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Research Article

Identification of Water Scarcity and Providing Solutions for Adapting to Climate Changes in the Heihe River Basin of China

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In ecologically fragile areas with arid climate, such as the Heihe River Basin in northwestern China, sustainable social and economic development depends largely on the availability and sustainable uses of water resource. However, there is more and more serious water resource shortage and decrease of water productivity in Heihe River Basin under the influence of climate change and human activities. This paper attempts to identify the severe water scarcity under climate change and presents possible solutions for sustainable development in Heihe River Basin. Three problems that intervened land use changes, water resource, the relevant policies and institutions in Heihe River basin were identified, including (1) water scarcity along with serious contradiction between water supply and demand, (2) irrational water consumption structure along with low efficiency, and (3) deficient systems and institutions of water resource management along with unreasonable water allocation scheme. In this sense, we focused on reviewing the state of knowledge, institutions, and successful practices to cope with water scarcity at a regional extent. Possible solutions for dealing with water scarcity are explored and presented from three perspectives: (1) scientific researches needed by scientists, (2) management and institution formulation needed by governments, and (3) water resource optimal allocation by the manager at all administrative levels.

1. Introduction

In most arid and semiarid areas, water resource is the core and the linkage between the ecosystem and the economic system [1]. It not only plays a vital role in the formation, development, and stability of desert oasis, but also is a key component of the ecosystem environment and services [2]. Most of the inland rivers in China are faced with severe water resource shortage and serious ecological deterioration. The north and northwest of China account for half of the total area of China but have less than 20% of total national available water resource [2, 3]. 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 [4]. The water issue in arid and semiarid inland areas is thus receiving considerable attention worldwide [5].

Climate change emerges as one of the major forces that affect water availability in the future [6, 7]. The Intergovernmental Panel on Climate Change [8] points to the high sensitivity of semiarid and arid regions to climate, considering the already existing water stress driven by growth in agricultural, industrial, and urban demands. The need for more research on the impact of climate change on surface and ground water has been addressed by the current research [9, 10]. Meanwhile, human activities have exerted great impacts on water resource. Global urban water utilization increased over 20 times within the past century, from $200 \times 108\,\text{m}^3$ in the year 1900, to $600 \times 10^8\,\text{m}^3$ in the year 1950, to $1500 \times 10^8\,\text{m}^3$ in the year 1975, and to $4400 \times 10^8\,\text{m}^3$ in the year 2000 [11]. With continuous population growth and urbanization progresses, the availability of water with sufficient quantity and quality is one of the anticipated future problems.

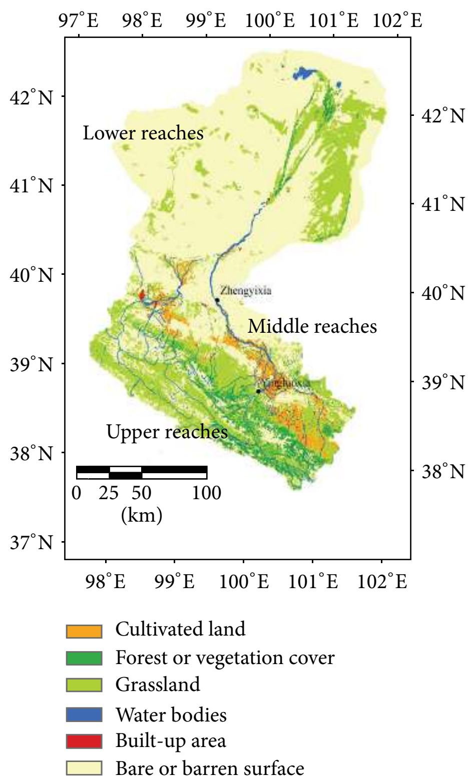

Figure 1: Location of the Heihe River Basin.

The Heihe River Basin (HRB), well-known for dry climate with intense evaporation and scarce but concentrated precipitation, is the second largest inland river basin in China (Figure 1). Some issues such as watershed management, water-saving policies, environmental degradation, and ecosystem restoration have drawn great attention, making the HRB become the ideal case study area for sustainable development of arid regions [12–15]. The main feature of the water resource of the HRB is that the runoff is produced in mountains in the upper reaches but is mostly utilized and consumed in middle reaches and lower reaches. However, water and ecological environment has experiencing rapid deterioration since the 1950s [12]. In fact, the HRB could be vulnerable to water stress under climate change because of the limited water availability and the increasing demand for water from agriculture irrigation and industry sectors.

