dynamic panel-data model, 220
Bowen ratio, 109
BP neural network, 39, 51, 52, 54, 56

C
Case-based reasoning (CBR), 36, 39, 40, 42, 44, 47, 48, 53, 54
Case similarity, 42, 44
China
  uneven water use, 214–218
  urbanization and economic development, 64
  water consumption, 63
  water scarcity, 73
Chinese Academy of Sciences (CAS), 79
Climate change, 154, 247, 249
  in Heihe River Basin, 246
  on water productivity, 256–264
Coase theorem, 218
Computable general equilibrium (CGE) model, 65, 71, 75, 254, 273, 275
Constant elasticity of substitution (CES), 75
Conventional development scenario (CDS), 344
Crop coefficient, 187, 190, 206
Crop planting structure, 187, 188, 193, 194, 205, 206
Curve number (CN) method, 78

D
Decision support system (DSS), 113, 114
Decision support system for integrated and adaptive governance of water resources (IAGWR-DSS)
  application of, 401–407
  computable general equilibrium model, 394–405
  decision making process, 390–392
  model integration, 398–400
  system architectures, 391–392
  water economic model, 394
Drag effects, 153, 166
Dynamics of Land System (DLS) model, 138, 139, 141
Dynamic panel-data model with systematic GMM (DPD-SYS), 220

E
Ecological function zoning, 372, 373
Ecological Water Diversion Project (EWDP), 29
Ecological water, 337, 338, 341, 343, 345, 348, 349, 351, 354, 357
Economic development, 63, 66, 70, 83
Economy-priority development scenario (EPDS), 344, 345

X. Deng, J. Gibson (eds.), *River Basin Management*, Ecohydrology,
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Ecosystem services
  aquatic, 366
  hydrological, 363, 366
  regional hydrological, 378
    (*see also* Regional hydrological ecosystem services)
  theory and methodology of, 363
Environmental variables, 163
Environment sustainable development scenario (ESDS), 345
Evapotranspiration (ET), 107, 108, 110, 112, 115, 133, 185, 187, 189–191, 193, 194
  spatiotemporal variation of, 234–235
Everglades Landscape Model (ELM), 336

F
FAO Penman-Monteith Equation, 187, 189–190, 206
Farmer's income, and water use, 217–224
Forecast, industrial water, 35
Forecasting system, 397
Forestation, water yield, 130–134
Forestry change, 128–130

G
Genetic algorithm, 336
  WPLE, 348
Glacier melting, 249, 253, 258, 260, 275
Global Trade Analysis Project-Water (GTAP-W) model, 73, 399
Grey incidence analysis, 36, 39, 41, 45, 46, 52, 55, 56
Grey Model, 52, 56

H
Heihe River Basin (HRB), 18, 21, 22, 28, 29, 64, 66, 71, 74, 79, 115, 121, 186, 286, 290, 310, 336, 338, 342, 345, 356, 401–414
  agricultural oasis expansion, 226–228
  agricultural production activities, 338
  climate change, 246
  DSS, 114
  energy conditions and water conditions, 98
  environmental problems, 96
  and hydrological stations, 99
  irrational water consumption structure, low water efficiency, 101–102
  land use/cover changes in, 98
  land use patterns and changes in, 224–226
  location, 95, 224, 248
  lower reach, 96
  middle reach, 96
  semi-arid and sub-humid temperate continental monsoon climate zone, 94
  study sites in, 99
  upper reach, 96
  USGS classification, 97
  virtual water flows in, 310–320
  water management, deficient systems and institutions on, 104–105
  water productivity in, 248
  water resource utilization, 114
  water scarcity, 122–124
  water stress assessment for, 6–11
  water stress at county level in, 326–328
  water supply and demand, 98–101
  water usage, high intensity of, 96
Hydrological process, 120, 122, 123, 128, 129, 131, 136, 142, 143, 148
Hydrological response units (HRUs), 129
Hydrology, 63, 65, 78–80

I
IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade), 71
Industrial transformation, 80–85
Industrial water demand, 35, 36, 38, 41, 45, 48, 49, 51, 53, 55
Integrated river basin management, 3, 22, 30
Integrated water resources management (IWRM), 186, 283, 363, 366, 380, 385, 391, 414
  ecological function regionalization and optimization, 383–384
  regional hydrological ecosystem services, 382–383
Irrigation water price, 299, 301, 302

L
Land use, 363, 365, 375, 378, 380, 383, 385
Land use and land cover changes (LUCC), 93
  application-oriented DSS, 113
  energy balance, 106–107
  Heihe River Basin of China (*see* Heihe River Basin (HRB))
  impacts of, 93, 94
  research-oriented DSS, 113

surface energy, 107–108
  USGS land classification system, 97
  water balance, 106–107, 110–112, 115
  WRF model and simulation schemes, 105–106
Land use changes, 121, 136, 148
Living water, 335, 337, 341, 343, 344, 348, 349, 351, 354, 355, 357

M
Macro-Social Accounting Matrix (Macro-SAM), 287
Malmquist total factor productivity index, 230, 237
Microsoft Access, 393
Millennium Ecosystem Assessment (MEA), 114, 283
Multi-regional input–output (MRIO) model, 313–315
Multi-temporal NDVWI, 187, 188

