Environ Geol (2006) 50: 793–801
DOI 10.1007/s00254-006-0251-z

ORIGINAL ARTICLE

Xibin Ji
Ersi Kang
Rensheng Chen
Wenzhi Zhao
Zhihui Zhang
Bowen Jin

The impact of the development of water resources on environment in arid inland river basins of Hexi region, Northwestern China

Received: 8 February 2006
Accepted: 7 March 2006
Published online: 6 April 2006

X. Ji (✉) · E. Kang · R. Chen
W. Zhao · Z. Zhang · B. Jin
Laboratory of Watershed Hydrology and Ecology, Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Building 320, Donggang West Road, Lanzhou 730000, China
E-mail: xuanzhij@ns.lzb.ac.cn
Tel.: +86-931-4967156

Abstract Water resources use is a key parameter in the hydrological cycle, especially in arid inland of Northwest China, groundwater movement and circulation processes are closely related to the surface water, while recoverable and renewable groundwater mainly comes from the conversion of surface river water, and there is extensive transfer among rainfall, surface water and groundwater. Human activity, in particular, large-scale water resources exploitation and development associated with dramatic population growth in the last decades, has led to tremendous changes in the water regime. There are misuse and wastage of surface water with traditional multi-channel irrigation for most rivers, which in turn leads to over-exploitation of groundwater to augment supplies. This situation has been exacerbated by rapid population growth and socio-economic development, with decreased irrigational systems return to groundwater due to the irrigation system in the middle reaches of rivers in the Hexi region becoming better. The investigations of this study revealed that over the last decades, man-made oases have developed rapidly in various inland river basins. With the increasing human demand for water, the contradiction between water demand and water supply is becoming increasingly acute and the amount of groundwater usage significantly increased. Notwithstanding the annual surface water from mountains is relatively stable in the Hexi region, the recharges of groundwater have been reduced by 11.1%, with a maximum reduction of 50% in the Shiyang River basin. Groundwater abstraction increased by approximately six times, particularly in the Shiyang River basin, groundwater abstraction exceeds recharge by 4.1×10^8 m^3 $year^{-1}$ in recent decades. Consequently, the groundwater level has declined widely by 3–16 m, with a maximum decline of 45 m in several groundwater observation wells in the Minqin basin on the lower reaches of the Shiyang River basin. These cause serious human activity-induced environmental problems, such as water-quality deterioration, vegetation degradation, soil salinization and land desert desertification, etc. It is suggested that modernized irrigation technology and new regulation to cover water resources management and allocation with the river basins are urgently needed to achieve a sustainable development. The aim of this study is to analyze the impact of the development of water resources on the environment in arid inland river basins in

Northwestern China, which were analyzed by comparing the three main river basins (i.e., the Shuilei, the Heihe and the Shiyang River basins) with different water resources development cases.

Keywords Water resources development · Environment · Human activity · Arid inland river basin · China

Introduction

Water shortages have become an increasingly serious problem in China, especially in the arid inland zones of the northwest (Kang 2000; Ji et al. 2005a). Situated deep in the hinterland of Eurasia, the arid inland watersheds of Hexi region are one of the driest zones in the world (Kang et al. 2004). Water resources in the Hexi region are mainly distributed in a number of relatively independent inland river basins, of which the cold alpine areas are the runoff-forming regions, while the piedmont plains or basins are the runoff loss regions (Kang 2000; Gao et al. 2004; Gao and Wu 2004). Such topographic features and spatial distribution characteristic of runoff result in the unique hydrological and water resources systems in Northwest China. In the inland river basins of Hexi region, the hydrological processes in the arid areas and cold alpine areas are interrelated and interacted, and the extent of transformation between surface water and ground water is significant (Wang and Cheng. 1999; Ji et al. 2005b). Water resources in arid inland river basins of the Hexi region are not only valuable resources, but also an important environmental factor due to low precipitation and the dry climate (Ma et al. 2005b). Enormous volumes of water have been developed to supply the increasing economic development. Since the 1950s, human activity, in particular large-scale water resources exploitation and development associated with dramatic population growth in the last decades, has led to tremendous changes in the water regime (Ji et al. 2005b). The recharges of groundwater has been reduced by 11.1%, with a maximum reduction of 50% in the Shiyang River basin, and groundwater abstraction increased by approximately six times, particularly in the Shiyang River basin, groundwater abstraction exceeds recharge by 4.1×10^{8} m^{3} $year^{-1}$ in recent 50 years (Ding and Zhang 2002, 2004). Consequently, the groundwater level has declined widely by from 3 to 16 m, with a maximum decline of 45 m in several groundwater observation wells (Zhang 2005). These have led to the deterioration of groundwater quality, the degradation of vegetation, and an expansion of soil salinization and land desert desertification, etc. The results of research concerning the features of water resources changes and analyses problems of water resources development and its impact on environment are generalized. Also countermeasures are recommended, including overall planning, rational allocation of water resources exploitation and utilization, realizing the comprehensive management of regional hydro-ecologic cum socio-economic systems, and using water-saving techniques at a large scale to solve the water crisis in arid inland river basins of Northwestern China.

