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Spatial variations of river–groundwater interactions from upstream mountain to midstream oasis and downstream desert in Heihe River basin, China

Yi Cai, Wenrui Huang, Fei Teng, Beibei Wang, Ke Ni and Chunmiao Zheng

ABSTRACT

The Heihe River basin consists of three different characteristic regions: upstream mountain area, midstream oasis region, and downstream desert region. Understanding the river–groundwater interactions in different river reaches is important for sustainable water resources management. In this study, river–groundwater interactions in three different river regions are investigated by the analysis of geophysical characteristics, meteor-hydrological characteristics, agricultural irrigations, and channel water balance equation in the river reaches in different seasons. Results indicate that the river–groundwater interactions vary geographically in the three different regions, and change seasonally with the strongest interactions during the summer. Groundwater discharges into the river in the upstream mountainous reach (annual $2.57 \times 10^8\ m^3$) while the river water seeps into aquifers in the downstream desert reach (annual $10.39 \times 10^8\ m^3$). In the midstream oasis region, pumping water for agriculture irrigation significantly affects the river–groundwater interaction. The river loses water to the ground during the major- and medium-irrigation periods, and gains water from groundwater during the minor-irrigation period in the midstream reach. The characteristics of the river–groundwater interactions are primarily dominated by physiographic features and precipitation in the upstream mountainous region, by human activities and precipitation in the midstream oasis region, and by evaporation and human activities in the downstream desert region.

Key words | desert, Heihe River, mountain, oasis, river–groundwater interaction

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INTRODUCTION

With changing climate, increasing population and developing economy, water has become increasingly scarce in river basins worldwide, especially in semi-arid and arid areas, and this has triggered many environmental problems such as land desertification and ecosystem degradation (Botes *et al.* 2003; Marquès *et al.* 2013; Qin *et al.* 2014). For sustainable use of water resources, it is important to understand hydrologic processes such as rainfall, surface water and groundwater flow in river basins. Considering the contrast in spatio-temporal scales in which these (i.e., surface water and groundwater) processes operate, these processes have been commonly studied as independent of each other. However, as the two important components of the hydrologic system, rivers and aquifers interact in basic ways: rivers gain water from aquifers through the riverbed, they lose water to aquifers through the riverbed, or they gain in some reaches and lose in others. There is, therefore, a growing concern with river–groundwater interaction in hydrologic studies and basin-scale water resources management.

In recent years, some studies have been carried out to understand the interaction between rivers and groundwater and its driving factors on a basin scale. The work of Boyraz & Kazezyılmaz-Alhan (2014) indicate that the geometric parameters of streams such as slope and flow path of streams are influential in defining stream–groundwater interactions. A theoretical and modeling method was employed by Brunner

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et al. (2009) to quantify the influence of hydrogeological parameters (e.g., groundwater table depth, the thickness and hydraulic conductivity of the clogging layer) on the river–groundwater connection status. Vegetation plays an important role in the river–groundwater interaction by forming an unsaturated zone between surface water and groundwater and affecting the connection state (Banks et al. 2011; Srivastava et al. 2014). Soil is one of the factors governing the moisture exchange between soil water and groundwater and, consequently, affects the surface water–groundwater interaction (Zhu et al. 2013; Zang et al. 2013). Land use conditions are critical for the hydrology and ecology of river basins and the variations in land use could alter the flow processes of surface water and groundwater (Moiwo & Tao 2014; Ratha & Sarkar 2015). The effect of climate change on river–aquifer interactions is also well documented (Chen et al. 2011; Wang et al. 2011; Zhang et al. 2011; Leterme et al. 2012; Bourgault et al. 2014; Xu et al. 2014). The interactions between a river and an aquifer are governed to a large extent by physiography such as terrain and geology (Radhakrishnan & Elango 2011; Ali et al. 2012). In addition, human activities including agricultural development, urban construction, water withdrawal, drainage of the land surface and modification to river valleys is broad, which affect the interaction of surface water and groundwater (Winter et al. 1998; Zhou et al. 2003; Hu & Jiao 2010; Wang & Hejazi 2011; Wu et al. 2013; Li et al. 2015).

Based on these recent studies, it is indicated that many factors, including natural conditions and human activities, can affect river–groundwater interaction. However, most existing studies focus on surface water–groundwater interaction at field scale or in a relatively small basin. For large river basins that span over a wide range of hydrogeological and climate conditions like the Heihe River basin in Northwest China, very few studies have been done to reveal how the river–groundwater interactions vary in different regions such as mountain, oasis, and desert, and how human activities may affect the river–groundwater interactions in such large-scale river basins (Srivastava et al. 2014).

In view of gradual environmental deterioration and complex hydrologic characteristics of the Heihe River basin, the impact of natural conditions and human activities on the hydrologic cycle has been a great concern for researchers and government recently. Qin et al. (2013) reported the runoff characteristics varying with the forest coverage in the upper Heihe River basin. The effect of climate change on water resources in the Heihe River basin has been investigated by many researchers (Li et al. 2013; Wang et al. 2013). Furthermore, there have been some past studies focusing on the relation between other factors (e.g., land use, terrain, pedologic characteristics, and human activities) and the hydrologic behavior of the Heihe River basin (Wang et al. 2007, 2010; Xi et al. 2010). As far as the river–groundwater interaction is concerned, the previous studies mostly report the interaction between surface water and groundwater in the middle oasis reach or the lower desert reach of the Heihe River basin. A three-dimensional groundwater flow model was established by Hu et al. (2007) to simulate the hydraulic connection between aquifers and rivers in the midstream region of the Heihe River basin and analyze the discharge exchange among springs, rivers, and groundwater. Akiyama et al. (2007) used the isotope data of water collected from the Heihe River to analyze the surface water–groundwater interaction in the lower desert reaches and its seasonal variation. Results show that surface water is available in the lower desert reaches throughout the non-irrigation period while it is often dried up during the irrigation period. Owing to the deficiency of observation data, such as groundwater level and hydrogeologic characteristics, it is very difficult to develop the numerical model to simulate the river–groundwater interaction in the upstream region of the Heihe River basin.

A river constitutes a continuum of physical environments and associated ecological communities (Vannote et al. 1980). The continuum influences the hydrological processes of a river system in which downstream processes are linked to upstream processes. Although previous studies have provided valuable information about the river–groundwater interactions in the middle or lower reaches of the Heihe River, it is necessary to study the hydrologic behavior of all the three regions together to gain insight on spatial variability in river–groundwater interactions within a river basin and identify primary controls over these interactions, which is beneficial to a basin-wide integrated water resources management.

The objective of the study is to investigate the variations of river–groundwater interactions from upstream mountainous region to midstream oasis region and downstream desert region in the Heihe River basin. Geophysical and hydrometeorological data, as well as agricultural irrigation records, are analyzed to characterize the difference in the three different regions. A river water balance is used to quantify the spatial and temporal exchange between river and groundwater flow in different regions during different seasons. Through the analysis of river–groundwater interactions, some water management recommendations are discussed. Results from the study are expected to provide some reference for water resources research and management in other river basins with complex hydrologic characteristics.

STUDY AREA AND DATA

Study site

The Heihe River with a length of 821 km is the second largest river in the interior of Northwest China. It originates in the Qilian Mountains and flows to the Gobi desert. Annual precipitation of the Heihe River basin is approximately 300–500 mm in the upstream mountain area and 30–50 mm in the downstream desert area. The basin is, therefore, generally classified into three regions: the upstream mountain area, the midstream oasis irrigation area, and the downstream desert area, as illustrated in Figure 1. Notwithstanding abundant freshwater from the melting of snow and glaciers in the mountains, a series of environmental issues such as water shortage and lake extinction have been triggered in middle-lower Heihe River reaches due to the changing climate, a growing population, and the overuse of water resources for agricultural irrigation in recent decades (Wang & Cheng 1998; Qi & Luo 2005; Xiao & Cheng 2006; Yang *et al.* 2006).

