



# Water resource system risk and adaptive management of the Chinese Heihe River Basin in Asian arid areas

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## Abstract

Water scarcity is a challenging environmental problem in global arid regions in the twenty-first century. Global climate change and urban economic development exacerbate the problem of limited water supply and water shortage. In Asian arid areas, water has been being an important economic lifeline to maintain a healthy and sustainable oasis system. This study took the Heihe River Basin (HRB) in China's north-western arid area as a typical case region, identified an analytic framework of water resource system risk (WRSR) and analysed systematically the WRSR degree from the different perspectives. The results indicated that the runoff from mountainous watershed showed an increasing trend, but the total amount of watershed water resource showed a decreasing trend in the HRB in the past 50 years. Besides serious drought risk in recent 20 years, the WRSR is mainly from excessive water use in agriculture irrigation. Overall, the WRSR has increased from the year 2000 onward and is expected to increase and fluctuate in the future. Similarly, the potential WRSR is also huge in some arid watersheds relied heavily on glacial runoff in the world. In order to reduce water scarcity risk, it is necessary to implement and carry out effectively the watershed management policies of water resource; coordinate with the balance between the river and tributaries, surface water and groundwater and water quantity and quality to ensure the reasonable water supply in the different regions and water sectors; and promote rational industry structure adjustment and the innovations and applications of water saving and conservancy science and technology.

**Keywords** Arid area · Water resource · Risk analysis · Risk management

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## 1 Introduction

Arid areas are characterized by scarce and unpredictable precipitation. These dry lands cover approximately 41% of the global land surface and support over 2.5 billion people, 90% of whom live in developing countries (Reynolds et al. 2007). Large parts of arid areas are characterized by a semiarid to arid climate. Therefore, areas close to shallow groundwater, rivers and lakes are characterized by unique water-dependent ecosystems and human societies which have developed over millennia in close interaction with the naturally limited water resources (Karthé et al. 2015). Under future climate scenarios, the risk of global drought will become further exacerbated (Burke and Brown 2008; Aleksandrova et al. 2015). Due to vulnerable natural conditions and severe human disturbances, it is evident that water shortages (security) will continue to remain an important negative risk affecting eco-social systems in global arid areas (Wang et al. 2012; IPCC 2013). The arid area in north-western China is an important part of Asian and even global arid regions, including the vast areas in the western zone of the Helan Mountains (e.g. Xinjiang, Hexi Corridor in the Gansu and Alxa Leagues of Inner Mongolia), in which the land area is more than  $200 \times 10^4$  km<sup>2</sup>; this accounts for 24.50% of China's total land (Cheng and Zhao 2006). This region is in the hinterland of the Eurasian continent, featuring an arid climate and scarce rainfall; the entire basin mainly depends on mountain rainfall and glacier runoff (Gao et al. 2011). For example, the supply of glacier runoff in the Hexi Corridor in Gansu accounts for 14.10% of the total river flow. Strong glacier melting will inevitably lead to increased runoff in a certain period of time. In Asian arid areas, a desert will become an oasis if there is water; otherwise, it will remain a desert. An oasis is an isolated area of vegetation in a desert, typically surrounding a spring or similar water source. Oases provide habitats for organisms and humans. At the basin scale, a desert and oasis are both opposite and interdependent. Although oases cover only 4–5% of the area of the arid region in north-western China, they contain over 90% of the population and 95% of the social wealth of this area.

The inland river basin in the north-western arid area is an important ecological security barrier, where water resources are undoubtedly an important lifeline maintained by the healthy and sustainable development of an oasis system. However, the water resource system here is relatively fragile, which is mainly reflected by the increase in extreme hydrological events, uncertainty in water resources and changes in the water cycle process (Hagg et al. 2007; Chen et al. 2012; Cheng et al. 2014). Additionally, due to frequent and strong human activities and the increased demand of water resources, the phenomena of oasis atrophy and desertification have begun to appear and become worse, thus causing oasis ecological security to fall under serious threat in recent decades (Fu et al. 2009). Along with the implementation of the transnational “the China Belt and Road” initiative, the processes of industrialization and urbanization will accelerate development, which will cause demand for water resources to further increase and water resource shortages to become increasingly apparent. Thus, it is clear that water shortage or security is becoming a serious restraining factor for economic and social sustainable development in global arid regions.

Especially, the retreat and disappearance of glaciers will have major consequences on water resources, especially in arid regions such as the South American Andes, the North American Rocky Mountains and Asian Tianshan mountains (Wang et al. 2018), where many dry season river flows depend on glacier melt water. Worldwide glacier retreat and associated future runoff changes raise major concerns over the sustainability of global water resources. The largest relative reductions in basin runoff due to glacier runoff change are projected in central

Asian basins in September or October (Huss and Hock 2018). However, previous studies have over-understood water resources risks from natural attributes such as glaciers, precipitation and drought (Gleick 2015). In fact, the factors affecting regional water resource security include both natural factors and social factors, which have been determined by studies performed in different research fields (Gain et al. 2012; Chen et al. 2013; Padowski et al. 2015; Deng and Zhao 2015). The water resource system (WRS) is a complex system related to water security that includes hydro-meteorological and hydrological conditions, runoff, water infrastructure, water-related industries and water resource management subsystems. Simonovic (2009) and Gain et al. (2012) determined that the WRS comprises three linked subsystems: individuals, organizations and society, which are all nested within the environment. Bossel (1999) and Hamouda et al. (2009) correlated a variety of factors, such as individual development, social systems, government systems, economic systems, infrastructure systems and water resources to determine their influences on regional water resource security. The complexity and character of water-related challenges in global arid areas mean that management approaches need to be integrative, taking into account the natural resource basis, environmental limits and the socio-cultural and geopolitical dimension (Karthé et al. 2015). To achieve sustainable water resource management, the interactions among the different types of subsystems influencing water resources must be appropriately integrated into decision-making. At present, the integrated water resources management (IWRM) has been internationally accepted as the way forward for the efficient and equitable management of water resources. Borchardt et al. (2016) reviewed systematically the concept, contemporary research efforts and the implementation of the IWRM, analysed the starting points and historical developments of the IWRM concept and finally expanded on relations with recently upcoming concepts emphasizing adaptive water management and the land–water–food–energy nexus.

Given the above information, there is an urgent need to intensively study the interaction mechanism of WRS based on multi-scale and multi-view studies of typical inland river basin in the Asian arid area, which can provide a scientific basis for rationally utilizing water–land resources and protecting ecological environments in global arid areas. This study took the Chinese Heihe River Basin as a case region, defined the WRS and then used the driving force–pressure–state–impact–response (DPSIR) model (Jäger et al. 2008) to analyse the water resource system risk (WRSR). Based on the DPSIR model, this study systematically revealed the WRSR degree from three aspects of driving force and “pressure” of the WRSR, analysed total amount of water resources change and impacts on oasis system due to the driving force or pressure and, finally, described the various types of responses in the context of water resources status and impacts on eco-social system in the HRB. The purpose of the paper is to propose the adaptive water resource strategies suitable for Asian arid areas through the evaluation results of the WRSR. This study will become increasingly critical to plan and manage available water resources for achieving basin-scale water sustainability in eco-social systems, global arid areas under arid climate and arid hydrological background.