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 [16]. 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 [12, 17]. 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 [12, 13, 17, 18]. 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.

The objectives of this paper are to review and identify the key issues on the HRB and present possible water management approaches for sustainable development of the HRB. The remaining parts of this paper are organized as follows. Firstly, the geographical and hydrological background of the HRB is introduced in the second section. This is followed by a brief elective review of the main water problems in the HRB in the third section, and three knowledge gaps that exist within the HRB are identified. In the fourth section, possible adaptive solutions to water problems in the HRB are discussed. We conclude by discussing the pressing matters for reforming the water management systems in the HRB and the possibility of the inspiration for other inland rivers.

2. Geographical and Hydrological Background of the Heihe River Basin

The Heihe River Basin (90°E–102°E, 37°50′N–42°40′N) is located in the north of Qilian Mountains and the middle part of the Hexi Corridor. It covers Qinghai Province, Gansu Province, and Inner Mongolia, with a river length of 821 kilometers and a catchment area of 14×10^4 km^2 (Figure 1). Heihe River breeds the prosperity and civilization of the HRB basin. The average evaporation is up to 84 mm/a. The total water resource is 2800 mm^3/a, which includes surface water 2470 mm^3/a and ground water 330 mm^3/a. From south to north, the special variation of the HRB is evident and can be divided into three subunits. The upper reaches of the HRB, located in Qilian Mountain, belong to the northern margin of the Tibet Plateau. It is the birthplace of Heihe River as well as the runoff area, with abundant rainfall, less evaporation, and cold and damp climate. Being the oasis of the Hexi Corridor and the desert plain, the middle reaches of the HRB are the key area for agriculture and they are the grain base for Gansu province. The lower reaches of HRB, north of the Langxinshan Gorge, form the oasis in Inner Mongolia, making it an essential ecosystem barrier of Northern China.

The upper reaches are the runoff producing area of the HRB. The southern Qilian Mountains, with remarkable vertical zonality, are composed of a series of parallel mountains and basins in northwest-southeast direction. The high mountain range serves as the water source for inland rivers, which flow to basins and form internal stream systems. The alpine desert accounts for 22% of the area of upper reaches. In addition, it has a length of 303 kilometers, with 68% runoff contribution rate and 85% runoff coefficient. The elevation of this area ranges from 2000 to 5500 meters and the mean annual precipitation ranges from about 250 mm in the low mountain zone to 500 mm in the high mountain zone. With an altitude of over 4000 meters, most middle and high mountains are covered with snow all year round coupled with modern glaciers, and it is the natural reservoir of Hexi Corridor. Meantime, in the area with an altitude of lower than 3000 meters, the vegetation is relatively fair and the land is covered mainly by natural ecosystems, including cold deserts, mountain forests and shrubs, alpine meadows and steppe, and ice and snow. The vegetation on Qilian Mountain is called water conservation forest because of its good regulatory role on water resource.

The middle reaches of the HRB are the runoff and water using area, which is characterized by irrigation agriculture. The irrigation area is up to 205, 230 hectares, accounting for 91% of the area of cultivated land in the whole basin. 95% of the population lives in this region and they produce over 80% of GDP for the whole region. Annual rainfall ranges from 300 mm to 100 mm, and annual potential evaporation is about 1900 mm/a. The middle Hexi Corridor, with an area of 17,000 km^2, is sandwiched between the southern Qilian Mountains and the northern Mazong Mountains. The topography is fairly smooth, and the elevation ranges from 2000 to 1000 meters, correspondent with a decrease of the mean annual precipitation from 250 mm to less than 100 mm. Irrigation agriculture is dominated by farmland vegetation. It develops very well but is based on high consumption of water. In the area where the rivers flow through, there are a series of oases with loamy soil and abundance of sunshine, making the HRB one of the five bases of national commodity grain. In addition, here various artificial oases exist, including the counties of Mingle, Shandan, Linze, Gaotai and Jinta, Zhangye, Jiuquan, and Jia Yuguan. Meanwhile, Gobi and desert are largely scattered in other areas of the HRB.