Study area description

The Hexi region (37°00′–42°40′N, 92°00′–104°20′E) lies in the transition zone between the monsoon and westerlies, and is an important location because of its ecological fragility and climatic sensitivity (Fig. 1). From the south to the north, there are three large terrain units: the Qilian and Altun mountains are over 4,500 m above sea level, the corridor plains with altitudes of around 2,000 m in the southwest and 1,500 m above sea level, the Alxa highland (from 1,500 m south to 1,300 m a.s.b), and the deserts to the north (about 1,300 m a.s.l.). From the east to the west, the water drainage can be divided into three large basin systems: Shiyang, Heihe and Shulei River basins. Annual precipitation drops from more than 500 mm in the southern mountains to less than 100 mm in the northern desert, with a mean evaporation rate of about 2,000 mm $year^{-1}$ (Ding and Zhang 2004). Seventy-five to eighty-five percent of rainfall occurred during the period July–August (Kang 2000). Annual mean temperature is 2–10°C. The vegetation is characterized by lower coverage degree and poor species, and soil by simple profile salinization, sandy and gravel texture. The landscape represents the vertical zones on the desert base in the southern mountains, irrigation oases and desert are inter-distributed in the corridor and artificial oases scatter in the vase desert in the northern highland.

Rivers of the Hexi region originating from the Qilian Mountains are ephemeral, and flow from south to north, through oases and disappear in the deserts to the north. The ice/snow melt-water from high altitude mountain zones is an important water supply to the rivers. Large volumes of unconsolidated Quaternary sediments were deposited in the foreland depression, creating large, high storage aquifers. The Quaternary basins can be divided into discrete geomorphologic units, including piedmont alluvial plain, alluvial lacustrine plain, and desert; and the sediment compositions gradually change from coarse-grained gravel to medium and fine-grained sand and silt, respectively. The Quaternary aquifers are closely interconnected with streams originating in the mountains. Transfer of surface water to groundwater

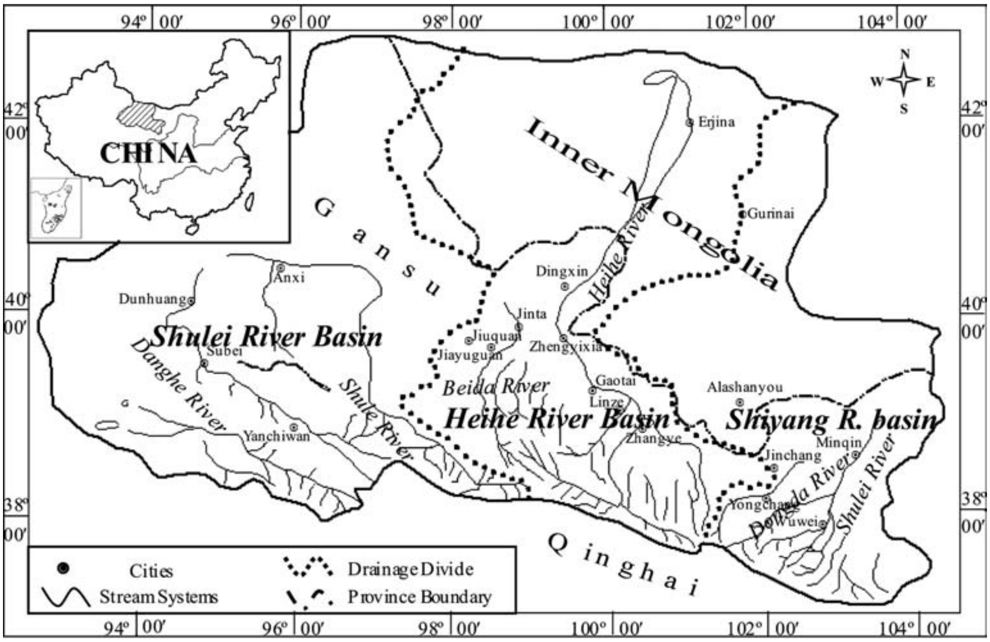

Fig. 1 Sketch map of the Hexi region with the distribution of different river basins, Northwestern China

and back in the Quaternary basins may be repeated many times. Consequently, a river basin can be regarded as a total hydrological system in which meteoric water; surface water and groundwater transfer between each other to form a complete water cycle.