Available data

Topography

A 30-meter-resolution elevation data set from ASTER, covering latitudes 37 ° N to 44 ° N and longitudes 96 ° E to 105 ° E,

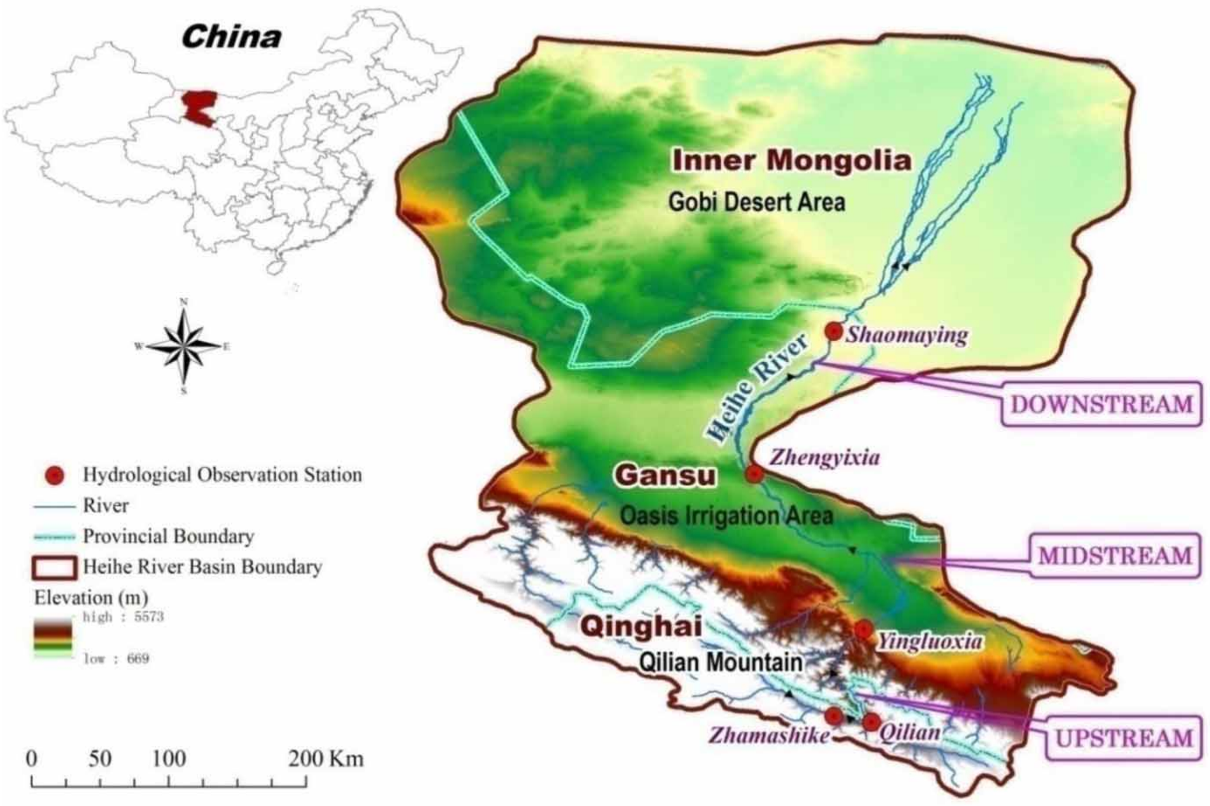

Figure 1 | The upstream mountain, midstream oasis, and downstream desert regions in the Heihe River basin.

was collected to prepare the digital elevation model (DEM) of the study area. Through overlaying of layers including DEM, water system, and hydrological observation stations, elevation values of some control points along the main channel of the Heihe River are extracted in a geographic information system (GIS) environment. As shown in Figure 2, the elevation substantially changes from upstream to downstream along the Heihe River. The elevation is higher than 1,700 m (National Vertical Datum 1985) in the upstream reach (ending at Yingluoxia Station), between 1,200 and 1,700 m in the midstream reach (from Yingluoxia to Zhengyixia Stations), and lower than 1,200 m in the downstream (beginning from Zhengyixia Station). Therefore, it is obvious that the slope is much steeper in the upstream reach than those in midstream and downstream along the main channel flow direction.

Three cross sections were selected to characterize the variations of lateral slopes in upstream, midstream, and downstream regions. According to the approach proposed by Gichamo *et al.* (2012), the three representative cross sections (i.e., A-A', B-B' and C-C') of the Heihe River are extracted based on DEM data, and are graphically described in Figure 3. It shows that the lateral slope is much steeper in the upstream reach than those in the midstream and downstream reaches. Mild lateral slope appears in the midstream reach, and near-flat lateral slope occurs in the downstream desert reach.

Soil type

A soil texture map of 1:1,000,000 (Lu *et al.* 2011) was obtained from the Cold and Arid Regions Science Data Center at Lanzhou (http://westdc.westgis.ac.cnb). In order to clearly depict the distribution of various soils hydrologically connected with the river course studied from Zhangmashike Station to Shaomaying Station, the hydrology tools provided in ESRI ArcGIS were employed to delineate the boundaries of the three catchments that pertain to the upstream, midstream, and downstream reaches of the Heihe River (Childs *et al.* 2004). Considering the description of geohydrologic characteristics of different soils, all soil types available in the digital soil map are classified into four groups: high-permeability soil (sand, loam sand, and sandy loam), medium-permeability soil (sandy clay loam, loam, and silt loam), low-permeability soil (clay loam, clay, and silty clay) and impermeable rock, based on the work of Rawls *et al.* (1982). Figure 4 gives the soil distribution from the upstream to downstream region of the Heihe River basin. It is found that the soil type of the Heihe River basin varies geographically. Soil is extensively

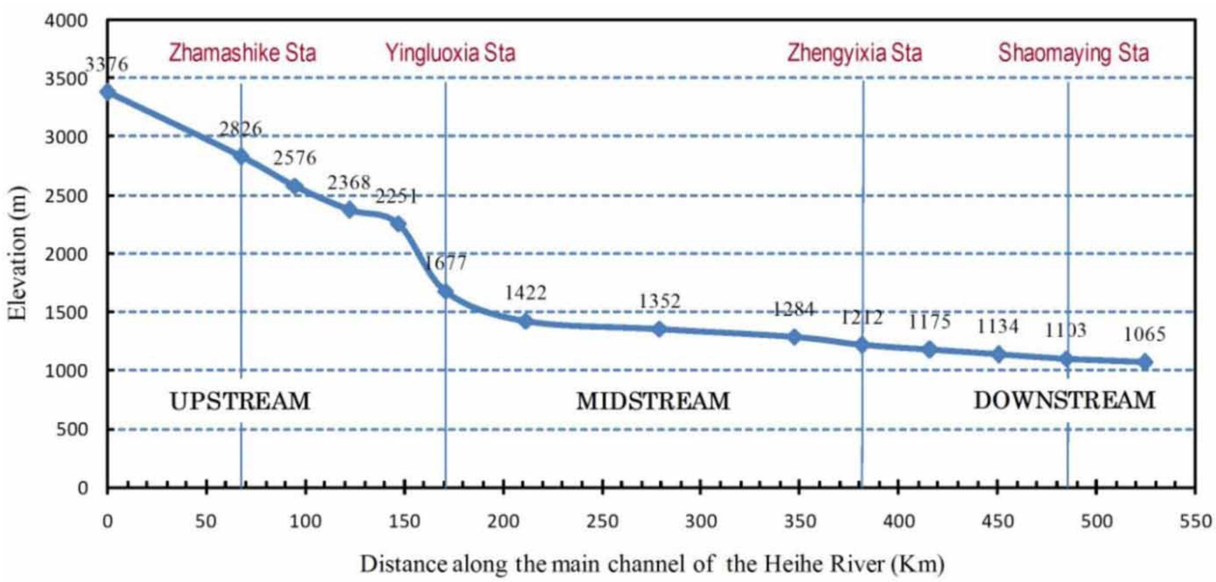

Figure 2 | Elevation changes along the river, showing substantial reduction of channel slope from the upstream to downstream reach.