The lower reaches of the HRB are the runoff disappearing area. With a mean elevation of around 1,000 m and mean annual precipitation of 50 mm, it is mainly occupied by Gobi, desert, and bare land. The precipitation in the lower basin is only 55 mm/a, while the annual potential evaporation reaches 2300 mm/a. Ejina, covering an area of 114,000 km^2, is located at the end of the HRB and in the west of Inner Mongolia of China. The Gobi and desert occupy over 90% of the total land area of Ejina. According to the runoff data of the Langxinshan hydrological station, the discharge of the Heihe River has decreased since the year 1950, and the shortage of water caused the Ejina Oasis to shrink considerably. From the year 1960, with the decrease of discharge from the Heihe River, the oasis of Ejina began to shrink and caused a series of environmental problems. For instance, the areas of West Juyan Lake and East Juyan Lake were 267 km^2 and 35 km^2, respectively, and dried up in the year 1961 and the year 1992, respectively [19]. In addition, both overgrazing and overcultivation have resulted in severe ecological deterioration in Ejina, where rivers and lakes are drying out, groundwater table is decreasing, water quality is deteriorating, and biodiversity is degrading.

3. Water Scarcity of the Heihe River Basin

Water plays an important role in economic development and ecological balance of the middle reaches and lower reaches of the HRB. Lacking of effective coordinated water management system, the amount of water flowing into the lower reaches has continually been decreasing. As a result, the rivers and lakes dried up intensively in the lower reaches, along with declining groundwater table and a high level of water mineralization. Meanwhile, the area of vegetation coverage is reducing sharply, leading the HRB to becoming a source of dust for sandstorms in Northwestern China.

3.1. 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. 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 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 (Figure 2). 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 [20].

Aside from precipitation, water resource is mainly supplied by springs, subsurface flow, and solid glacier in Qilian Mountain [21]. 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%) [21]. 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 [21].

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 1985, the number of reservoirs (the small plain reservoirs and embankments with a volume less than 100 thousand m^3 are not

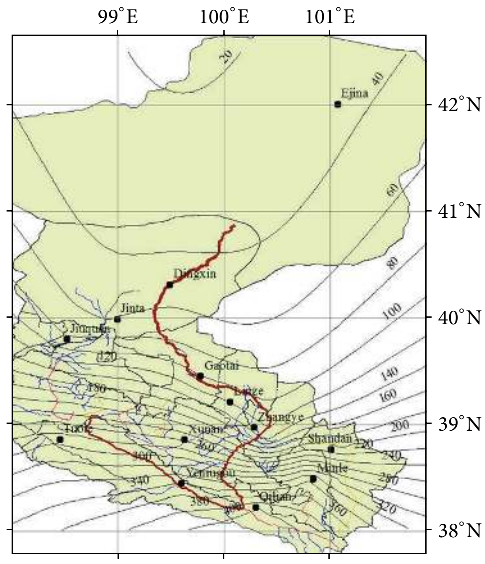

Figure 2: Spatial distribution of the average precipitation (mm) in the Heihe River Basin for the year 1960–2006 [20].

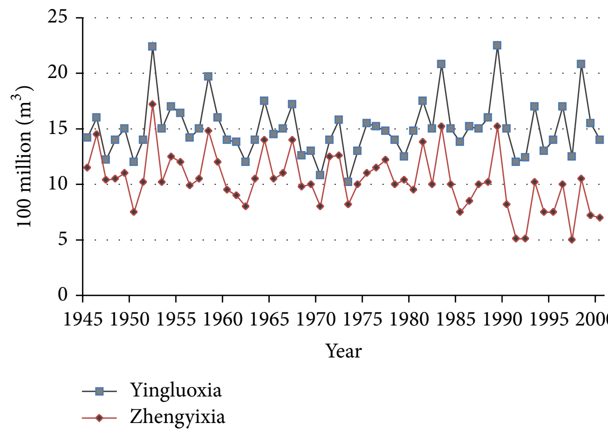

Figure 3: Change of the surface runoff through the Yingluoxia in the upper reaches and the Zhengyixia in the middle reaches.