Groundwater is recharged by vertically infiltrating surface water, meteoric water in the basin and laterally flowing fracture water in bedrock along the basin margins, as well as irrigation return flow. The limited precipitation in the plains of the river basins accounts for less than 7% of the total groundwater recharge (Gao and Wu 2004; Ding and Zhang 2002), the aquifer in inland river basins, to a large extent, is recharged by surface water via river infiltration, diversion canal systems seepage and farmland irrigation water seepage. In other words, surface water and groundwater are integrated in the middle and lower basins, and the upper, middle and lower reaches are united in using water resources. The water resources in the different parts of the basins are inseparably linked: the groundwater resources in the plain area are recharged from precipitation in the Qilian Mountains. Groundwater and surface water are closely linked due to the gradient and the uniquely permeable nature of the sediments near the mountains. To a large extent, the groundwater is transferred back to surface water before flowing out of the section. Surface water in the midstream of rivers therefore mainly comes from surface water and spring water originally present as short residence time groundwater within the alluvial and diluvial plain in the low flow periods.

Characteristics of water resources in the Hexi region

The water resources of Hexi region have the following characteristics:

1. Surface runoff originated from mountain decreases from the south to the north and from the east to the west, and flows towards and then disappears in the piedmont plains. Its distribution coincides with warm and humid seasons of the year. As practically no surface runoff occurs in the piedmont plain, precipitation and ice/snow melt-water from the mountains represent the renewable water resources available for the entire inland river basins. The total water resources are 7.68×10^9 m^3 in the Hexi region (Table 1). The variability of surface runoff (i.e., trunk stream and its tributaries) displays a large period of 30 years and the small fluctuations from 4–7 years (Fig. 2). Two-third of the surface runoff, forming in the mountains, changes to ground runoff and converges in the loose Quaternary deposition in the structural basins.
2. Surface water and groundwater are integrated in the middle and lower basins, and the upper, middle and lower reaches are united in using water resources. From the mouth of the mountains reaches to the piedmont plains, the surface soil's composition turns gradually from large-pore gravel deposit (in the diluvial fan group) to medium and fine sand and silt (in the fine earthy plain). This allows a large amount of surface water in the piedmont fans to seep down

Table 1 Water resources in the Hexi region

Basin	Area (km^2)	Rainfall (mm)	Ice/snow melt-water ($\times10^6$ m^3)	Surface runoff ($\times10^6$ m^3)	Groundwater ($\times10^6$ m^3)	Total water ($\times10^6$ m^3)
Shuilei R.	168,228	148	494	1,634	133	1,767
Heihe R.	60,623	121	98	3,777	455	4,232
Shiyang R.	41,347	91	85	1,570	115	1,685

and recharge groundwater. However, in the fine earthy plain belt, the groundwater overflows onto the surface in the form of spring water and is transformed into surface streams or rivers. Such transformation processes of surface water to groundwater to surface water in the plain region may be repeated many times until the water finally converge into the terminal lakes. Various water resources such as surface water, groundwater, and spring water, etc., have an inseparable internal relation in the formation cause (i.e., the precipitation in the mountains is their common source). Of the groundwater replenishment in the middle and lower reaches of the inland river basins in the Hexi region, 84% is transformed from surface water.

3. Because annual rainfall is less than 150 mm in the alluvial plain of the middle reaches and the desert plain of the lower reaches, the surface runoff emerging from the mountain regions is the lifeblood for economic development and maintenance of an environmental balance. The utilization of water resources in the upper, middle and lower reaches has become a closely integrated system. In any part of the river basins, the three factors—society, economy and environment are inseparable, and any improper use or distribution of water resources brought above by one factor will have repercussions for the other two factors.

Water resources development and hydrological effects

Water resources development

The water and land resources were then exploited wantonly; larger-scale water conservation and more and more agricultural oases were set up in virgin lands along