N
National economy, 283, 285, 287, 292, 294
.NET Framework, 392
Net primary productivity (NPP), 283
Normalized difference vegetation-water index (NDVWI), 187

O
Oasis farmer's income, and water use efficiency, 214–224

P
Patuxent Landscape Model (PLM), 336
Personal Geo-Database, 393
Pool-OLS regression, 218
Poverty, 154
Production water, 335, 337, 342, 348, 349, 351, 354, 355

R
Regional hydrological ecosystem services, 363, 364
  on human well-being, 380–382
  for IWRM, 382–384
  LUCC on, 366–380
Resource-restrained economic growth model, 158

S
SAM, *see* Social accounting matrix (SAM)
Scenario analysis, WPLE, 344–354
Snowmelt, 250, 253, 258
Social accounting matrix (SAM), 284, 285
  data for, 290
  decomposition, 288–290
  multiplier, 285, 288–290, 292, 302
Social Accounting Matrix and Environmental Accounts (SAMEA), 285
Soil and water assessment tool (SWAT), 65, 78, 129, 130, 132, 137, 138, 142
  simulation model, 249, 257, 259, 266, 275
Soil conservation, water use efficiency for, 235–237
Solow growth model, 160
Spatiotemporal surface, AWR in HRB, 187–199
Stochastic Frontier Analysis (SFA) model, 162, 230
Streamflow simulation, 249
Surface runoff, 123, 124, 132, 143, 146
Sustainability of Semi-Arid Hydrology and Riparian Areas (SAHRA), 29
Sustainable development, 185, 186, 205, 206, 208, 247, 269, 276

T
Temperature lapse rate (TLAPS), 131
Theory of green infrastructure, 156
Three-stage data envelopment analysis, 178
TM/ETM+ RS images, 193

U
Uneven water use, China, 214–218
Urbanization
  modeling, 74–75
  water availability, 63
  water supply and demand, 81–82
U.S. Geological Survey (USGS) classification system, 97

V
Virtual water, 308, 309
  flows in Heihe River Basin, 310–320
  national-level studies on, 327
  and physical use, 326
  strategy application facing challenges, 328–329

W
Water allocation
  inferential valuation method, 65
  modeling, 75–80
  stated preference method, 65
Water allocation scheme
  in integrated water-ecosystem-economy system, 338
  of WPLE, 337, 344–354
Water and land resources, 152
  on agricultural development, 153
  agricultural production in Heihe River Basin, 169–175
  attenuation rates, 161
  drag effects, 153, 166–167
  influencing factors, 168–169
Water availability, 63
Water balance, 258, 261
  analysis of, 275
  component, 259
Water constrain, 122, 136, 138
Water consumption, 68
  in China, 63
  composition of, 337
  definition, 337
  structure with low water efficiency, 124–125
Water consumption of production, living and ecology (WPLE), co-evolution of, 335
Water economic model (WEM), 394
  dynamic extension mechanism, 397
  principles of, 395
  validation of, 399–401
Water-ecosystem-economy system, 335, 336
  water consumption, 337–344
  in Zhangye of HRB, 344–354
Water management, with unreasonable water allocation scheme, 125–127
Water markets, 16–21
Water price
  described, 17–18
  farmers' response to, 20–21
  reform in HRB, 18–21
Water productivity
  in agriculture, 261–263
  calculation, 256
  climate change on, 256–264
  in Gansu, 262
  in Heihe River, 248
  indicator, 260
  of industrial industry, 263
  of urban construction, 263
Water projects, 29
  investments on, 13
  from 2002 to 2008, 15
Water resource availability, and land use/cover change, 127–147
Water resource embedded social accounting matrix (WSAM) model, 285
  sector disaggregation for, 303
Water resources management, 34
Water scarcity, 3, 4, 11, 14, 16, 20, 25, 29, 64, 73, 282, 283, 302
  assessment of, 4–11
  in Heihe River Basin, 122–124
  and stress, 120
Watershed integration model, 390
Water stress index (WSI)
  adjustment, 325
  at county level, 327
Water use efficiency
  for agriculture, 230–231
  driving factors, 237–240
  and farmer income, 217–224
  measurement, 228–231
  and oasis farmer income, 214–224
  for soil conservation, 228–229
  soil conservation amount, 231–235
  and TFP rate, 237–239
  using Tobit model, 231
Water User Associations (WUAs), 104, 125
Water yield, 259
  forestation on, 130–134
  variation, 128–134
Weather research and forecasting (WRF) model, 105

Y
Yingluoxia hydrological station, 79, 124

Z
Zhangye City
  of HRB, 337
  integrated water-ecosystem-economy system in, 344–354
  location, 339
  optimal water allocation scheme of WPLE in, 354–356
  precipitation in, 338
  scenario-based water allocation scheme of WPLE in, 349–354
  water consumption of, 338–341
  water consumption quota in, 343
Zhangye City, 36, 38, 41, 52, 53, 67, 69, 70, 76