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 been explored, and the number of motor-pumped well had doubled from the year 1985 to the year 1994 [22]. 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 HRB, which partly determined the hydrological process [16]. 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 [22].

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 independent 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 mainstream became the seasonal river below the Zhengyixia (Figure 3). 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.

3.2. 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 courses 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 1). 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

Table 1: Statistics of water consumption (1000 m^3) of the Heihe River Basin by counties 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

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 [23]. 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, as well as the restriction on the crop types, planting technologies, crop rotation, land management patterns, and unguaranteed maintenance costs, the water-saving renovation project cannot be effectively promoted, and leading 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 or units 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.

3.3. 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 [24]. 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 its own management focuses and time schedules and that 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 that fact that the high water demanding just happens in the dry periods [22]. 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.

4. Water Solutions of the Heihe River Basin

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.

4.1. Research Findings on Decision Making for Water Management. There are significant differences in ecosystem structure among 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, researches on the HRB should firstly focus on simulation of hydrologic process of the basin with the help of complex systematic modeling technology [25]. 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 researches, which are focused on the hydrologic process as well as the impacts of human activities on water resource. These researches basically conceptualized the basic laws of ecohydrological process in the HRB and revealed mechanisms on water cycling and ecological system evolution as well as the coupling mechanism between them.

The modeling work on the HRB is highlighted by model integration and meanly based on subregional modeling. There has been a lot of researches 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 [12]. 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 subwatershed and the unity of atmosphere-vegetation-soil-permafrost-snow cover. As for the model integration in the middle reaches in the HRB, these researches 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 simulating evapotranspiration and surface-groundwater interaction and achieved systematic simulation for hydrological cycle in the middle reaches of the HRB. More comprehensively, a genuine farmland ecohydrological model was established by integrating MODFLOW (groundwater model), Hydrus-1D (soil water model), and 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 considering 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 ecohydrological processes, water use mechanism of the typical plants, and their characteristics when responding to stress. A series of ecohydrology process model had been introduced, interpreted, or set up [26], including the Noah for ecological and hydrological processes, MODFLOW models for groundwater process, SWAT model for distributed hydrological processes, HYDRUS model, and the systematic conceptual model Gouburn-Broken Catchment for atmosphere-hydrology-vegetation interaction. At the upper reaches of the HRB, the integration research on ecohydrology 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 ecohydrological 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" [12, 27]. Human activities have becoming 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 researches on the former are very weak [28]. 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 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 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 and 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 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 (Figure 4). 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 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.

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 (Figure 4). 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