## 2 Study area, data and methods

### 2.1 Study area

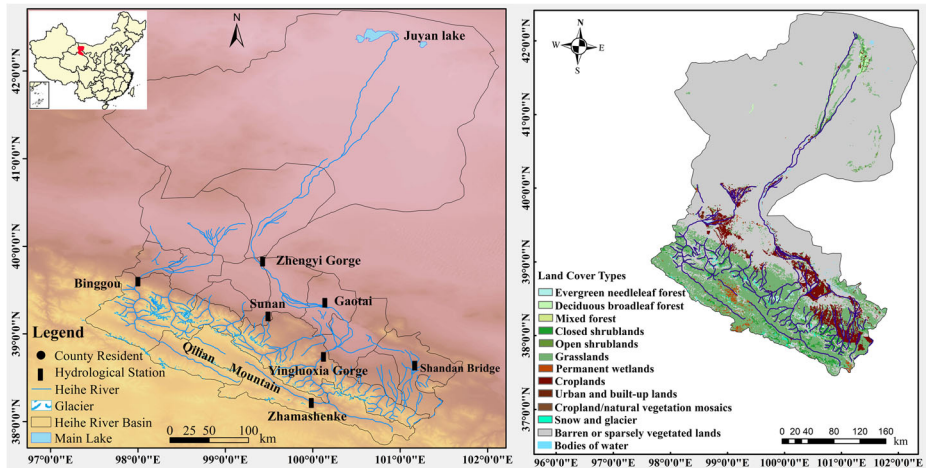
The Heihe River (HR), which has a total length of 821 km and is the second largest inland river in China, originates from the Qilian Mountains in Qinghai Province, flows through a

middle basin called the Hexi Corridor in Gansu Province and ends in the Juyan Lake, a terminal lake in the desert of the Inner Mongolia Autonomous Region. The Heihe River Basin (HRB) is representative of the arid area in Asia. It is located between  $96^{\circ} 45' - 102^{\circ} 06' E$  and  $37^{\circ} 44' - 42^{\circ} 40' N$  and has an approximate area of  $128,000 \text{ km}^2$  (Li et al. 2001). The HRB is divided into its upper, middle and lower basins by the Binggou Gorge ( $39^{\circ} 36' E - 98^{\circ} 00' N$ , 2337 m), Yingluo Gorge ( $100^{\circ} 11' E - 38^{\circ} 48' N$ , 1710 m) (which contains two control stations of mountainous runoff) and Zhengyi Gorge ( $99^{\circ} 28' E - 39^{\circ} 49' N$ ), respectively (Fig. 1).

The mountain areas in the upper reaches are the main water formation region and the source of most of the HRB's water supply. Here, the runoff size is influenced by the combined effects of rainfall, snow and glacier runoff and land surface; runoff distribution is very uneven during the year. The middle reaches (between the mountain outlet of the Yingluo Gorge and the middle reach outlet of the Zhengyi Gorge) are the main areas that use this runoff. Here, the river flow is mainly used to irrigate wheat and corn in the main agricultural oasis (i.e. the Hexi Corridor) (Peng et al. 2015). Due to the limited precipitation (long-term annual averaged precipitation decreased from 500 to 47 mm from the upper mountain area to lower reaches of the basin), both the river flow and groundwater withdraw are applied for regional agriculture (He et al. 2009; Wang and Niu 2016), in which cultivated area accounts for more than 80% of the total oasis area in the HRB. Water shortage has become the largest limiting factor of the oasis development. The northern desert zone is downstream of the Zhengyi Gorge, in which Juyan Lake is the consumption area of the HR flow.

## 2.2 Data

The data in this paper includes crop and food planting area, food output change, water quality, total amount of water resource, land use change, agricultural water use ratio and allocation quota of water resource, population and economy. Among them, runoff data from three hydrological stations are sourced from the “hydrological yearbook of Gansu Province (1961–2010)”, for which some annual missing data are calculated by interpolation of values from adjacent years. Data on water supply and demand as well as agricultural, industrial,



**Fig. 1** Spatial distribution of river, hydrologic stations and land cover types in Heihe River Basin

domestic and ecological water use are derived from the “Gansu Province Water Resources Bulletins (2000–2013)” and “China Water Resources Bulletins (1998–2013)”, respectively. Groundwater data from continuous annual and monthly observations in 1985–2013 are derived from the “Water Management Report of Hydrology of Water Resources Bureau of Gansu Province” (Mi et al. 2015), in which the Zhangye and East Jiuquan Basins contain 45 and 15 observation wells, respectively. Monthly precipitation and potential evapotranspiration data used to calculate the Standard Precipitation Evapotranspiration Index (SPEI) come from the National Meteorological Information Centre of the Chinese Meteorological Administration (NMIC/CMA). Before calculating the SPEI, these data are passed through quality control procedures and then undergo time series homogenization. This study also uses economic and social data (e.g. population, economy, crop and food planting area and allocation quota of water resource), which are mainly derived from the Statistics Yearbook of Gansu Province (1987–2012), Rural Yearbook of Gansu Province (1987–2012), Water Conservation Gazette of Gansu Province (1987–2014) and the Statistics Yearbook of Zhangye, Jiuquan, Jiayuguan Cities in Gansu Province, Qianlian County in Qinhai Province and Ejina of the Inner Mongolia Autonomous Region (1960–2014).

## 2.3 Methods

### 2.3.1 The standardized precipitation evapotranspiration index

The degree of water resource system risk is primarily affected by natural droughts, followed by unreasonable water use patterns (Van Loon 2015). In the arid region of north-western China, drought is controlled not only by temperature and precipitation but also by high-intensity evapotranspiration, which is the main factor resulting in drought phenomena. For example, in the upper reaches of the HRB, the annual precipitation is 200–700 mm, and the annual evaporation is approximately 700 mm; in the middle reaches, the average annual precipitation is 140 mm, and the average annual evaporation is 2000–4000 mm; in the downstream basin, the average annual precipitation is only 42 mm, and the average annual evaporation reaches 3755 mm. The SPEI was developed by Vicente-Serrano to determine drought. At present, the SPEI has been used in an increasing number of climatological and hydrological studies. The SPEI considers not only precipitation in its calculations but also temperature data by means of evapotranspiration, thus allowing for a more complete approach to exploring the effects of climate changes on drought occurrences under global warming. The detailed procedure to calculate the SPEI can be found in Vicente-Serrano et al. (2010). Table 1 illustrates the eight drought severity classes of the SPEI: mild, moderate, severe and extreme.

**Table 1** Classification scales of meteorological drought grades for SPEI

SPEI values	Drought category	Probability (%)
2.0 and above	Extreme wet	2.3
1.5 to 1.99	Severe wet	4.4
1 to 1.49	Moderate wet	9.2
0 to 0.99	Mild wet	34.1
0 to -0.99	Mild drought	34.1
-1 to -1.49	Moderate drought	9.2
-1.5 to -1.99	Severe drought	4.4
-2 and less	Extreme drought	2.3

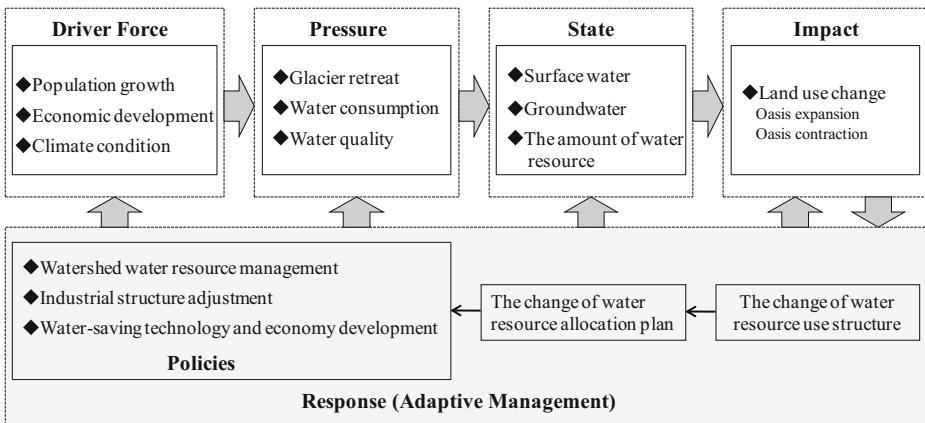
### 2.3.2 Water resource system risk

Risk is a compound measure combining the probability and magnitude of an adverse effect. With the gradual improvement of theoretical approaches, risk research has been widely used in different areas of study, such as ecological security, disaster management, land use, climate change, public health and sustainable science, among others (Cutter 1996; Turner et al. 2003; Fussel and Klein 2006; Ziad and Amjad 2009; Martensa et al. 2009). Currently, research on global change risk has begun to develop towards the direction of comprehensive interdisciplinary research between natural and social science and policy-driven research, which aims to provide important information and generate specific proposals by allocating limited resources, reducing risk and enhancing adaptive capacity by implementing adaptation strategies for different interest groups and policy makers. Water resource system risk (WRSR), as one of the most important consequences of global climate change, includes the increasing degree of supply and demand imbalance and other security issues (including flooding and water pollution events) which are the results of hydroclimatic change, water use structure change and changes in water quantity and quality due to the stress of global climate change; it can also be viewed as the degree of stability of an eco-social system with a normal water demand. Generally, the WRSR can be understood as a function of the variability and magnitude of water-related climate, hydrological processes and water supply and demand and the ability of a system to adapt to adverse effects.