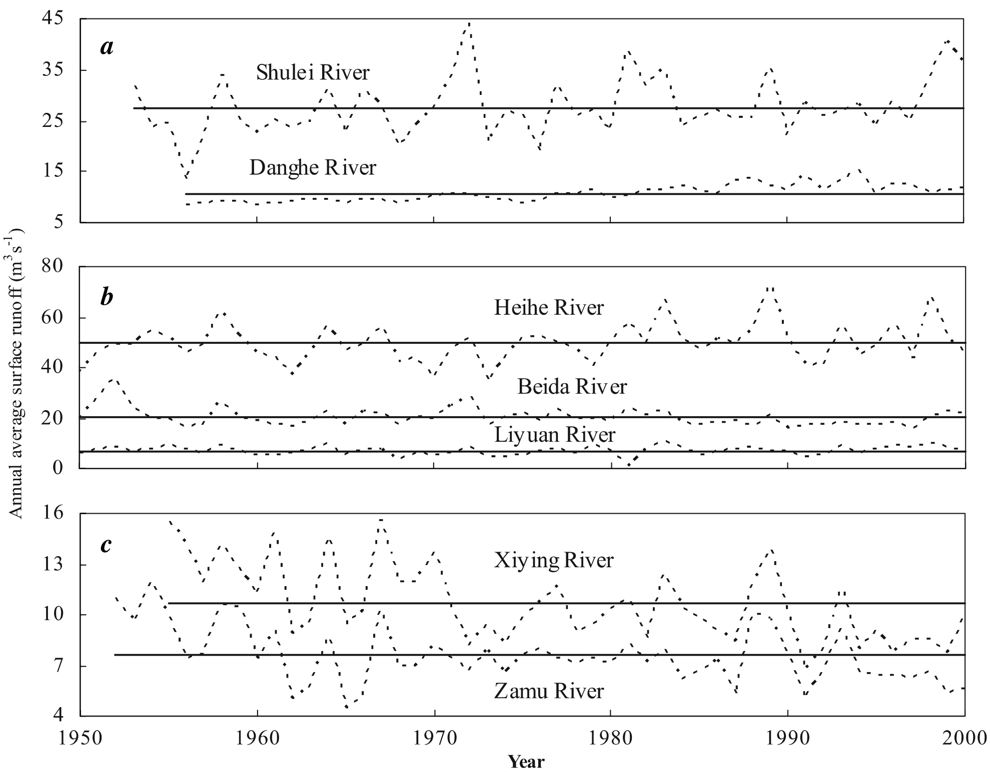

Fig. 2 Variation of surface runoff in the Hexi region from the available historic record: **a** Shulei, **b** Heihe, and **c** Shiyang River basin. *Continuous lines* refer to the long-period average discharge, *dashed lines* to the mean monthly discharge

Table 2 Water resources development in inland rivers basins of Hexi region

Water resources development	Year	1950s	1960s	1970s	1980s	1990s
Diversion surface water ($\times10^6$ m^3 a^{-1})	Shuilei R.	812	983	1,002	1,087	1,150
	Heihe R.	1,404	1,538	1,533	1,582	1,676
	Shiyang R.	703	752	779	807	868
	Total	2,919	3,273	3,314	3,476	3,694
Groundwater exploitation ($\times10^6$ m^3 a^{-1})	Shuilei R.	0		34	85	136
	Heihe R.	77		154	233	538
	Shiyang R.	185		676	931	1,137
	Total	262		864	12.49	1,811

the middle and lower reaches of the rivers after 1949, the new Peoples Republic of China. The irrigated area was only 361.8$\times10^3$ ha in 1949, but increased to 800$\times10^3$ ha (Ding and Zhang 2004). Simultaneously, the scale of surface water resources development in the Hexi regtion increased significantly (Table 2). The irrigation canals were also rapidly developed. For example, in the 1970s, in the Heihe and Shulei River basins, there were about 2,818.4 and 200 km of main and branch canals, but by the 1990s the total length had increased to 3,967.6 and 6,716 km, respectively (Ding and Zhang 2002). Accordingly, its channeled surface runoff in the 1990s amounted to 1.67$\times10^9$ and 0.89$\times10^9$ m^3 year^{-1}, respectively, which was about 44.2 and 54.5% of the total surface runoff originated from the mountain, respectively.

Since the 1950s, the exploitation amount of groundwater has also been increasing. For example, in the Shiyang River basin, the volume of groundwater exploitation increased from less than 0.19$\times10^9$ m^3 year^{-1} in 1950s to more than 1.1$\times10^9$ m^3 year^{-1} in the 1990s, and in the Heihe and Shuile River basins, the average annual increased by the rate of 9.22$\times10^6$ and 1.7$\times10^6$ m^3 year^{-1}. Note that there were 981 wells in the Hexi region, with a groundwater exploitation of about 0.26$\times10^9$ m^3 year^{-1} in the 1950s, but in the 1990s, the number of wells had reached over 25.5$\times10^3$, and groundwater abstraction had reached 1.8$\times10^9$ m^3 year^{-1}, far exceeding the 1.4$\times10^9$ m^3 year^{-1} groundwater recharge (Zhang 2005).

Hydrological effects

Due to large-scale water resources over-exploitation in the middle and lower reaches of inland river basins, water flow into the lower reaches has been cutoff due to the construction of channel diversion along rivers and also the diversion of water into farmlands. As a consequence, many rivers have been reduced to natural oases. Although the discharge of the inland rivers from mountains has remained at a stable level since the 1950s (Fig. 2), the flow into the lower reaches has decreased. In the 1950s, e.g., the annual discharge of the Shiyang River basin at the Hongya station into the Minqin plain was 0.57$\times10^9$ m^3 year^{-1} (Ma et al. 2005b), which accounts for 36.3% of the total runoff of the catchments. However, in the 1990s only 0.15$\times10^9$ m^3 year^{-1} out of 1.57$\times10^9$ m^3 year^{-1}, just 9.6% of the total runoff, reached the Minqin Basin. In the 1950s, the annual discharge of the Heihe River into the lower reaches was about 1.2$\times10^9$ m^3 year^{-1}; however, in the 1990s, it was less than 0.7$\times10^9$ m^3 year^{-1} (Gao and Wu 2004). As a result, groundwater in recent years has been extensively affected.