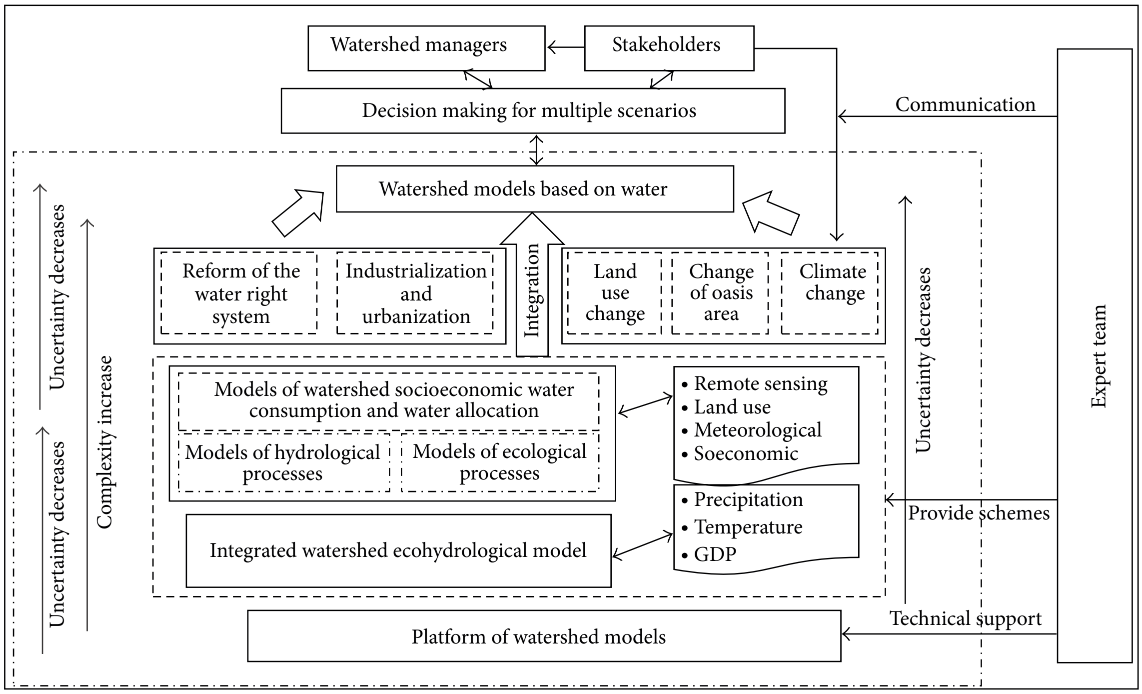

Figure 4: Framework and components for a DSS for the integrated water management in the Heihe River Basin.

activities (irrigation, livestock activities, and institutional change) on water [29]. However, compared to the study on the ecohydrological process and modeling research on the HBR, the mechanism studies water resource allocation are relatively weak. In this sense, both the system and institution design for water management and the optimal water resource allocation would be extended as follows.

4.2. 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" and "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 sets up Heihe River Bureau, an institution belonging 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 longstanding and widespread recognition that the river basin is the natural unit for water management [30, 31] (Table 2). 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 [30, 31]. Specifically, a far-reaching work was the Universal Soil Loss Equation (USLE), an empirical predictor for soil loss by water erosion [32]. 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 to move into the substantial scientific research period, with good public participation mechanism and considering water, ecology, and social economy in the basin scale [33, 34]. Water management of basins in Colorado and Sacramento are based on the IWRM model. IWRM was also applied to water management practices in Murry-darling basin in Australia, River Rhine Basin, and The River Thames basin in Europe and received satisfactory results [35–37]. In addition, 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 Africa development community (SADC) also tried to improve the water efficiency in arid area with the help of IWRM method to confront the food crisis and poverty [38].

Table 2: 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 multisectors and organizations at multilevel, including the military institutions composed of representatives from federal government and state government and 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.	(i) Strengthening the legal system and establishing a series of watershed management regulations to constraint the behaviors from various stakeholders. (ii) Managing the whole basin that relies on subbasin as the unit by sharing information and cooperating by various institutions. (iii) 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.	(i) Authority for watershed management should be established on consultation mechanism. The full participation in proposal making is the key. An effective organization system can guarantee the implementation of the protocol. (ii) Introducing a new theory and method in the water distribution, separating the water right from the land right, and providing water for trading to formulate water market. (iii) Making 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 and achieved remarkable success.	(i) Giving preference to prevention and source controlling and formulating detailed, standardized strict to regulate basin development. (ii) Paying emphasis on real-time monitoring and evaluation of the watershed management measures. (iii) Increasing storage capacity both in cities agriculture area to reduce water loss and soil erosion. Prohibiting development in riverbed. (iv) Presenting new concept of river ecosystem management and paying attention to the river health function and social economic factors as well as the support from modern science and technology.

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 [39]. Although this command has been implemented for nearly 10 years, the management condition of these cross-border rivers is still in the stage of national independent development and management, and the mechanism of cooperation and negotiation within countries still needs 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.

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 HRB. For instance, the responsibilities for water management in response to drought are unclear, water management authorities based on subriver basin have not paid enough attention compared to government management authority based on administrative regions, and economic and legal measurement still needs 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 subwatershed rather than administrative regions, three-layer coordination (decision level, execution level, and coordination level), and 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 systems, and global positioning systems (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.