### 2.3.3 DPSIR framework of the WRSR

Studying the interactions among the various factors affecting regional water resource security is necessary for outlining necessary management strategies (Hamouda et al. 2009; Karthe et al. 2015; Borchardt et al. 2016), in which the driving force–pressure–state–impact–response (DPSIR) model can describe the interactions and impacts of human activities, water resources and environment during the processes of economic and social development (Odermatt 2004; Rapport and Singh 2006; Benini et al. 2010; Gain et al. 2012; Nuttle and Fletcher 2013; Gain and Giupponi 2015; Gain et al. 2015; Giupponi et al. 2015). DPSIR is a generally recognized conceptual model that connects causes (i.e. driving forces and pressures) to states and activities (i.e. policy measures and decisions), as well as their impact on humans (Jäger et al. 2008). The specific process of running the DPSIR model is as follows: rapid economic development (i.e. a driving force) puts pressure on an already fragile system, the state of the system subsequently changes and the risk to or impact on the system is increased. Finally, a variety of actions and measures will in turn produce responses with feedback properties to the driving force, state and impact. The DPSIR model can also monitor the continuous feedback mechanisms among the various indicators of the DPSIR chain. Before monitoring, five basic questions need to be answered, including determining where the pressure comes from, what happened, what the present situation is, what the impact is and how to respond or adapt. Similarly, the connotation of the WRSR can be interpreted using the internal mechanism of the DPSIR conceptual framework. Using system theory and the DPSIR model, this study constructs an analytical framework of the WRSR that is suitable for Asian arid areas (Fig. 2).

In the WRSR–DPSIR conceptual model, the driving force represents the initial cause. That is, it refers to the driving force of water resource change caused by human activities and climate change, including demographic, economic, social or political activities (e.g. population growth, economic growth, or the demand for food) or a serious climatic or hydrological



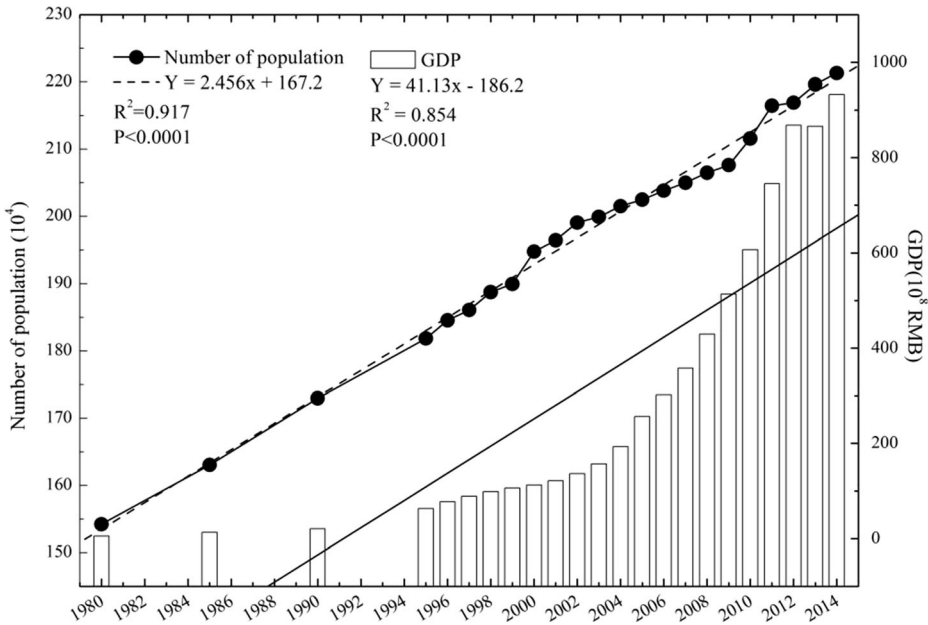
**Fig. 2** Integrated analysis framework of water resource system risk based on the DPSIR

drought. Pressure refers to the stress points that impact a system and manifest themselves as changes in environmental conditions (e.g. shrinking glaciers, increasing irrigation area and poor water quality). State refers to the trend of water resource change due to the driving force or pressure, such as change in surface water or groundwater or change in the total amount of water resource. Impact refers to the specific effects of the driving force or pressure change on a water-related system in a state of water shortage, such as the shrinking of an oasis or land degradation. Response generally refers to the societal and institutional reactions or efforts (e.g. laws, taxes or migration) that reduce the driving force and pressure or make it possible to adapt to the changed condition (i.e. the state) and its impact, such as change in water use and water allocation, watershed management of water resource, the adjustment of industrial structures and the promotion of water-saving techniques (Fig. 2).

### 3 Result and analysis

#### 3.1 Driving force

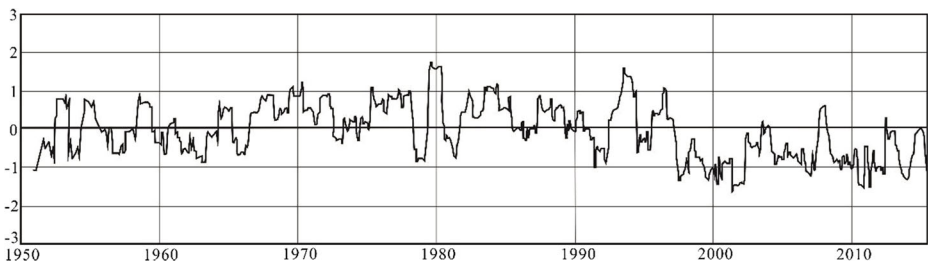
The original water resource system is theoretically stable. However, this steady state can be broken by the stress of external forces, in which the rapidly changing population, economy and serious drought climate are considered to be the three main driving forces of the WRSR in arid areas (Falkenmark 2013). Population growth and economic development cause changes in water demand, while this increasing demand makes the water resource system more vulnerable, which in turn affects ecology and food security. For example, the population of the HRB in the 1980s was less than  $170 \times 10^4$  people, whereas it comprised nearly  $190 \times 10^4$  people in the late 1990s and exceeded  $220 \times 10^4$  people in 2014. Over the past 35 years, the population has increased to  $50 \times 10^4$  people with a growth rate of 29.41%. With the inertia of population growth, these demographic changes will continue to increase in the future (Fig. 3). Additionally, the demand for increased water use with economic growth is bound to be much higher than that of population growth. The total GDP in the HRB in 1980 was relatively low at  $5.26 \times 10^8$  RMB; in 2000, this GDP quickly raised to  $112 \times 10^8$  RMB; and in 2014, the GDP exceeded  $930 \times 10^8$  RMB. Over the past 35 years, the GDP has increased 175.81 times, and



**Fig. 3** Demographic and economic change in the HRB from 1980 to 2014

the annual percentage growth rate of the GDP was over 5% (Statistical Bureau of Zhangye City, 1980–2015). In particular, since 2000, economic growth has shown a markedly accelerated trend and rapid economic development will undoubtedly squeeze a large amount of water resources (Fig. 3).