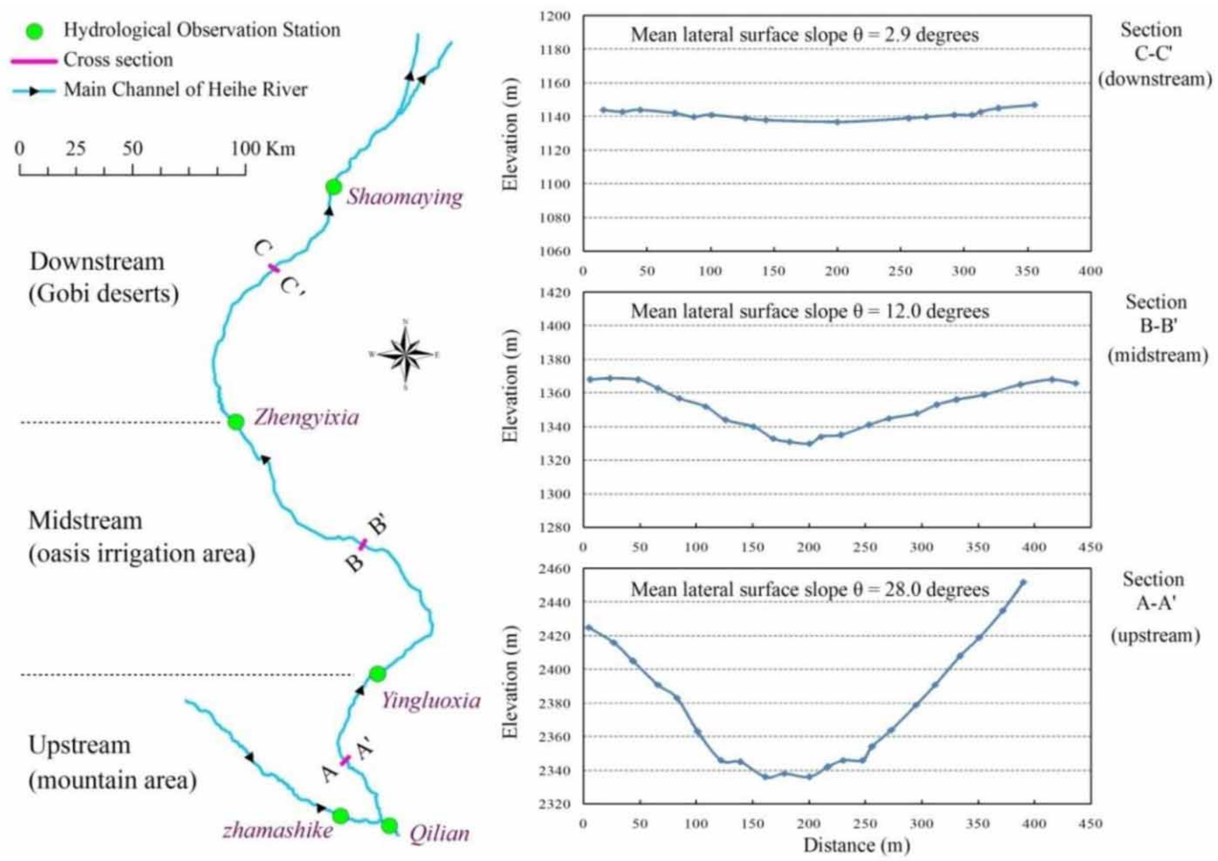

Figure 3 | Variations of lateral elevations across the river, showing steeper lateral slope in upstream mountain, mild slope in midstream oasis, and nearly flat slope in downstream desert reach of the Heihe River.

distributed in the basin while rock rarely is. Furthermore, low-permeability soil is mainly distributed in the downstream region of the basin.

Land use

The 1:100,000 land-use data in 2000 (Wang *et al.* 2001) were collected from Cold and Arid Regions Science Data Center at Lanzhou. The data were processed to generate the digital land use map of the study area where land use is classified into 10 categories: (i) agricultural land; (ii) forest; (iii) grass; (iv) urban area; (v) water body; (vi) Gobi; (vii) desert; (viii) saline-alkali land; (ix) marshland; (x) bare land. Figure 5 displays the distribution of land use in 2000 from the upstream to downstream region of the basin studied. It is apparent that forest is mostly distributed in the upstream mountain areas. Agricultural land is concentrated in the midstream region and near the boundary between the midstream and the downstream. Desert areas are extensively distributed in the downstream region.

Precipitation

In order to investigate the variation of precipitation with space and time, the daily rainfall data from 2004 to 2008 were collected from 13 rain gauges scattered across the study area. Thiessen polygons, as illustrated in Figure 6, were created to calculate areas related to specifically placed rain gauges and then compute respectively the weighted average amount of precipitation that fell in the upstream, midstream, and downstream regions of the Heihe River basin (Croley II & Hartmann 1985; Cai *et al.* 2012). Figure 7 shows the variation curves of average precipitation for the three regions studied. It is obvious that three curves share a similar changing trend which implies that the rainfall in the basin is mostly concentrated in summer

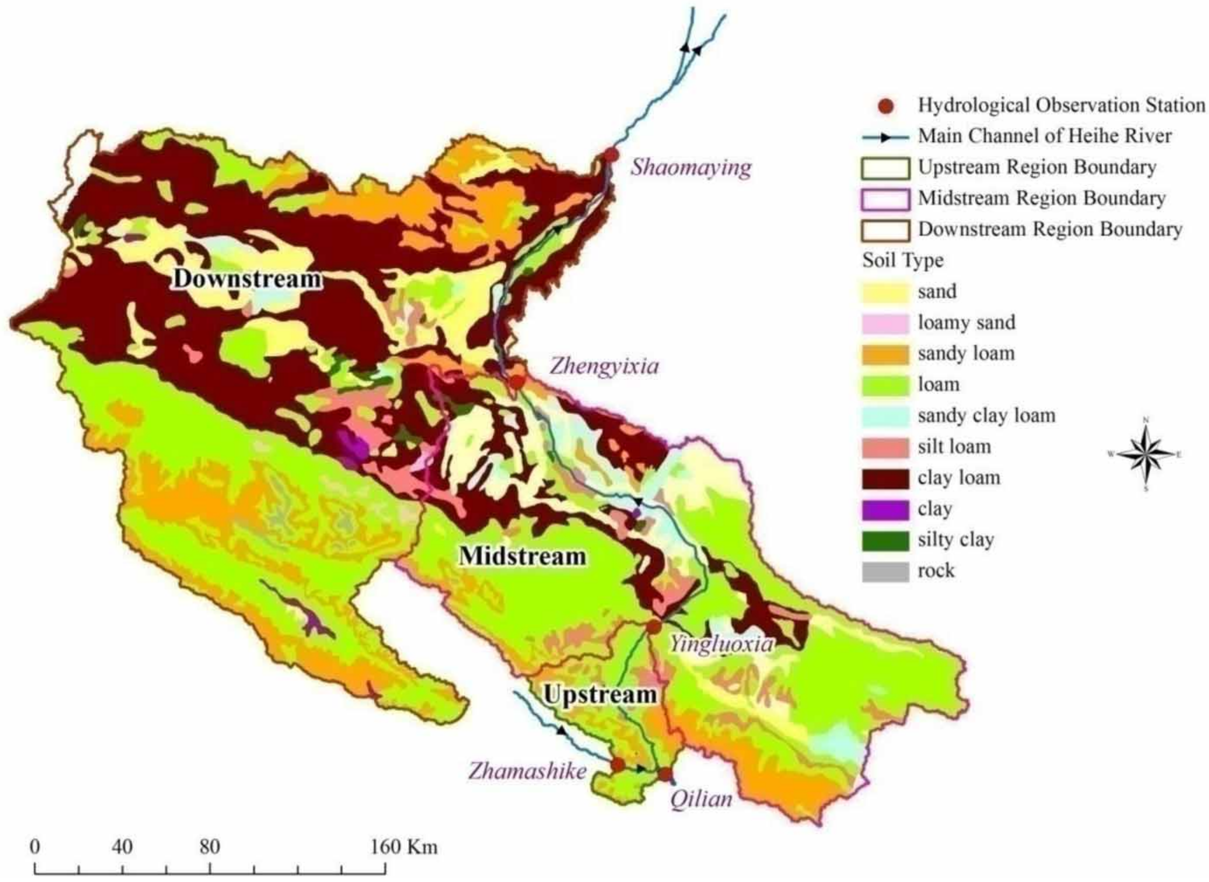

Figure 4 | Distribution of soil type in the upstream, midstream, and downstream regions of the Heihe River basin.

from June to September. In view of the significant influence of human activities on surface water and groundwater in arid inland river basins (Bao & Fang 2012; Liu *et al.* 2013), a calendar year is divided into three periods in the investigation: (A) Period-I (major agricultural irrigation season from June to September), (B) Period-II (medium agricultural irrigation in spring and autumn), and (C) Period-III (minor agricultural irrigation season from December to next March).