In recent 30 years, the dynamic processes of groundwater hydrology in inland river basins of the Hexi region have been disturbed by human activities. The disturbances are mainly manifested in the reduction of groundwater recharge caused by the increased use of river water and the over-abstraction of groundwater (Tables 2, 3). For example, the total groundwater recharge has greatly decreased in the past decades. Some 6.2$\times10^9$ m^3 year^{-1} water recharged the Quaternary aquifers of the inland river basin in the Hexi region in the 1950s, but less than 5.6$\times10^9$ m^3 year^{-1} in the 1990s, a reduction of 11.1%. In particular, for the lower reaches of the Shiyang River basin, groundwater recharge in the Minqin basin decreased by 75% from 0.5$\times10^9$ m^3 year^{-1} in the 1950s to 0.1$\times10^9$ m^3 year^{-1} in the 1990s (Ma et al. 2005b).

Secondly, over-exploitation of groundwater resources combined with surface water use has led to aquifer storage depletion and a decline in groundwater levels. In the alluvial–diluvial fan zone in the southern portion of the middle reaches of the Shiyang and Heihe River basin, since the 1950s the water table has declined annually by the rate of 0.6–1.0 m year^{-1}, with a maximum decline of 18–22 m seen at Xiying (Wuwei city) and Sanbao (Minle county). In the irrigation areas of middle reaches of river basins, owing to large-scale pumping wells, groundwater levels have declined obviously. For example, at the fine earthy plain and the gravel-plain, groundwater levels have declined annually at a rate of 0.3–0.7 and 0.1–0.4 m year^{-1}, respectively. From 1992 to 2000, at Changma irrigated district in the Shulei River basin, the fluctuation of groundwater levels was characterized by the decline of 1.2–5.7 m, with a maximum decline of 3 m at the Anxi-Dunhuang basin, the lower reaches of Shuilei River basin, which resulted in a

Table 3 Changes in the recharge of groundwater in different basins

Year	Groundwater recharge resources ($\times 10^6$ m^3)					
	Stream seepage	Diversion channel seepage	Irrigated fields infiltration	Lateral inflow in mountains	Precipitation penetration	Total recharge
1955s	2,570.2	2,283.9	838.7	264.4	284.1	6,241.3
1970s	2,343.9	2,177.9	976.2	264.4	284.1	6,046.5
1999s	2,259.7	1,701.9	1,041.3	264.4	284.1	5,551.4

remarkable reduction in surface area of the Yueyaquan lake, well known at the Dunhuang city, with its surface area reduced by 90%. In the terminal lake area, the lower reaches of inland river basins, the fluctuations of the groundwater table are still in a largely natural state, except for the Shiyang River basin (i.e., groundwater levels with a decline of 18–22 m). According to some incomplete statistical data from the recent investigation reports, due to continuous decline of regional groundwater levels, in the Zhangye and Wuwei region of the middle reaches of Heihe and Shiyang river basins, all wells less than 20 m depth have been exhausted and abandoned, about 60–80% of wells with 30–50 m depth have been exhausted and the average volume of discharge of wells with more than 60 m depth were reduced by 10–30%.

Consequently, increasing utilization of water resources has also led to great temporal and spatial changes in the inner-annual water distribution and groundwater recharge across the upper, middle and lower reaches, which in turn has resulted in serious groundwater and environmental problems.

Environmental impact

Water-quality deterioration

The quality of shallow groundwater has deteriorated with increasing mineralization caused by the decrease of runoff and the significant evaporation occurring in the lower reaches of the different river basins. The groundwater in the study area is of alkali-sulphate type in the recharge area, changing to alkali-sulphate-chloride type along the groundwater flow direction and finally becoming sodium chloride type at the terminal lake (Table 2) (Ding and Zhang 2002). Increased water consumption has accelerated the transfer of water between surface water and groundwater stores, which have led to significant salinization of groundwater, especially in the Shiyang River basin. For example, the average total dissolved solids (TDS) of groundwater increased from about 2 g l^{-1} during the period of the 1950s to 4–6 g l^{-1} in the 1990s in the Minqin Basin; the maximum was 16 g l^{-1} in the lake of Mingqing oasis (Li et al. 2004, Ma et al. 2005a); In the lower reach of Heihe River basin, Ejina oasis, the average TDS of shallow groundwater increased by 50%, up to 0.8–1.2 g l^{-1} in the 1980s and 2–3 g l^{-1} at the beginning of the 2000s (Nie et al. 2005).