Drought is another driving force of natural systems. As seen in Fig. 4, the 12-month SPEI exhibited a significant downward trend ( $R^2 = 0.177$ ,  $P = 0.003$ ) with an obvious drought trend and a linear trend that reached  $-0.017/10a$  during the past 64 years. Prior to the late 1990s, there are fewer drought events, and frequent droughts mainly occurred in nearly every 20 years. Since 1997, the SPEI continuously remained in a relatively dry state, and the drought frequency substantially exceeded 95% (Fig. 4). The longer (12-month) time scale recording lower SPEI values implied that a water shortage occurred in the HRB after the late 1990s, which could have been associated with the decrease in the amount of water resources during the same period. The SPEI is the result of temperature and precipitation interaction, which is closely related to potential evaporation. A study by Gao et al. (2014) indicated that variation in



**Fig. 4** Time series of 12-month SPEI for the HRB from 1951 to 2014



annual potential evaporation tended to increase during 1957–2012 and that the largest increase occurred after 1995; this trend is also consistent with the SPEI change (Fig. 4).

### 3.2 Pressure

In Asian arid areas, the pressures of the WRSR come mainly from two categories: glacier change and human activities. Here, these two aspects are characterized by glacier change, water consumption by the primary industry and water quality. In Asian arid areas, glacier runoff is another water resource besides precipitation, and its changes directly affect the water resources and annual distribution. Previous studies have shown that many rivers have passed the “glacier inflexion”, after which point the contribution of glaciers to water resources will continue to decrease (Ye et al. 2003; Farinotti et al. 2015). It has been found that glaciers have shrunk significantly in the HRB over the past 50 years, from 1960 to 2010, during which time the total number of glaciers (967 in the 1960s) was reduced by 17.27% and the total glacier area (389 km<sup>2</sup> in the 1960s) decreased by 36.08%, with a retreating rate of 2.78 km<sup>2</sup> per year (Bie et al. 2013; Huai et al. 2014) (Fig. 5).

Temperature and precipitation are the two main controlling factors of glacier change, in which the summer temperature determines the amount of glacier melting, and the annual precipitation influences the amount of glacier accumulation. These results indicated that during the past 50 years, from 1961 to 2010, the annual mean air temperature in the upper HRB recorded a markedly upward trend with a warming rate of 0.43 °C/10a ( $R^2 = 0.632$ ,  $P < 0.001$ ), which is significantly higher than the national warming rate of 0.30 °C/10a ( $R^2 = 0.684$ ,  $P < 0.001$ ). Similarly, the annual precipitation also showed a significant increase, as its annual variation rate reached 15.55 mm/10a ( $R^2 = 0.16$ ,  $P < 0.01$ ), which is slightly higher than the increased amplification (13.75 mm/10a) recorded in the northwest arid area over the same period (Xu et al. 2014) (Fig. 6). It can thus be said that the climate background will accelerate the rate of glacier melting, which will increase the WRSR degree and will finally produce further water demand in the eco-social system in the middle and lower reaches in the future.

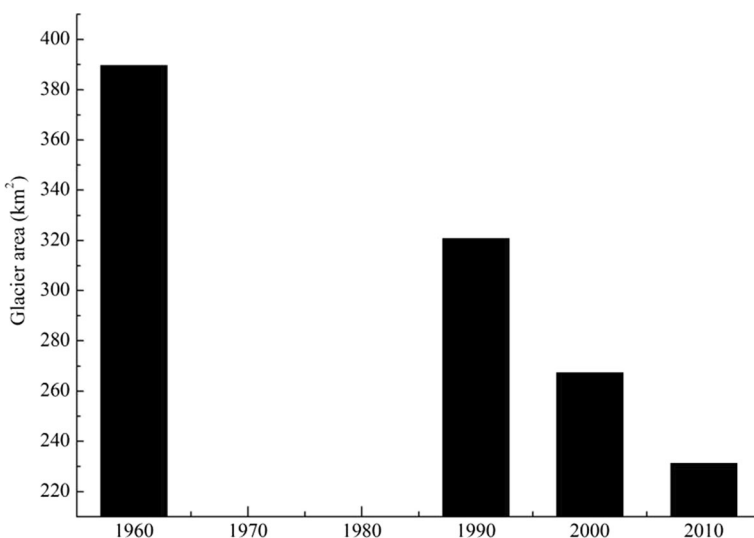
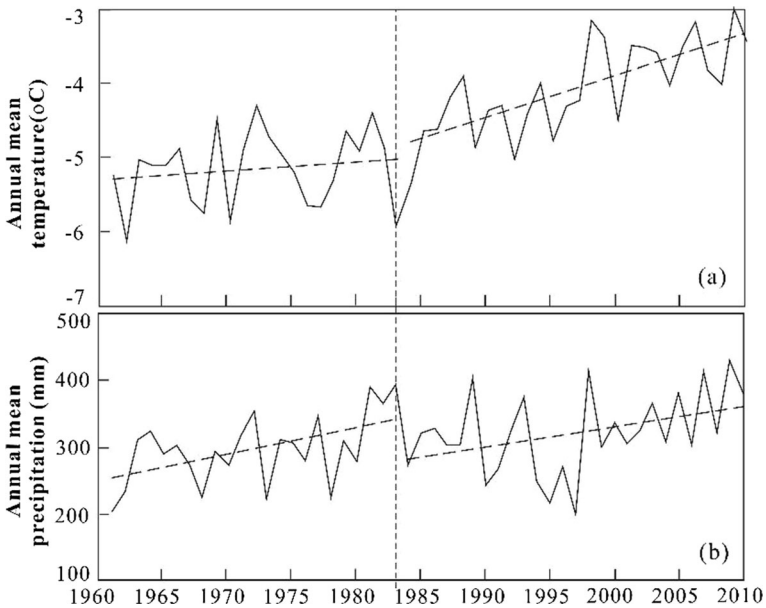