River flow

Observed river flow at five hydrological observation stations (see Figure 1) were selected to analyze the hydrological characteristics of the upstream, midstream, and downstream reaches of the Heihe River. The stations include Zhamashike Station, Qilian Station, Yingluoxia Station, Zhengyixia Station, and Shaomaying Station. In the upstream reach, there are two branches of inflows (Zhamashike Station and Qilian Station) and only one outflow at Yingluoxia Station. For midstream and downstream reaches, there is only one inlet and outlet for the other two river segments. Based on the daily discharge data collected from the five stations, the channel water gain analysis was carried out by subtracting the sum of river discharge at inlets (inflow) from the river discharge at outlet (outflow) for the three river segments.

Figures 8–10 show the mean channel water gains of the three river segments in major-irrigation period, medium-irrigation period, and minor-irrigation period, respectively. It is found that the mean channel water gain is positive for the upstream segment while negative for the midstream and downstream segments in any particular major-irrigation period of 2004–2008. It implies that during a major-irrigation period, the upstream segment gains water from inflows of tributaries or groundwater whereas the other two river segments lose water to diversion structures,

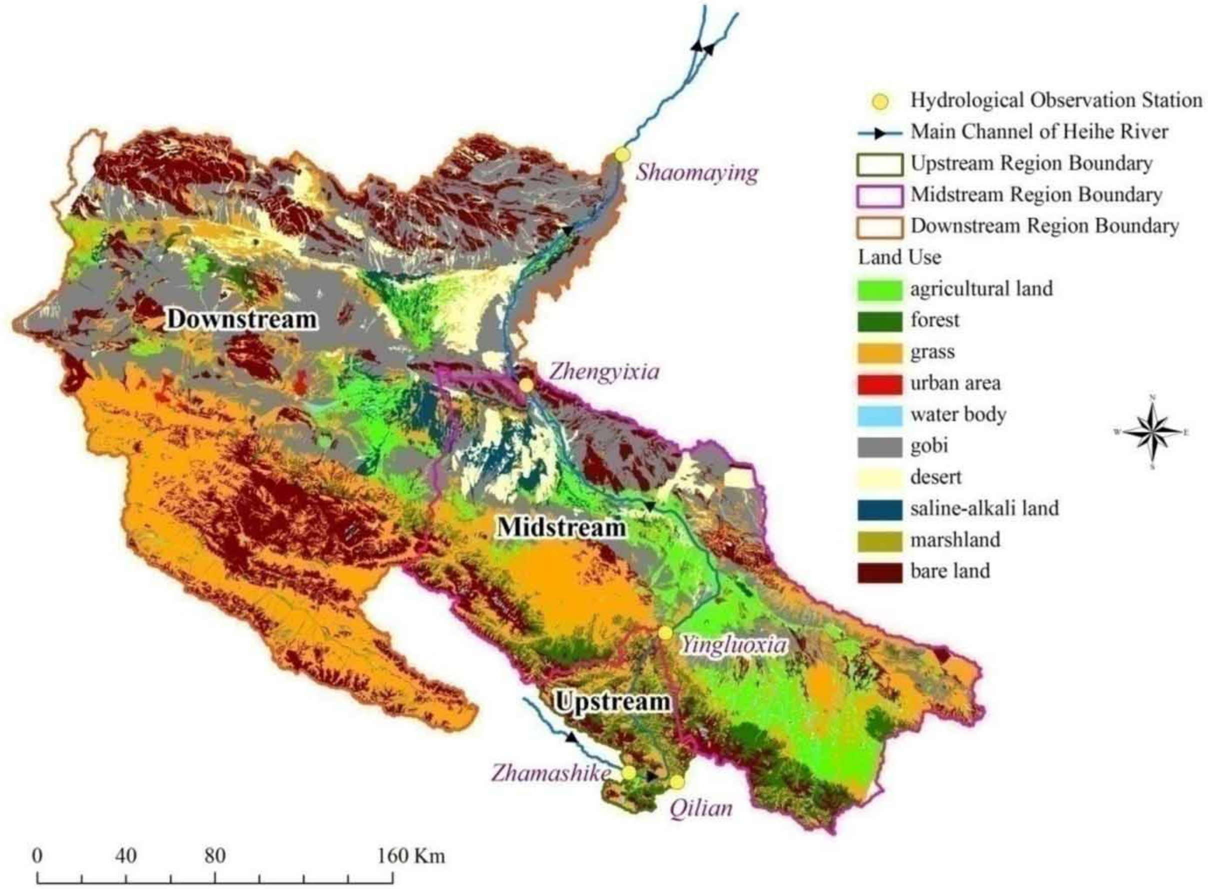

Figure 5 | Distribution of land use in the upstream, midstream, and downstream regions of the Heihe River basin in 2000.

mainly for agricultural irrigation or to groundwater by outflow through the streambed. During a medium-irrigation period, the main channel of the Heihe River experiences positive water gain in the upstream segment and negative ones in mid- and downstream segments, as it does in a major-irrigation period. As for a minor-irrigation period, the river with positive gains is located in the up- and midstream segments whereas there is negative value for water loss in the downstream segment.

Water diversion

Monthly water diversion records of water intakes located in the main channel of the Heihe River between Yingluoxia and Zhengyixia gauge stations were gathered from the relevant irrigation zones (i.e., Banqiao, Daman, Liuba, Luocheng, Pingchuan, Shansan, Xijun, Yanuan, Yingke, Youlian, and Liaoquan). The distribution of water intakes in the midstream region is reported by Gai *et al.* (2014). Figure 11 shows the amount of water diversion from the main channel of the Heihe River in different irrigation zones in July 2006.

There are very limited data of water diversion available in the downstream desert region, where there are much fewer human activities. Among irrigation zones within the downstream region, water for agricultural irrigation in Dingxin irrigation zone comes from the main channel of the Heihe River, while those in other zones come from tributary streams or reservoirs. Thus, only Dingxin irrigation zone is considered for calculating water diversion from the lower reach of the Heihe River. The crop-cultivation-area ratio values of Dingxin vs the above-mentioned irrigation zones within the midstream region were computed serving as their water-diversion ratio to estimate the amount of water

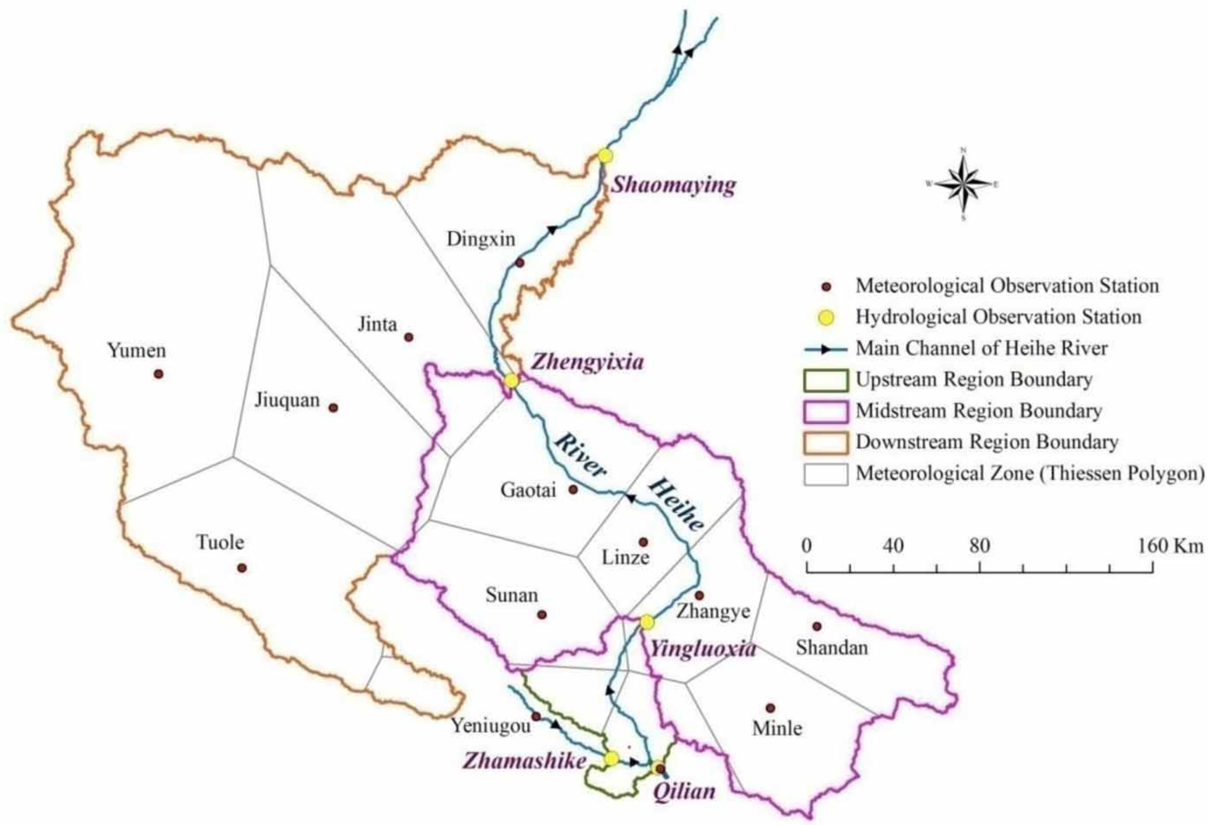

Figure 6 | Thiessen polygons of precipitation based on 13 meteorological observation stations across the Heihe River basin.

diverted from the downstream river segment of the Heihe River for any particular year of 2004–2008, based on the data set of the Heihe River social economy (Zhao 2011) (download from http://westdc.westgis.ac.cnb). The relationship between monthly water diversions for each irrigation zone in the midstream region was calculated separately and the average of these ratio values was adopted to allocate the yearly water diversion in Dingxin irrigation zone to 12 calendar months.