In addition, significant groundwater pollution was noted in different river basins. The present study indicates that the groundwater is of bad chemical quality. The majority of samples are beyond the permissible drinking limits of WHO, which have higher chloride and sodium than permissible limits. These include shallow and deep groundwater. Iron and other heavy metals such as Pb, Cd, Cr, Zn, Hg and Ni, also exceed the permissible limits in some shallow groundwater samples. The levels of COD (chemical oxygen demand), BOD (biological oxygen demand) and total bacteria are constantly increasing and have exceeded national standards for second grade water quality. Domestic, industrial and agricultural activities are responsible for the high concentrations of heavy metals in the groundwater (Table 4).

Vegetation degradation

Increasing utilization of water resources has also led to great temporal and spatial changes in the inter-annual water distribution and groundwater recharge across the upper, middle and lower reaches, which in turn has resulted in serious environmental problems. Due to the changes in inland basin hydrological regimes, vegetation has been seriously degraded or destroyed (Ma et al. 2003). There are many dry riverbeds with degraded vegetation, and the hydrophytes and swamp vegetation that once grew in large areas have declined or dried out. For example, according to recent data, the natural shrub forest distributed along riparian regions in the Minqin basin, the lower reaches of Shiyang River, which in the 1950s comprised an area of 133.6 thousand hectares (Li et al. 2004), and consisted of shrub forest dominated by species such as *Haloxylon ammodendron*, *Tamaric chinensis Lour*, *Nitraria Sibirica Pall*, *C.korskinii*, *Tangutorum* and *Elaeagnus angustifolia*, had been reduced to 71.2 thousand hectares in 1999 (Lu et al. 2001). Another 17.2 thousand hectare of *Elaeagnus angustifolia* and 27.4 thousand hectare of shrub forest distributed on the edge of the desert oasis present in

Table 4 Variation of water quality in the Hexi region (from the result of Ding and Zhang (2002))

Water type	Alluvial fan		Fine earthy plain		Water retention zone		Terminal region	
	TDS (g l^{-1})	Water chemical type	TDS (g l^{-1})	Water chemical type	TDS (g l^{-1})	Water chemical type	TDS (g l^{-1})	Water chemical type
Surface	0.3–0.7	HCO_3–Ca–Mg	0.6–1.0	HCO_3–SO_4–Ca–Mg	0.9–1.8	SO_4–HCO_3–Ca–Na	2.0–55.0	SO_4–Cl–Na–Mg
Shallow	0.2–0.8	HCO_3–Ca–Mg	0.5–1.1	HCO_3–SO_4–Ca–Mg	1.3–2.8	SO_4–HCO_3–Ca–Na	3.0–16.0	Cl–SO_4–Na–Mg
Deep	< 0.5	HCO_3–Ca–Mg	0.4–0.9	HCO_3–Ca–Mg	0.8–2.7	SO_4–Cl–Na–Ca		SO_4–HCO_3–Mg–Na

1959 (a total of 44.6 thousand hectare) have been reduced to 30.2 thousand hectares in 1999 (Meng et al. 2003). In addition, about 43.6% of 1.02×10^6 ha available grassland in the basin has either disappeared or been degraded as a result of the reduction in groundwater level (i.e., plant with shallow root) (Guan and Wang 2002).

Before 1950, in the lower reaches of Heihe River basin, there were large-scale and exuberant scrublands and meadows composed of *Elaeagnus angustifolia L.*, *Populus diversifolia Schrenk*, *Tamarix ramosissima Ledeb*, *Phragmites communis Trin.*, *Achnatherum splendens Nevski*, etc., which covered the whole triangular district of Ejina; however, today the area of the natural forests wood species such as *Elaeagnus angustifolia L.*, *Populus diversifolia Schrenk* were reduced by 57.6 thousand hectares, about 3.3×10^6 ha available grassland has disappeared (Jin and Zhang 2003). In the Zhangye region of the middle reaches, there were over 0.12×10^6 ha of hydrophytes or swamp vegetation and a grass yield of 1,200–1,800 kg ha^{-1}; however, today the area has been reduced to 50×10^3 ha and grass yield to 450–550 kg ha^{-1} (Hou et al. 2004).

In the Shulei River basin, there were thick stands of shrubbery distributed around the west lake in Anxi with the area of 33.8×10^3 ha; however, today it grows poorly and reduced to 0.56×10^6 ha (Meng et al. 2003). Especially, there are many hydrophytes and swamp vegetation that once grew along the Shuilei River riverbed and around the Yanbozi Lake that have dried out; and these regions have evolved as landscape with the sandy wind erosion. In the recent 30 years, over 82.6% of 87.6×10^3 ha grassland in the middle reaches of Shiyang River basin has either disappeared or been degraded (Ding and Zhang 2002).