Fig. 5 The decadal variation of glacier area in the upper HRB

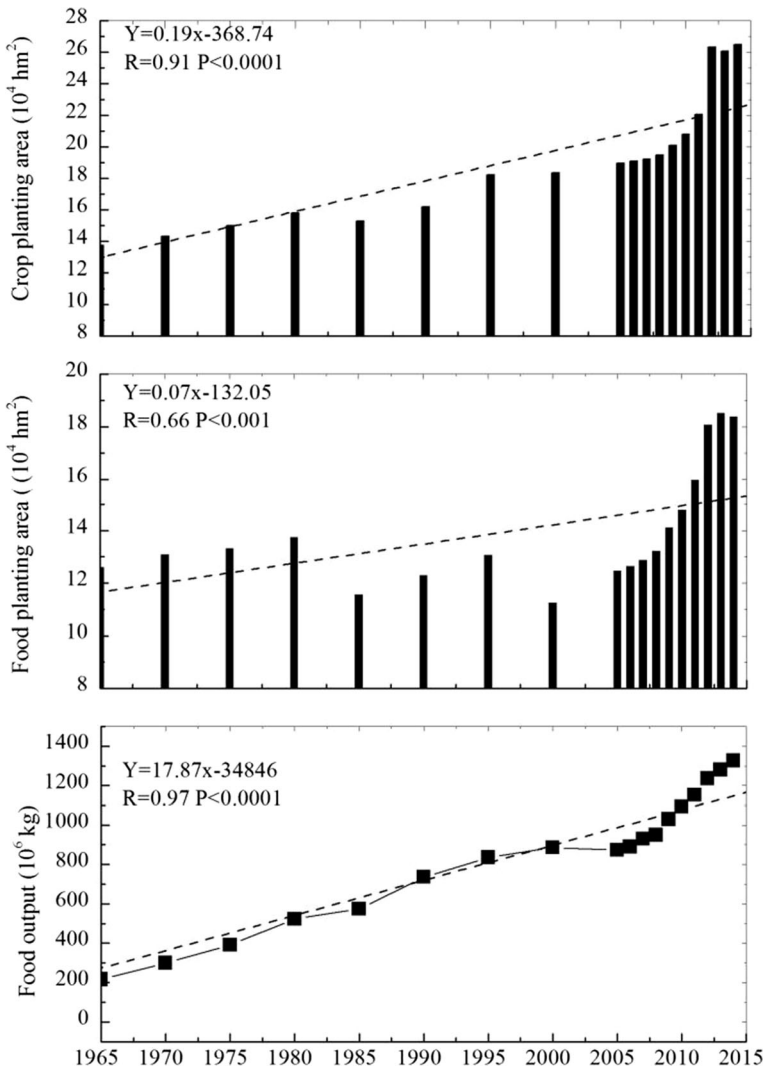


**Fig. 6** Variation of the annual mean temperature (a) and precipitation (b) in the upper HRB

Agricultural activity is a main social cause of the WRSR; however, irrigation water plays a major role in agricultural production, as the region is currently experiencing both water and food scarcity. In the arid area of north-western China, agriculture is the largest industry for water demand and consumption. The demand of agricultural water use is more than 90% of the total amount of available water resources, whereas its water consumption rate exceeds 45% of the total water use efficiency. For example, from 1965 to 2014, crop planting (including food and economic crop) areas and food planting (cereal, beans, yam crops) areas both showed significantly increasing trends, with rates of  $0.19 \times 10^6$  km<sup>2</sup>/a and  $7.00 \times 10^4$  km<sup>2</sup>/a, respectively. With the increase in cultivated land, food production has also shown a rapidly increasing trend, with a rate of  $17.87 \times 10^6$  kg/a over the same period (Fig. 7).

However, larger crop planting areas are also associated with larger irrigated crop areas, in which higher excessive irrigation water use or consumption largely influences the WRSR degree. The results also showed that the trend of real crop irrigation area change is consistent with that of crop water consumption from 2000 to 2013, as both first showed an overall decrease, followed by an increasing trend. From 2000 to 2013, the real crop irrigation area and crop water consumption decreased by 3.86% and 6.56%, respectively, but crop irrigation areas still accounted for more than 60% of the total land area in the middle HRB. Thus, future water demand pressures are still very severe (Fig. 8).

Water environmental issues also represent an impact factor for the WRSR. Poor water quality limits the healthy and sustainable development of the eco-social systems in the HRB. Water quality data from the Zhamashenke, Yingluoxia, Gaotai, Zhengyixia, Sunan and Shandan bridge hydrological stations (Fig. 1) in the HRB demonstrated an overall good trend in NH<sub>3</sub>-N levels over many years. In these results, no clear trend occupied 66.70%, the downward trend occupied 33.30% in NH<sub>3</sub>-N level, in which the greatest concentration change



**Fig. 7** Crop, food planting area and food output change trend during 1965–2014

trends were seen at the Gaotai, Zhengyixia and Shandan bridge stations. Regarding the trend of CODMn (chemical oxygen demand measured by the potassium permanganate method) over many years, the sections with rising and declining trends accounted for 16.70% and 16.70%, respectively, while the inconspicuous trend accounted for 50%, and the largest concentration change trend occurred at the Zhengyixia and Gaotai stations (no CODMn data in Shandan bridge) (Li 2014). From 2000 to 2013, the proportion of reaches with water quality in class IV (only suitable for agricultural and landscape water requirements) and above (referring to the environmental quality standard for surface water of GHZB 1–1999) showed a relative decreasing trend with a change rate of  $-1.30\%/a$  ( $R^2=0.44$ ,  $P=0.009$ ) (Fig. 9). However, the pollution is still serious, and the potential risk of water quality is greater in a scenario of accelerating industrialization.

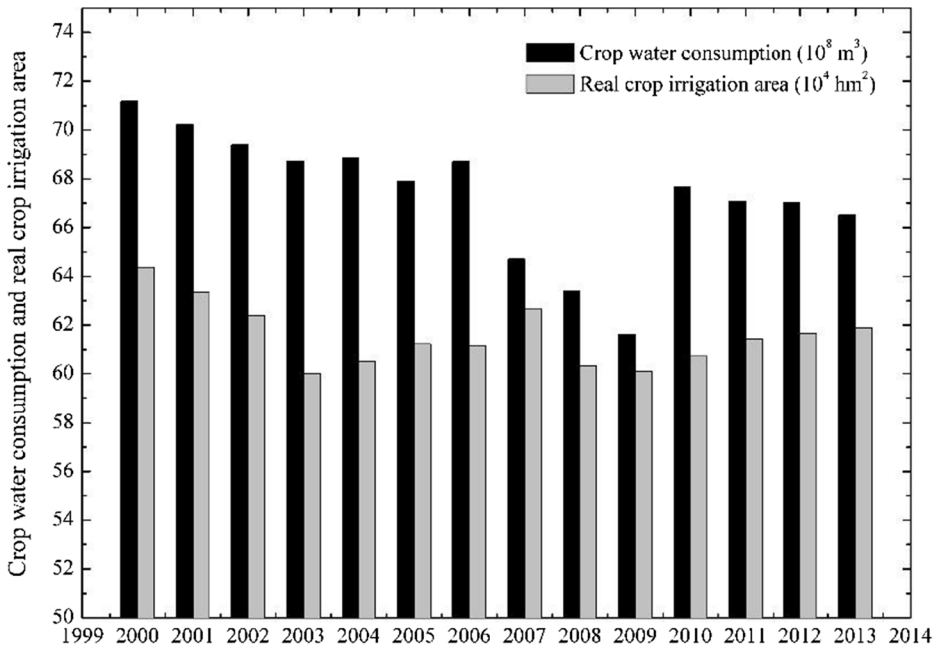


Fig. 8 Real crop irrigation area and crop water consumption change trend during 2000–2013

### 3.3 State

Under the combined stress of an arid climate and strong agricultural activities, the state of the WRSR mainly reflects changes in surface water, groundwater and the total amount of water resources. A study by Xu et al. (2014) showed that the runoff from the Binggou station in the

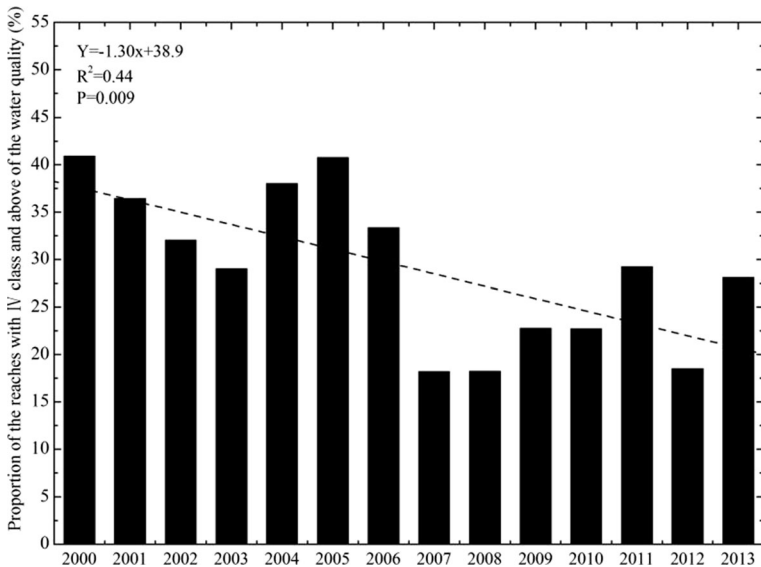


Fig. 9 Proportion of the reaches with IV class and above of water quality during 2000–2013

upper HRB had a slightly decreasing trend with an annual change rate of  $-0.10 \times 10^8 \text{ m}^3/10\text{a}$  ( $R^2 = 0.026$ ,  $P = 0.26$ ) from 1961 to 2010 (Figs. 1 and 10a). Theoretically, the interannual variability of mountain-pass runoff should significantly increase with obvious warming, strong melting of snow and glaciers and abundant precipitation. However, runoff instead shows a weak decrease in the same period. In addition to increased evapotranspiration, the important factor of land use change resulted in this runoff reduction. Runoff from another hydrological station (Yingluo Gorge) in the upper HRB exhibited an insignificant increasing trend of  $0.086 \times 10^8 \text{ m}^3$  from 1961 to 2010, in which the increase in runoff became more significant after 2003 (Figs. 1 and 10b).