METHODOLOGY

Characterizing river–groundwater interaction by water budget analysis

Besides meteorological conditions and human activities, the interactions between surface water and groundwater in the riparian area affect the channel water budget of the Heihe River. For understanding the variation of river–groundwater interactions with time and space, the channel water balance equation reported by Kosheleva *et al.* (2006) was adopted and modified in order to reflect the actual situation in the Heihe River basin (see Equation (1)). The modified equation for any particular river segment of the Heihe River within a given time interval dt includes seven items concerning meteor-hydrological information, river–groundwater interactions, and water diversion from the river.

$$\sum Q_{up} - Q_{dn} + Q_{sr} + Q_{pr} - Q_{evp} + Q_{gr} - Q_{wd} = 0 \qquad (1)$$

where $\sum Q_{up}$ and Q_{dn} are the river flow discharges in the upper and lower sections of the target river segment within dt, respectively; Q_{sr} the surface runoff to the river segment; Q_{pr} the precipitation on the water surface; Q_{evp} the evaporation from the water surface; Q_{gr} the discharge of

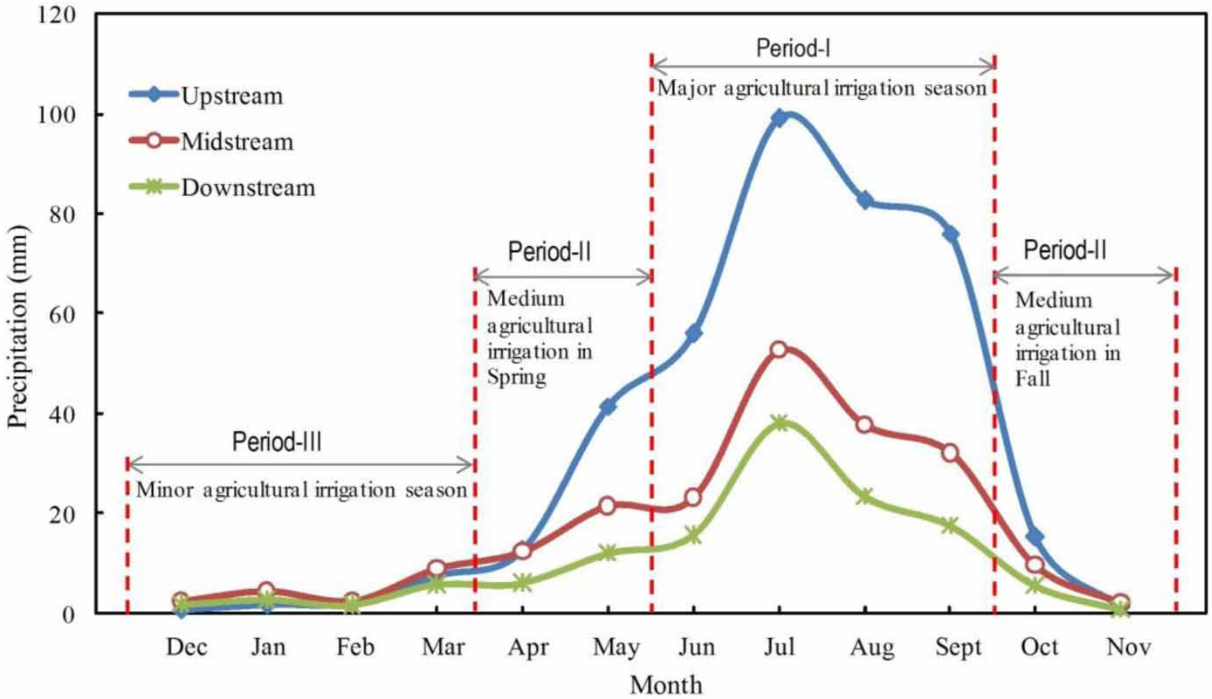

Figure 7 | Average monthly precipitations in the upstream, midstream, and downstream region of the Heihe River basin during 2004–2008.

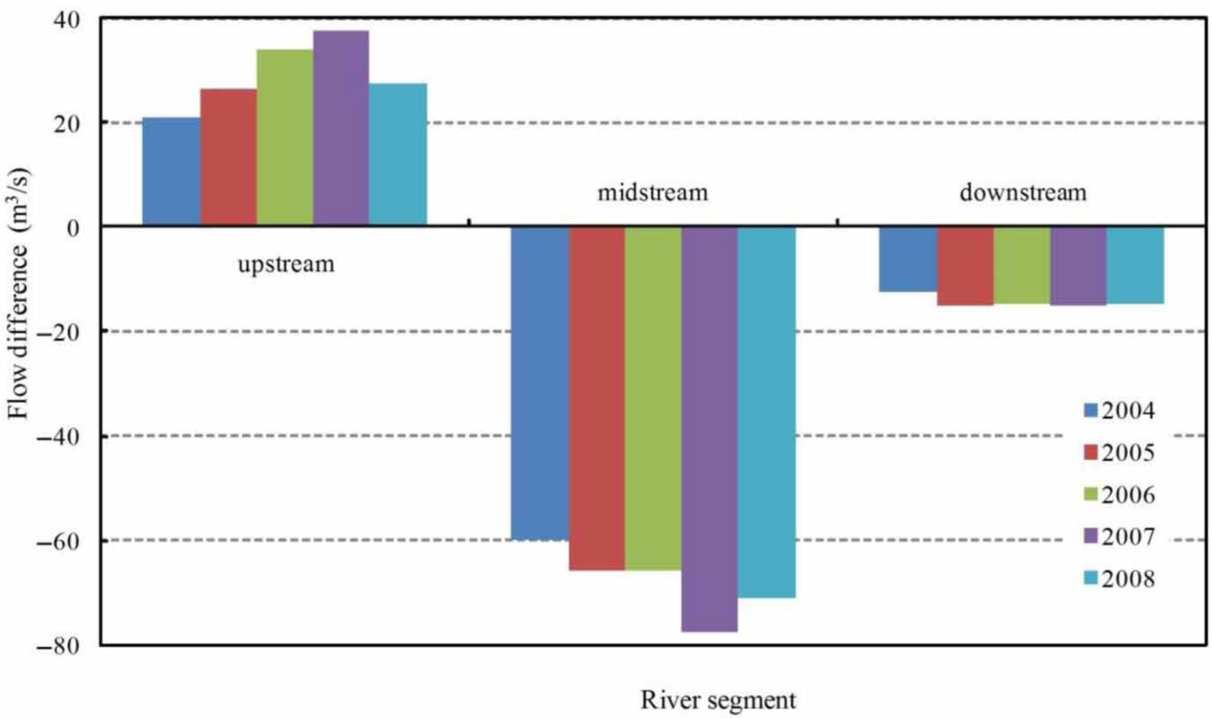

Figure 8 | Mean flow difference between outflow and inflow in the upstream, midstream, and downstream segments of the Heihe River in major-irrigation periods (June to September) of 2004–2008.