Soil salinization and land desertification

In the middle reaches of arid inland river basins of the Hexi region, almost 84% of the total surface runoff has been diverted for irrigation, which has not only made the groundwater level to rise inside the cultivated oases but has also increased the salinized area (Gao and Wu 2004). Many river courses of inland rivers in the Hexi region are now dry and show a marked decline in vegetation with the formation and encroachment of sand dunes (Ding and Zhang 2004). The changes in hydrological status and the degradation of vegetation have promoted land desertification and soil salinization in the entire middle and lower reaches of inland river basin. The phenomena of soil salinization and land desertification have significantly increased in recent decades. Comparison of air photos taken in the 1950s and 1990s showed that the area of desertification has increased by 1.6×10^6 ha from the 1950s to 1990s, and the salinized area has increased by 0.2×10^6 ha in the middle reaches of Hexi regions (Wang 2000). Especially, in the lower reaches of Shiyang River basin, the land area of soil salinization has increased from 17.4×10^3 ha in the 1950s to 36.7×10^3 ha in the 1990s (Ma et al. 2005b), particularly around the Minqin Lake. The area of alkali-saline and salinized cultivated land now is 15.4×10^3 ha, which accounts for 42% of the total cultivated land (Yang 2002). From the 1950s to 1990s, the area of desertification has increased by over 901.7×10^3 ha and the salinized area has increased by 29.6×10^3 ha in the middle reaches of Heihe River basin (Meng et al. 2003). In the region of the Ejina oasis of the lower reaches, 30.7×10^3 ha of cultivated land has been reduced to only 3×10^3 ha and the rest of the cultivated oasis has turned into desert (Lu et al. 2001). Since the 1960s, the area of degraded forest and desertified grassland has increased by 350.9×10^3 ha, equivalent to 54% of the total cultivated land area in the triangle district (Jin 2005). Desertification is expanding at a rate of about 11–13×10^3 ha year^{-1}. In 1995, the area of salinized and desertified lands reached 57.2×10^4 and 1555.3×10^4 ha, respectively, accounting for 70.8% of the total area of the whole river basin. In addition, from the 1950s to 1990s, the area of desertification has increased up to 133×10^3 ha in the Shulei River basin (Jin and Zhang 2003).

Conclusions

In the inland river basins of Hexi region (i.e. Shuile, Heihe and Shiyang River basins), situated in the typical arid area of Northwestern China, large volumes of unconsolidated Quaternary sediments were deposited in the foreland depression, creating large, high storage aquifers. The Quaternary aquifers are closely interconnected with streams originating in the mountains. Transfer of surface water to groundwater and back in the Quaternary basins may be repeated many times. A river basin can be regarded as a total hydrological system in which meteoric water, surface water and groundwater transfer between each other to form a complete water cycle. Consequently, increasing utilization of water resources has also led to great temporal and spatial changes in the inner-annual water distribution and groundwater recharge across the upper, middle and lower reaches, which in turn has resulted in serious environmental problems, such as water-quality deterioration, vegetation degradation, soil salinization and land desert desertification, etc. The development of the middle reaches of the aquifer system is taking place at the expense of environmental degradation of the lower reaches. The economic development of the upper reaches is occurring at the cost of destruction of the ecology and environment in the arid lower reaches. In particular, the inland river basins have seen over-exploitation of water resources due to a lack of rational planning and effective water saving measures.

The surface and its closely related or transformed form, groundwater, are the link between socioeconomic development and environmental protection in the upper, middle and lower reaches of the rivers. All of these reaches must be viewed as a closely integrated system in planning the use of water resources. Therefore, it is necessary to correctly understand and evaluate the environmental capacity and the quantity and quality of water resources in the area. Co-operation between and the upper, middle and lower reaches of inland river basins is needed in the exploitation, use, management and protection of water resources. To promote rational utilization of the limited water resources, the waste of water in the middle reaches should be minimized by popularizing water-saving irrigation techniques, and regulating water distribution. To alleviate the degradation of the environment, a holistic overview of the economy, ecology and society should be developed to encourage ultimate efficiency. A guide for the use of water resources should be utilized rationally and comprehensively, as well as permitting water flow into the lower reaches to maintain an ecological balance.

Over-exploitation of groundwater and decreased groundwater recharge inevitably leads to groundwater depletion, increase in depth to groundwater, and loss of desert vegetation that depends on shallow groundwater. For sustainable human development, it is essential that the long-term average recharge rates for groundwater storage be considered as the limit for the water extraction. If the development and use of groundwater resources cannot be balanced by surface water and recharge inputs, the development will not be sustainable and will result in an ecological calamity.

For these reasons, great efforts are being made to study the influence of human activities in the exploitation and utilization of water resources and the eco-environment, and then to establish a decision-making system for highly effective sustainable use and scientific management of water resources in the inland river basins. Therefore, the rational use of the limited water resources and the limiting of environmental degradation have become an urgent problem that needs to be solved.