With the increase in cultivated land and water consumption in the middle HRB, runoff at the Zhengyi Gorge station showed a relatively significant decreasing trend over the past 52 years. In particular, after the ecology water allocation project downstream (Juyan Lake) was fully implemented in 2002, runoff showed an obvious increasing trend (Figs. 1 and 10c). Overall, the long-term average annual runoff at the Zhengyi Gorge station reached  $9.50 \times 10^8 \text{ m}^3$ .

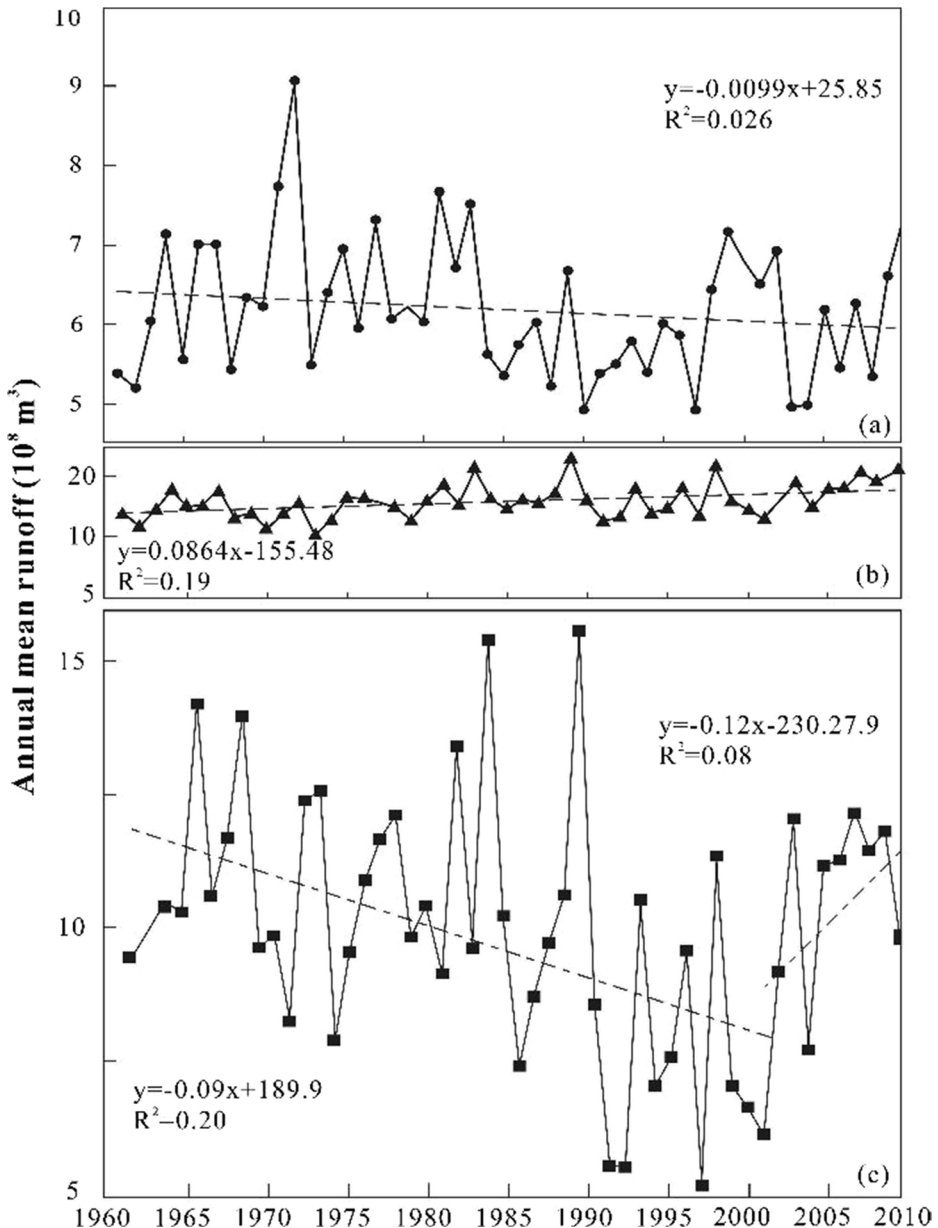
The groundwater level records the balance of ecological, industrial and agricultural water use and is also an important characterization factor of the WRSR change. The misallocation of surface water and arable land expansion has led to the over-abstraction of groundwater, which then lowered the groundwater table and the quantity of renewable water in the HRB. Studies by Mi et al. (2015) showed that the groundwater level declined from 1985 to 2004 and then presented a rising tendency from 2005 to 2013. The groundwater system has fallen to a severe negative balance, although the groundwater level recorded a rising tendency in the Zhangye Basin (in the middle HRB) during 2005–2013.

From 1960 to 2001, the average annual decreasing rate in east Juyan Lake in the lower HRB reached  $0.35 \text{ km}^2/\text{a}$  (Fig. 1). During this period, east Juyan Lake experienced three periods of drying in 1961–1963, 1973 and 1986 and went completely dry in 1992. In 2002, the implementation of the “Water Allocation Plan” project in the HRB basically guaranteed that the amount of water resources travelling from the Zhengyi Gorge to the lower reaches would be no less than  $9.5 \times 10^8 \text{ m}^3$ , which effectively prevented the gradual trend of ecological deterioration in the downstream region that had been ongoing since the late 1980s, to a certain extent. For example, in recent years, the regional groundwater level gradually increased, and the water area in east Juyan Lake reached more than  $40.30 \text{ km}^2$  in 2012. Meanwhile, the amount of water resources used in the middle reaches was reduced by  $2.4 \times 10^8 \text{ m}^3$ , from  $10.4 \times 10^8 \text{ m}^3$  in 1990 to  $8.0 \times 10^8 \text{ m}^3$  in 2010 (Nian et al. 2014, 2015).

Surface water and groundwater change ultimately influence the total amount of water resources. The Water Resources Bulletin of Gansu Province showed that the average annual water resources amounted to  $68.32 \times 10^8 \text{ m}^3$  in the HRB during 1997–2013. Before 2001, the average annual water resources were higher, and lower average annual water resources occurred after 2001. However, in the past 16 years, the total amount of water resources has presented an overall downward trend, which basically correlates with the SPEI index change (Figs. 4 and 11). Reducing the amount of water resources will inevitably increase the WRSR degree in the future.