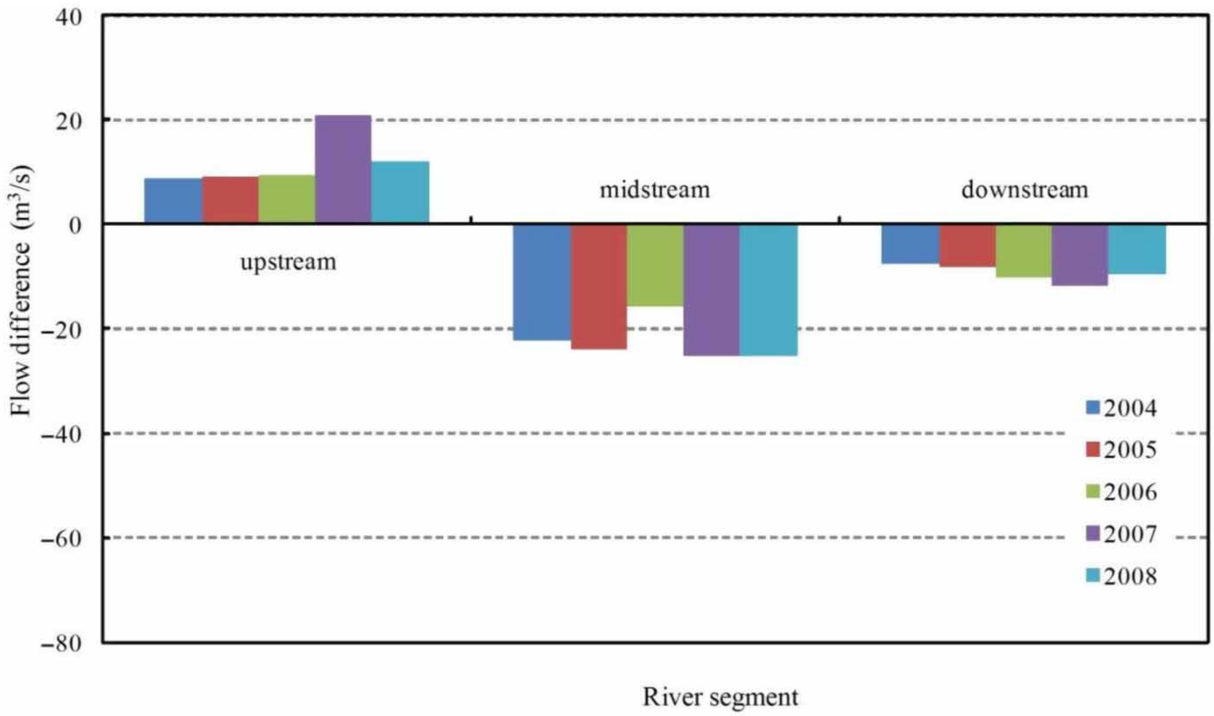

Figure 9 | Mean flow difference between outflow and inflow in the upstream, midstream, and downstream segments of the Heihe River in medium-irrigation periods (April to May and October to November) of 2004–2008.

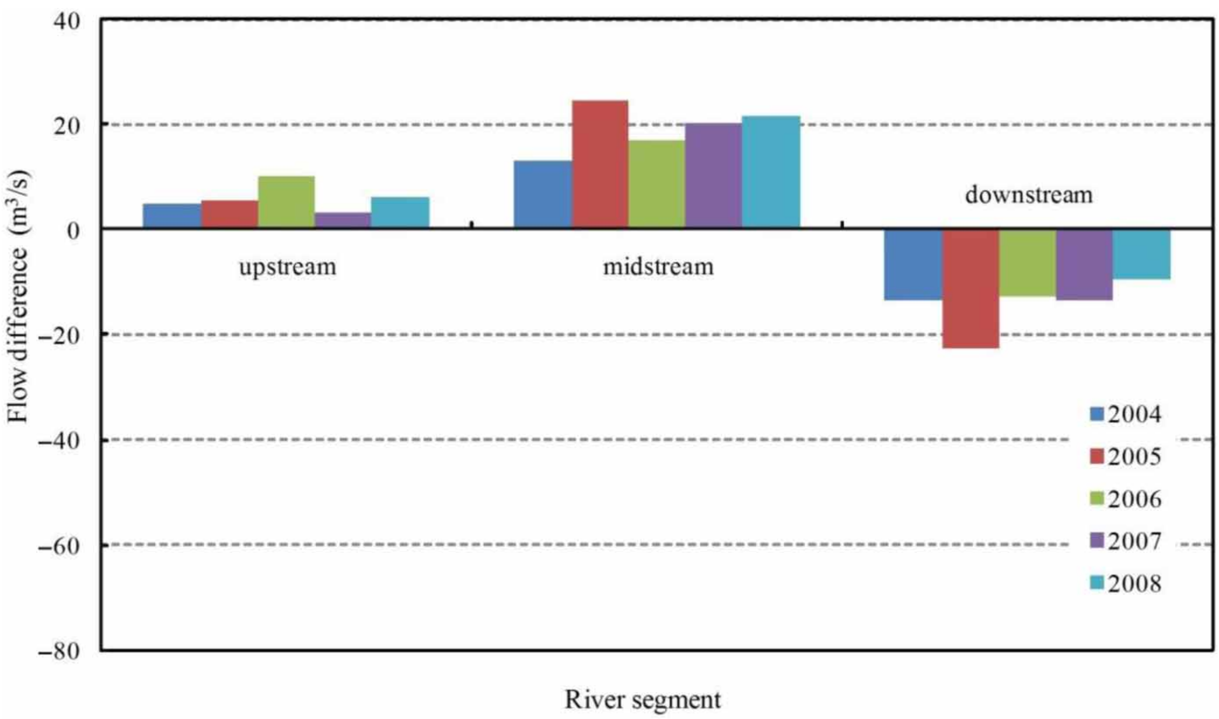

Figure 10 | Mean flow difference between inflow and outflow in the upstream, midstream, and downstream segments of the Heihe River in minor-irrigation periods (December to next March) of 2004–2008.

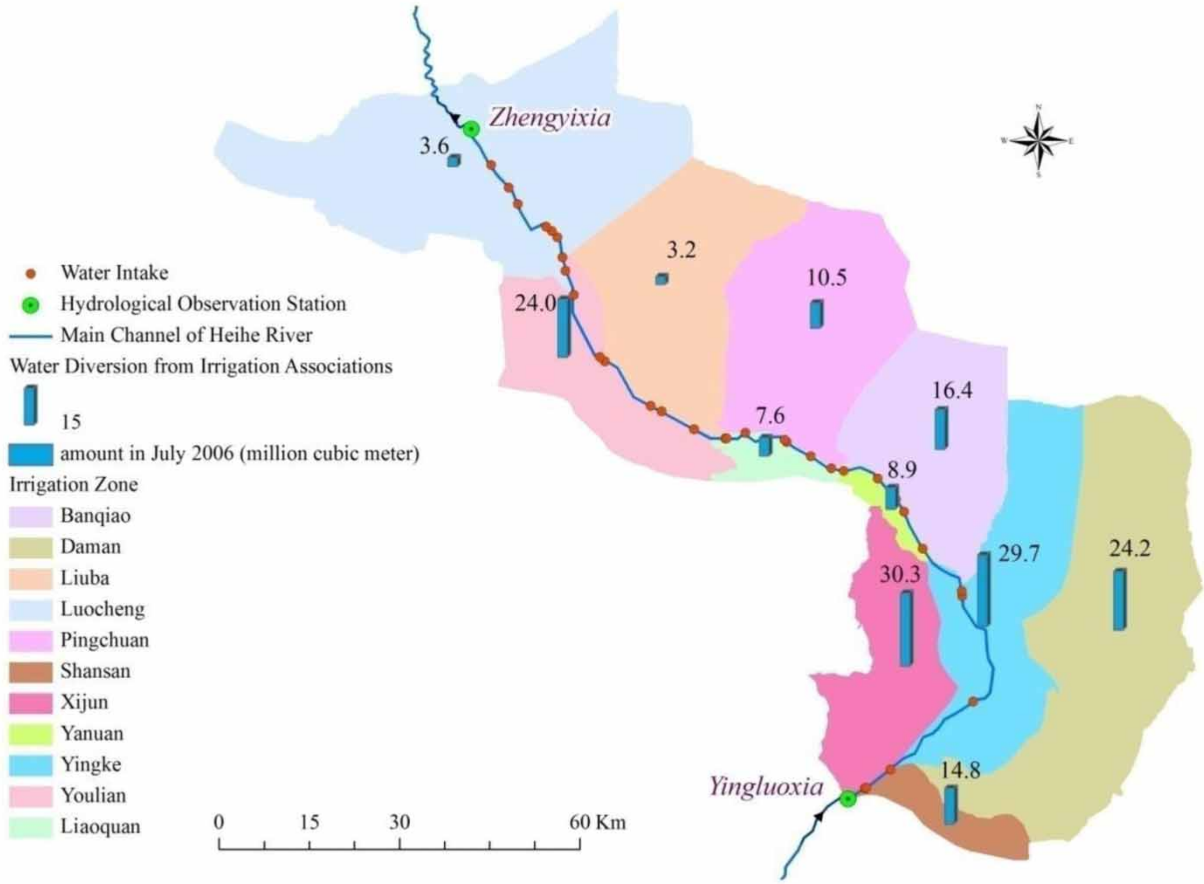

Figure 11 | Distribution of water diversion from the main channel of the Heihe River in the midstream oasis region in July 2006.

exchange between surface water and groundwater in which positive values indicate groundwater discharge to the river and negative values represent seepage of the river to the aquifer; and Q_{wd} is the water volume diverted from the river segment.