Acknowledgements This project was supported by the Chinese Academy of Sciences (Grant Nos. KZCX3-SW-329), the Knowledge Innovation program Foundation (Grant Nos. CACX2003102) from Cold and Arid Regions Environmental and Engineering Research Institute, CAS., and the National Natural Science Foundation of China (Grant Nos. 40401012). The authors are grateful to the Inland hydrological Observational and Experimental Station, CAREERI, and also to the reviewers and issue editor of the journal for their valuable comments, suggestions, and revisions to this manuscript.

References

Ding HW, Zhang HS (2002) Changes of groundwater resources in recent 50 years and their impact on ecological in Hexi Corridor. J Nat Resour 17(6):691–697

Ding HW, Zhang J (2004) Relationships between sustainable development and water resources in arid oases area-an example of Hexi corridor. J Arid Land Resour Environ 18(6):50–55

Gao QZ, Wu YQ (2004) Analysis of water cycle in inland river basins in Hexi region. Adv Water Sci 15(3):391–396

Gao QZ, Li XY, Wu YQ, Hu XL (2004) Transformation of water resources in the inland River basins of Hexi Region. J Glaciol Geocryol 26(1):48–54

Guan HP, Wang SH (2002) Analysis on the condition of the water resources and environment in Hexi Corridor, Gansu Province, China. J Lanzhou Railway Univ (Nat Sci) 21(4):17–21

Hou XY, Chang B, Yu XF (2004) Land use change in Hexi Corridor based on CA-Markov methods. Trans CSAE, 20(5):286–291

Ji XB, Kang ES, Cheng RS, Zhao WZ, Zhang ZH, Jin BW (2005a) Estimation of ground water budget at the representative irrigated area in the middle stream of Heihe River. Hydrogeol Eng Geol 32(6):25–29

Ji XB, Kang ES, Zhao WZ, Cheng RS, Xiao SC, Jin BW (2005b) Analysis on supply and demand of water resources and evaluation of the security of water resources in irrigation region of the middle reaches of Heihe River, Northwest China. Sci Agric Sin 38(5):974–982

Jin XM (2005) The variability of natural vegetation area in the Heihe River basin, north-west China. Earth Sci Front 12(Supply):166–169

Jin ZX, Zhang FQ (2003) Impact of water resources change to environment and ecology in Hexi Corridor. J Soil Water Conserv 17(1):37–40

Kang ES (2000) Review and prospect of hydrological studies in cold and arid regions of China. J Glaciol Geocryol 22(2):178–188

Kang ES Li X, Zhang JS, Hu XL (2004) Water resources relating to desertification in the Hexi area of Gansu province, China. J Glaciol Geocryol 26(6):657–667

Li XY, Zhang F, Xiao DN (2004) Comparison on landscape dynamics of Wuwei oasis and Minqin oais in middle and lower reaches of Shiyang-River watershed. J Soil Water Conserv 18(5):151–162

Lu l, Li X, Cheng GD, Xiao HL (2001) Analysis on the landscape structure of the Heihe River basin, Northwest China. Acta Ecol Sin 21(8):1217–1224

Ma MG, Dong LX, Wang XM (2003) Study on the dynamically monitoring and simulating the vegetation cover in Northwest China in the past 21 years. J Glaciol Geocryol 25(2):232–236

Ma JZ, Li XH, Huang TM, Edmunds WM (2005a) Chemical evolution and Recharge characteristics of water resources in the Shiyang River basin. Resour Sci 27(3):117–122

Ma JZ, Wang XS, Edmunds WM (2005b) The characteristics of ground-water resources and their changes under the impacts of human activity in the arid Northwest China—a case study of the Shiyang River Basin. J Arid Environ 61:277–295

Meng JJ, Li ZG, Wu XQ (2003) Land use changes of Hexi Corridor between 1995 and 2000. J Nat Resour 18(6):645–651

Nie ZL, Chen ZY, Cheng XX, Hao ML, Zhang GH (2005) The chemical information of the interaction of unconfined groundwater and surface water along the Heihe River, Northwestern China. J Jilin Univ (Earth Sci Edn), 35(1):48–53

Wang T (2000) Land use and sandy desertification in the North China. J Desert Res 20(2):103–106

Wang GX, Cheng GD (1999) Water resource development and its influence on the environment in arid areas of China—the case of the Hei River basin. J Arid Environ 43:121–131

Yang XP (2002) Water chemistry of the lakes in the Badain Jaran Desert and their Holocene evolutions. Quat Sci 22(2):97–104

Zhang HS (2005) A brief introduction of the changes in groundwater resources in the Hexi Corridor. Hydrogeol Eng Geol 32(4):81–84