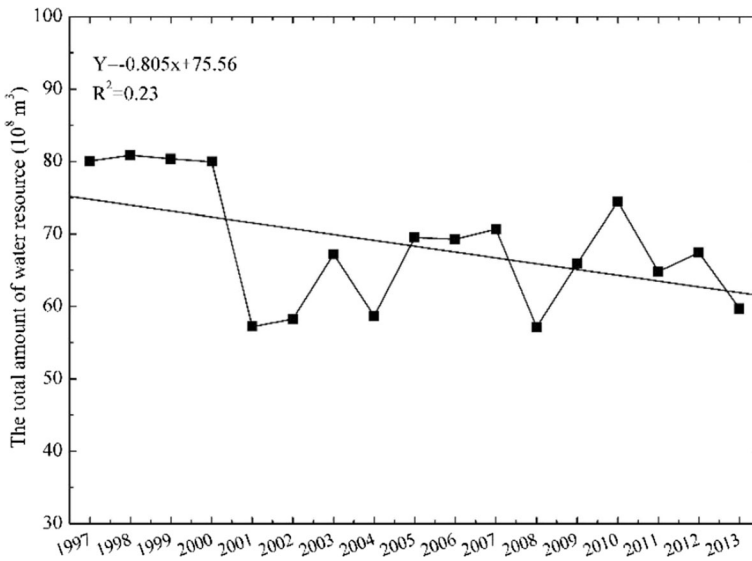
### 3.4 Impact

Land use change is most affected by the fluctuation of the water resource system. In arid areas, the shrinking of oases and land degradation are the two main factors reflecting land use



**Fig. 10** Annual mean runoff change in the Binggou (a), Yingluo Gorge (b), and Zhengyi Gorge (c) hydrological stations in the HRB

change. In the upper reaches, land use change has an evident periodicity. The grassland area decreased by  $436.02 \text{ km}^2$  from 1987 to 2010. Similarly, the forest area was also reduced by  $11.41 \times 10^4 \text{ km}^2$  in the same period (An et al. 2013). Although the state has implemented the policy of Conversion of Cropland to Forest and Grassland Program, an arid climate background has obviously led to the degradation of upstream vegetation. The combination of unstable precipitation and steadily rising temperatures caused the shrinking of glaciers and



**Fig. 11** Interannual variation of the total amount of water resource in the HRB

snow areas, the increase in unused land and the rise of the forest line. However, the water area increased by 60.26% over the past 23 years, which led to the rapid expansion (i.e. the expansion rate increased three times from 1987 to 2010) of cultivated land in the upper reaches.

In the middle and lower reaches, water resources and human activities are the two key influencing factors of dynamic land use change. The land type is mainly composed of oases and desert, in which oases consist of two main parts: the middle-reach oases and the low-reach oases. They are located in the midst of the Hexi Corridor (Zhangye, Jiuquan and Jiayuguan) in the middle reaches and in Ejina in the lower reaches of Inner Mongolia, respectively (Fig. 1). In these areas, oasis expansion was the main trend from 1963 to 2009. In the 46 years from 1963 to 2009, the oasis area increased by 2317.85 km<sup>2</sup>, and its growth rate reached 52.10%. However, in 1996 and 2002, there were two periods of short-term oasis atrophy. The oasis area increased especially rapidly after 2002, reaching a maximum value of 6766.49 km<sup>2</sup> in 2009 (Zhao 2012). During the process of oasis expansion, the increase in the crop planting area was extremely obvious (Fig. 7), yet this expansion was primarily transferred from desert to grassland. The serious ecological degradation of the Ejina Basin in the lower reaches had been of great concern to members of all levels of national government and academia since the 1980s and 1990s and ultimately led to the implementation of the “Eco-Water Allocation” and “Watershed Water Resource Management” policies in 2002. From 1963 to 2009, the oasis area showed a significant decrease with an annual change rate of 52.9 km<sup>2</sup>/a ( $R^2 = 0.55$ ,  $P < 0.05$ ) in the Ejina Basin, while the oasis area began to increase since 2002 and reached an area of 480.37 km<sup>2</sup> in 2009, which was far less than its area of 770.59 km<sup>2</sup> in 1986 (Xie et al. 2012).

### 3.5 Response

It is very difficult to change the arid climate background of the WRSR, but the degree of the WRSR can be reduced by adjusting the structure of water resource use and implementing the

policies of “Water Resource Allocation” and “Watershed Water Resource Management” in an eco-social system. The change in water resource use structure is an inevitable response to land use change in an arid climate background, while the implementation of water resource policies is the optimal choice for preventing ecological degradation in the upper, middle and lower reaches of the HRB.

In 2000, the ratio of the proportions of agricultural, industrial, domestic and ecological water use was 87.70:2.80:2.20:7.10 in the HRB, in which the water benefits (i.e. output) was only 2.81 RMB/m<sup>3</sup>. In 2004, the ratio of the proportions of agricultural, industrial, domestic and ecological water use reached 89.03:4.22:2.28:4.47, in which the proportions of agricultural and domestic water utilization were roughly the same, the proportion of industrial water use increased by 1.42% and the proportion of ecological water use decreased by 2.63% from the year 2000. In recent years, the water use structure has undergone significant changes. In 2013, the ratio of the proportions of agricultural, industrial, domestic and ecological water use reached 83.62:5.81:2.04:8.53 in the HRB. The proportion of agricultural water use was reduced by 4.08 percentage points. In contrast, the proportion of ecological water use increased by 3.03% to prevent oasis atrophy and ecosystem degradation over the past 14 years (Fig. 12). However, because the proportion of agricultural water use is still too high, the water use structure is still not reasonable. In the HRB, the current farmland irrigation quota is approximately 4400 m<sup>3</sup>/km<sup>2</sup>. In particular, the recycling rate of industrial water is only 45%, and the overall water use efficiency is still not high. At the same time, the agricultural irrigation structure with high water consumption led, in turn, to the low economic efficiency of water use. In 2013, the GDP output of water benefit per cubic metre reached 14.53 RMB, which was far higher than 2000’s value of 2.81 RMB.

To ease the worsening situation of ecological degradation and solve the increasingly prominent water event, the state began to carry out watershed water resource management and water allocation policies in 2001. In 2002, Hei River first dispatched to Juyan lake through manual dispatch (Fig. 1). The results show that 2000–2013, the cumulative flow from the Yingluo Gorge hydrological section of the upper reaches reached  $249.05 \times 10^8$  m<sup>3</sup>, with an average annual flow of  $17.79 \times 10^8$  m<sup>3</sup>, which was more than  $1.99 \times 10^8$  m<sup>3</sup> higher than the average annual flow. The discharged water volume from the Zhengyi Gorge section of the middle reaches accumulated to  $143.95 \times 10^8$  m<sup>3</sup>, which represented an increase of  $2.41 \times 10^8$  m<sup>3</sup> compared to the 1990s (Zhao and Huang 2015). During 2002–2013, the HRB allocated water resources 32 times to the east Juyan Lake, which dried up 10 times in 12 years, and the cumulative released water capacity reached  $6.95 \times 10^8$  m<sup>3</sup>, with an average annual water volume of  $0.53 \times 10^8$  m<sup>3</sup> (Table 2). A certain amount of released water capacity increases the soil water content and groundwater recharge, which effectively extend the ecological shelter belt of Ejina and block the evolution of the Badain Jaran Desert to the middle reaches.