Approximation of surface rainfall runoff to the river reach

For a large basin such as the Heihe River basin, it is very difficult to have details of spatial distribution of stream flow data over the basin for accurate estimation of the rainfall runoff. However, we can approximately estimate the surface rainfall runoff to the river segments by using the rational method, as described in Keller & Sherar (2003) and Arizona Department of Transportation (1993). The rational equation is given below:

$$Q_{sr} = RC*P_t*S*1,000 \quad (2)$$

where Q_{sr} is surface runoff in m^3, RC runoff coefficient representing a ratio of runoff to rainfall, P_t the total precipitation in mm within the region, and S is the tributary drainage area of the river segment in km^2.

Runoff coefficient is related with hydrologic soil group, slope, and land use (Liu et al. 2003; Ha & Stenstrom 2008; Taye et al. 2013). The layer of hydrologic soil group within the study area was prepared by reclassifying soil type into four classes (i.e., A, B, C, and D) ascendingly ordered by runoff potential, which can be viewed in Rawls & Brakensiek (1983). A percent slope raster was computed based on DEM and then classified into three categories, which are 0–2%, 2–6% and 6+%, to create the vector layer of percent slope. By overlaying the land use layer with the hydrologic soil group layer and the percent slope layer under GIS environment, a runoff coefficient layer was generated and the *RC* values assigned according to the table given by Browne (1990). Figure 12 indicates the spatial variability of runoff coefficient in the study area.

Estimation of precipitation and evaporation in different river reaches

As given in Keller & Sherar (2003), the precipitation on and evaporation from the water surface in a given open channel can be approximately calculated by using Equations (3) and (4), respectively.

$$Q_{pr} = CL*CW*P_r \tag{3}$$

$$Q_{evp} = CL*CW*E_r \tag{4}$$

where Q_{pr} and Q_{evp} are precipitation and evaporation estimated in a given open channel, respectively, in m^3; *CL* the channel length in km; *CW* the channel width in m; P_r and E_r are observed precipitation and evaporation from meteorological stations in mm.

The *CL* values of the river reaches were obtained by performing geometric calculation on the attribute table of the Heihe River layer in ArcGIS. Since the channel width varies along the river segment, an equidistance measurement method was employed to acquire 20 *CW* values of a given river segment with the help of Google Earth satellite images overlaid with the layer of measurement locations in kmz format (prepared in ArcGIS). The average of 20 *CW* values is assigned as the mean width of the corresponding river segment. Daily evaporation data during 2004–2008

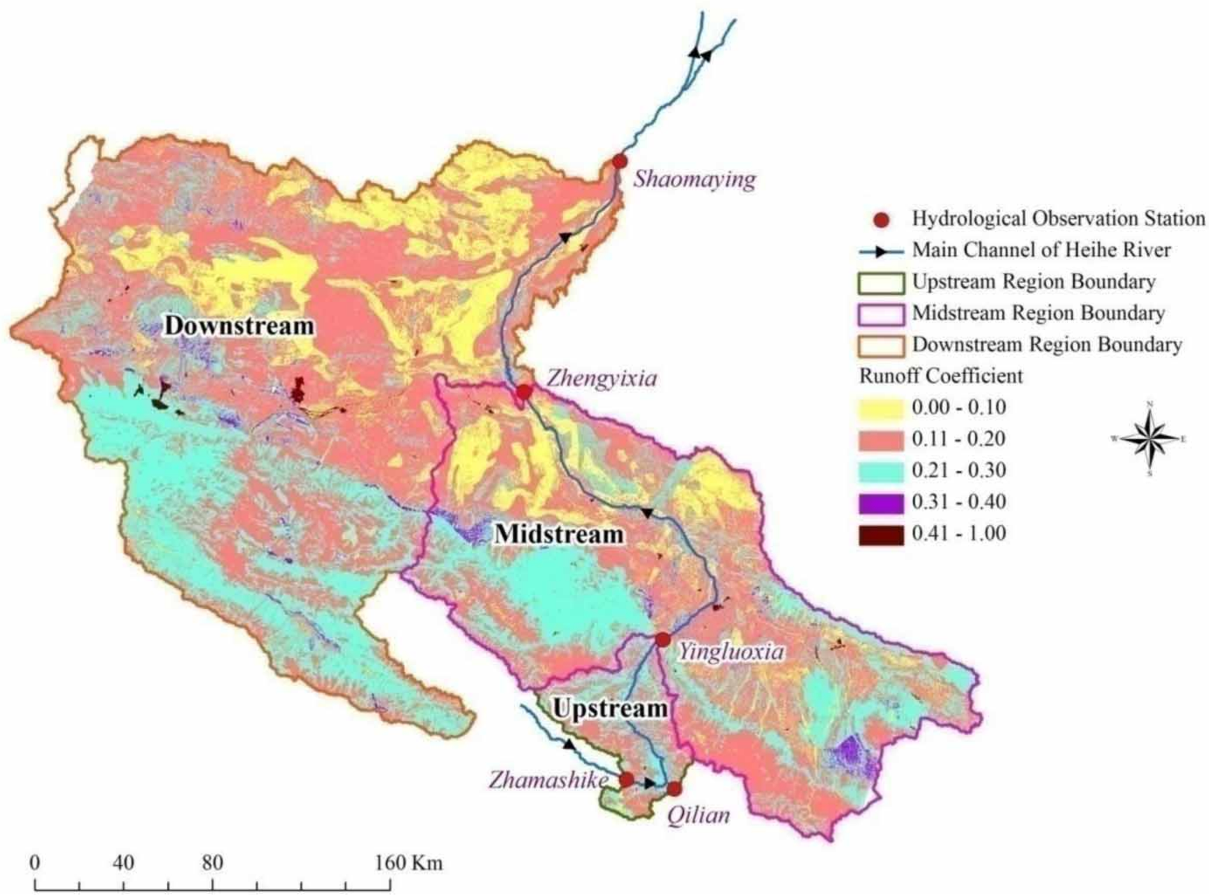

Figure 12 | Distribution of runoff coefficient in the upstream, midstream, and downstream regions of the Heihe River basin.

were collected from eight meteorological stations, including Yeniugou, Qilian, Sunan, Zhangye, Linze, Gaotai, Jinta, and Dingxin Stations, in as much as the target river segments only run through the Thiessen meteorological zones attached to these stations. Point rainfall/evaporation values at eight observation stations were converted into an average value along a given river segment by multiplying the point precipitation values with the river length ratio values (serving as weights) of their respective Thiessen polygon and then summing up all the weighted values.

RESULTS AND ANALYSIS

Geophysical characteristics

The mean slope values along and across the three target reaches, as well as the mean surface slope values for three study regions, are summarized in Table 1. It indicates the gradual decreases in mean slope by 0.55 degrees along and by 17.98 degrees across the main channel of the Heihe River, from upstream to downstream. Additionally, there is a notable decrease from 20.4 to 7.1 degrees in mean surface slope from the upstream to the downstream region of the basin. The steep lateral slope in the upstream mountain region indicates the existence of a hydraulic gradient from watershed to the river, which may drive the groundwater flow into the river in the upstream river reach.

Table 1 | Comparison of longitude slope along river, lateral slope across river, and mean surface slope in the upstream, midstream, and downstream regions of the Heihe River basin

Region	Longitude slope along river/degree	Lateral slope across river/degree	Mean surface slope/degree
Upstream	0.63	19.75	20.4
Midstream	0.13	2.04	7.6
Downstream	0.08	1.77	7.1

The statistic data of soil type for different reaches of the basin are shown in Table 2. For the upstream region, the area ratio of medium- vs high-permeability soil is approximately 1.5. It rises to 2.5 for the midstream region and declines to 1.1 for the downstream region. The distribution of low-permeability soil accounts for 38.7% of the downstream region, which make it comparatively difficult for rainfall to pass through the soil layer of the downstream region to recharge groundwater aquifers.