4.3. 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 needs 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, it needs to further our research at the administrational level, calrifying the WUAs, water consuming situations, water association system, and other social economic features. The performance evaluation for WUAs can clarify the situation of WUAs (organization, incentive mechanism, and institutional arrangement) and 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 the different land use 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 and thus can provide 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 introduce the "water right" for water resources management, the leverage function failed to play a role because of the deficient water rights trading market. Research shows that market-oriented water management framework is beneficial to allocating water and improving water efficiency [40]. 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 [41–43]. 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 [44]. 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 [41]. 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 [29]. Other relevant studies at different scales include the impact of water allocation on social economy of different districts in Yellow River basin and the economic impact of South-to-North Water Diversion Project on different Administrative Region [45, 46]. The social and economic data used in most of these studies are static and on a single period, which are unfavourable 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 water, and domestic water), and water efficiency (Figure 5). The framework of CGE model should incorporate the water and land use resource as the production inputs into the production function to characterize 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 refers to the fact 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, and 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.

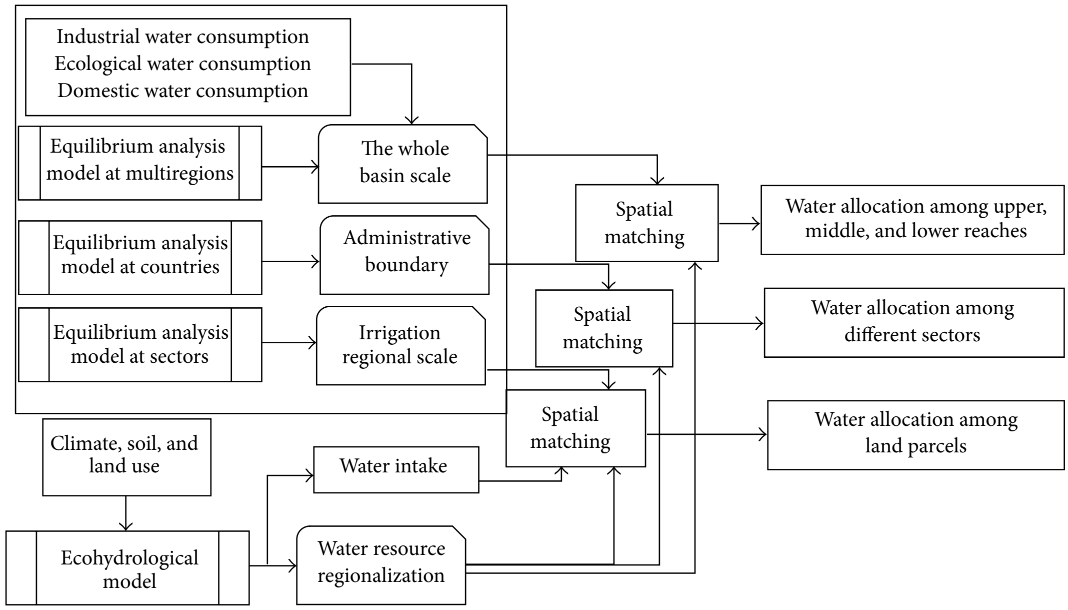

Figure 5: Multilevel water allocation strategy among irrigated area, counties, and sections of basin in the Heihe River Basin.

5. Conclusions

With high confidence to experience significant reduction in precipitation and water availability under potential climate change as indicated by the IPCC, the harmony between human being and water has become the theme of the development of river basin. As one of the largest inland river basins in Northwestern China, the HRB is characterized by fragile ecology as well as sensitive climate. Industrial and agricultural development in the middle reaches caused a decrease of incoming water and shrinking area of the Ejina Oasis in the lower reaches. Water security of the HRB is driven by multiple factors including agriculture and industry and livestock production, as well as ecology. Aside from a historical deceasing tendency in the water supply, water demand has changed dramatically during the 20th century in the HRB. Since water is a limited natural resource in the HRB, water scarcity is emerging when the demand outstrips the lands ability to provide the needed water. Sustainable development of the HRB needs a guarantee from water security, and there are a lot of emergent issues that need to be solved.

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. In particular, 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 ecohydrological model and social-economic model is to optimize the necessary premise of integrated river basin management. Generally, conflictions 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 HBR.

Contemporarily, there are a series of worldwide researches 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, and open dissipative "unstructured" or "semistructured" system. Considering the two dimensions (Nature-Society) driving character, for water reallocation, the existing modes and systems can not directly be copied and applied to the HRB.

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 and 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 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.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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