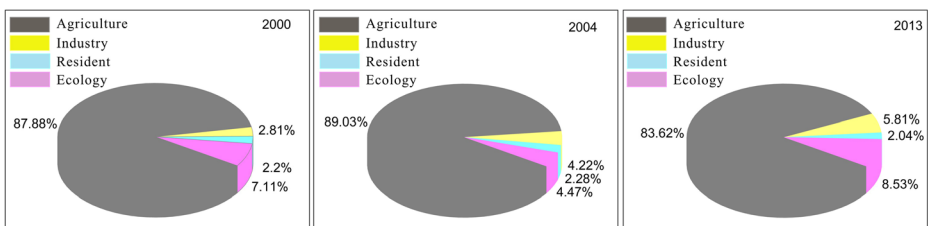


Fig. 12 Change trend of water use structure in different sectors in the HRB



**Table 2** Allocation quota of main hydrological stations during 2000–2013 ( $10^8$  m<sup>3</sup>)

Year	Yingluo Gorge	Zhengyi Gorge	East Juyan Lake
2000	14.62	6.50	
2001	13.13	6.48	
2002	16.11	9.23	0.49
2003	19.03	11.61	0.42
2004	14.98	8.55	0.52
2005	18.08	10.49	0.36
2006	17.89	11.45	0.69
2007	20.65	11.96	0.60
2008	18.87	11.82	0.65
2009	21.30	11.98	0.57
2010	17.45	9.57	0.48
2011	18.06	11.27	0.88
2012	19.35	11.13	0.62
2013	19.53	11.91	0.67
Total	249.05	143.95	6.95

## 4 Adaptive measures of water resource system risk

### 4.1 Watershed management

Water resource supply and demand planning needs to coordinate the relationship between the upper, middle and lower reaches, the whole watershed and different administrative regions and arrange and allocate the supply and demand of water resources in the different administrative regions, water sectors and reaches of the basin. Water allocation mainly solves the seriously mismatched scales of water and soil resources in the space scale, while allocation focuses on the incompatible scales between the smaller spring runoff and the much greater agricultural irrigation water use in the time scale. Water use allocation is mainly used to balance the relationship between economic development and ecological, agriculture and animal husbandry water demand; water source allocation deals primarily with the questions of excessive surface water use, lower development degrees of groundwater and greater prelatec evaporation; and water management allocation mostly settles the problem by prioritizing exploring water sources over saving water and taking the construction of water resource use more seriously than the management of epitaxial water resource use.

The HR has seasonally imbalanced characteristics in terms of its water resource supply and demand, and the contradiction between its water use and economic development is very prominent. In spring, the amount of water use in the middle reaches accounts for almost 50% of the total amount of water resource use in the whole year, while the amount of runoff in the spring represents only 25% of the total water resource use in the whole year. Therefore, we can set water prices at different spatial and temporal scales using market mechanisms. Because the runoff decreases in the spring, we can move some agricultural productions or activities to the summer, when there is increasing runoff, by improving the water price, which will effectively slow down the contradictions of agricultural water use. To solve the problem of contradictory water use and economic development, the HRB has currently implemented a series of water management policies, including the “Temporal method of Heihe River water allocation management (2000)”, “Recent Heihe river basin governance management planning (2001)”, “Heihe river basin water allocation plan (1999-2012)” and the “Statute of inter-

province water event coordination in the HRB” (2004), among others (Wang et al. 2008; Liu and Yang 2012; Chen et al. 2012). This unified water allocation balanced the water demand between ecological protection and economic development in different administrative regions and greatly improved the ecological environment in the lower reaches. Until 2012,  $120 \times 10^8 \text{ m}^3$  of water resource was allocated to the lower reaches; in 10 years, vegetation coverage increased by nearly 30% in the Ejina Basin.

## 4.2 Industrial structure adjustment

The relationship between industrial structures and water resources is very close, such that the adjustment of water use structure requires the industrial structure to change to some extent. Overall, the impact of water resources varies throughout the different stages of the evolution of an industrial structure. With the continuous evolution of the industrial structure, its impact will gradually be reduced. At the preindustrial stage, technology and productivity levels are relatively low, the economic structure is predominantly agricultural and the agricultural water demand and consumption is thus strong and enormous. At the industrial stage, along with technological innovation, the industrial structure begins to transform from labour-intensive industries to capital-intensive industries to technology-intensive industries, in which the degree of industrial water-independence will become relatively strong and water consumption will also decrease (Wu et al. 2014). At the post-industrial stage, when productivity and technology levels are highly developed, the economic structure relies mainly on knowledge-intensive industries. In this context, the industrial water demand becomes relatively small, the water use efficiency is relatively high, and the degree of industrial water-dependence has highly decreased.

For example, three industries evolved in Zhangye city in the middle reaches from 1980 to 2004. Overall, the economic development in Zhangye is consistent with the general evolutionary sequence of industrial structures. Prior to 2004, the first industry (i.e. agriculture) held a dominant position in the industrial structure. After that, the proportion of this primary industry decreased rapidly with industrial restructuring, while the proportions of the secondary and tertiary industries gradually increased. As of 2014, the proportion of the first industry accounted for 27.80% of the region’s GDP, which decreased by 23.42% compared to its proportion in 1980, while the proportions of the secondary and tertiary industries reached 34.80% and 37.40%, which represented increases in their 1980 values by 1.16% and 27.65%, respectively.

Previous studies have shown that agriculture-dominated regions are most often affected by water resource shortages (Sadoff et al. 2015) and that these regions need to consider diversifying their economic industries and improving the efficiency of their use of limited water resources in order to reduce the degree of industrial water-dependence on water resources. Although the proportion of primary industries has continued to decrease in recent years, the phenomenon of water resource shortages from oases in the middle and lower reaches is still serious.

## 4.3 Water-saving economy

Because an arid climate determines the reality of water shortages in arid areas, one solution is to open up water sources and regulate their flow; however, saving water is a fundamental measure of the integrated management of watershed water resources. The utilization rates of

water resources and water use efficiency are low in arid areas in Asia, and thus, industrial development must be undertaken to achieve a key breakthrough in improving the water use efficiency. Under the current economic conditions, the most important priority is to promote water-saving technologies and develop a water-saving economy. Agriculture is the most water-related sector in arid areas, as the amount of agricultural water use often accounts for more than 90% of the total available water resources. Therefore, water-saving agriculture should be centred on water conservation. The water use per unit ( $10^4$ ) GDP decreased by 1153.7  $\text{m}^3$  in the HRB from 2000 to 2010. In the past 11 years, the water use per unit GDP has shown an obviously decreasing trend, while the water use efficiency has increased significantly.

To further improve the water resource use efficiency, the HRB must be strengthened in the following areas. (1) Through the adjustment of industrial structures, cleaner production and repeated reuse and recycling of reclaimed water, cooling water and process water in industrial sectors should be encouraged to increase the utilization rate and recycling rate of industrial water and the water used by urban residents. At the same time, the proportion of drought-tolerant crop planting areas with low water consumption in the agricultural field should be actively increased. (2) Through water-saving and water retention engineering measures, river regulation should be accelerated, and the standards of diverse construction that can reduce leakage and evapotranspiration losses during the process of transferring water should be optimized. Based on the actual needs of crop irrigation, advanced irrigation systems, irrigation methods and dry land, water-saving and irrigation techniques (e.g. drip irrigation, sprinkler irrigation, micro-irrigation, mist irrigation, flooded irrigation and other techniques) that can reduce invalid losses through seepage and evaporation during the processes of irrigation and transferring water should be actively used.

## 5 Conclusions

This study highlights the importance of using the WRSR–DPSIR to diminish the increasing water supply and demand contradiction and to improve the efficient use of water resources. In the HRB, human activities are still intense, meteorological drought is serious, agriculture irrigation area has increased rapidly and ecological degradation in the lower reaches still exists. Overall, in the past 50 years, the runoff from the mountainous watershed of the HR has shown an increasing trend, but the total amount of watershed water resources has shown a decreasing trend. In addition to the risk of drought in recent years, the main reason for these trends is that water resources are strongly influenced by human activities, especially by agricultural water use. In the context of a changing environment, the sustainable and efficient use of water resources is a growing concern among policymakers. In order to reduce water scarcity risk, adaptation options need to be selected in a participatory way, in which one of the most important problems is determining how to scientifically optimize and allocate water resources, as well as how to make them sustainable and maximize their eco-social benefits. The water-related sectors should constitute and implement a set of strict laws and statutes concerning the protection of regional water resources to avoid the tragedy of developing economies in ecologically vulnerable areas that will destroy the eco-environment people highly depended on. Beyond this specific case area, our approach can serve as a reference for the scientific assessment of climate change and human impacts on water resources system in global arid regions. The study showcases not only the benefits of rational and sustainable water use but also the practical applicability of the DPSIR risk analysis model in dryland water management.

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