Table 3 gives the statistical data of land use in different reaches of the basin. In the upstream region, the area of forest and grass accounts for 75.6%, which is conducive to water conservation. The area ratio values of 15.3% and 1.3% are found for agricultural land and urban area in the midstream region, respectively, where a great deal of surface water is consumed to promote social development. The distribution of high evaporation areas such as desert and bare land accounts for 65.3% of the downstream region, which intensifies water shortage.

Hydro-meteorological characteristics

Table 4 summarizes the mean annual precipitation and three-period rainfall distribution for the three regions studied during 2004–2008. It can be observed that there is a significant decrease in annual precipitation from the upstream to the downstream region of the basin. Furthermore, rainfall of about 69%–79% is concentrated in the major-irrigation period from June to September and very little rainfall occurs in the minor-irrigation period from December to next March, regardless of the region. Since rainfall has a very close relationship to runoff, the three

Table 2 | Area ratio of different soil types in the upstream, midstream, and downstream regions of the Heihe River basin

	High-permeability soil			Medium-permeability soil			Low-permeability soil			
Region	Sand	Loam sand	Sandy loam	Sandy clay loam	Loam	Silt loam	Clay loam	Clay	Silty clay	Rock
Upstream	0	0	29.20	0	61.39	9.41	0	0	0	0
Midstream	13.25	1.66	9.08	6.37	47.83	6.45	14.68	0.06	0.45	0.17
Downstream	9.64	0.61	17.81	1.45	28.63	2.62	37.14	0.80	0.71	0.59

Table 3 | Area ratio of different land uses in the upstream, midstream, and downstream regions of the Heihe River basin

	Water resource holding areas				High evaporation areas				Human activity areas	
Region	**Forest**	**Grass**	**Water body**	**Marsh land**	**Gobi**	**Desert**	**Saline-alkali land**	**Bare land**	**Agricultural land**	**Urban land**
Upstream	34.12	41.58	1.78	0	0	0	0	21.40	0.96	0.16
Midstream	9.45	29.80	2.19	0.07	19.88	6.18	3.40	12.39	15.31	1.34
Downstream	1.54	27.10	0.82	0.41	32.71	7.28	2.59	22.68	4.35	0.52

Table 4 | Mean annual precipitation and average rainfall distribution in the upstream, midstream, and downstream regions of the Heihe River basin during 2004–2008

		Average rainfall distribution/%		
Region	**Mean annual precipitation/mm**	**Major-irrigation period (Jun–Sept)**	**Medium-irrigation period (Apr–May, Oct–Nov)**	**Minor-irrigation period (Dec–next Mar)**
Upstream	397	78.93	17.86	3.21
Midstream	210	69.36	21.80	8.84
Downstream	131	72.00	18.77	9.23

periods above are employed to investigate the hydrological characteristics of the upstream, midstream, and downstream reaches of the Heihe River.

Table 5 summarizes the mean flow difference between outflow and inflow in the three target segments for different irrigation periods during 2004–2008. It is seen that the mean flow difference between outflow and inflow in the upstream segment decreases greatly from 29.41 to 6.02 m^3/s, as time moves from a major-irrigation period to a minor-irrigation period. Since there are few human activities in the upstream mountain area, the upstream flow difference is mainly governed by natural conditions such as meteorology and geophysical settings. In the midstream segment, the mean flow difference increases significantly from −68.16 to 19.35 m^3/s, with rainfall decreasing from major-irrigation periods to minor-irrigation periods. It can be explained that the flow difference between outflow and inflow in the midstream segment is greatly influenced by human activities associated with agricultural irrigation in the midstream oasis areas. Compared to the upstream and midstream values, the flow difference between outflow and inflow in the downstream segment varies little ranging from −14.40 to −9.40 m^3/s across irrigation periods, due to the drought climate and few human activities.

Area-weighted *RC* value, region area A_r, and the mean seasonal surface runoff Q_{sr} were calculated respectively for the upstream, midstream, and downstream regions of the Heihe River basin, as summarized in Table 6. It is indicated that the mean surface runoff in the upstream region is estimated as much as $1.84 \times 10^8\ m^3$, approximately 28.9% of that in the midstream (or downstream) region during major-irrigation periods of 2004–2008, despite the relatively small size of the upstream region (equivalent to 12.1% of the midstream region and 7.4% of the downstream region in area). In medium-irrigation periods, the mean surface

Table 5 | Average flow difference between outflow and inflow in the upstream, midstream, and downstream segments of the Heihe River for different irrigation periods during 2004–2008 (unit in m^3/s)

	Major-irrigation period (Jun–Sept)			Medium-irrigation period (Apr–May, Oct–Nov)			Minor-irrigation period (Dec–next Mar)		
Segment	**Inflow (1)**	**Outflow (2)**	**Diff. (2) − (1)**	**Inflow (1)**	**Outflow (2)**	**Diff. (2) − (1)**	**Inflow (1)**	**Outflow (2)**	**Diff. (2) − (1)**
Upstream	79.90	109.31	29.41	34.28	46.50	12.22	11.76	17.78	6.02
Midstream	109.31	41.15	−68.16	46.50	23.96	−22.54	17.78	37.13	19.35
Downstream	41.15	26.75	−14.40	23.96	14.56	−9.40	37.13	22.74	−14.39

Diff. = outflow − inflow (or flow difference between outflow and inflow).

Table 6 | Runoff coefficient, region area, and mean seasonal surface runoff (Q_{sr}) in the upstream, midstream, and downstream regions of the Heihe River basin during 2004–2008

			Mean seasonal surface runoff (Q_{sr})/10^8 m^3		
Region	**Runoff coefficient**	**Area/km^2**	**Major-irrigation period (Jun–Sept)**	**Medium-irrigation period (Apr–May, Oct–Nov)**	**Minor-irrigation period (Dec–next Mar)**
Upstream	0.20	2939.36	1.84	0.42	0.07
Midstream	0.18	24346.76	6.38	2.01	0.81
Downstream	0.17	39596.26	6.35	1.66	0.81

runoff is around 0.42×10^8 m^3 in the upstream region, which corresponds to 20.9% of that in the midstream region and 25.3% of that in the downstream region. For minor-irrigation periods, the mean surface runoff of 0.07×10^8 m^3 in the upstream region is about 8.6% of that in the midstream (or downstream) region.

Table 7 summarizes the mean difference between precipitation and evaporation in the three target river segments for different irrigation periods during 2004–2008. It is found that, for any particular irrigation period, the mean difference between precipitation and evaporation increases significantly along the river channel from the upstream to the downstream. Furthermore, all values of Q_{pr} minus Q_{evp} are negative, notwithstanding changes in river segment or irrigation period, which implies that the precipitation is less than evaporation in such an arid basin.

River–groundwater exchange characteristics

The mean seasonal water diversions from three different river segments of the Heihe River during 2004–2008 are listed in the column 'Q_{wd}' of Table 8. It is shown that the water diversion from the midstream river segment is much more than those from the other two segments. Besides the upstream segment without water diversion, both the midstream and the downstream segments experience a variation of water diversion with the irrigation period. The mean water diversion in major-irrigation periods was almost twice as much as that in medium-irrigation periods in the basin during 2004–2008. In minor-irrigation periods of 2004–2008, there was mean water diversion of 0.45×10^8 m^3 and that of 0.04×10^8 m^3 approximately, from the midstream and the downstream segments, respectively, to be used to irrigate the winter season crops.

Seasonal flow volume difference ($\sum Q_{up} - Q_{dn}$) between the upstream inflow and downstream outflow was calculated by multiplying the difference between inflow and outflow (in m^3/s) with the corresponding irrigation period (in seconds). After four terms of ($\sum Q_{up} - Q_{dn}$), Q_{sr}, ($Q_{pr} - Q_{evp}$) and Q_{wd} are obtained, the river–groundwater exchange Q_{gr} can be easily quantified according to the channel water balance equation, as shown in Equation (1).

The mean values of ($\sum Q_{up} - Q_{dn}$) and Q_{gr} in the upstream, midstream, and downstream river segments of the Heihe River for different irrigation periods during 2004–2008 are shown in the columns '$\sum Q_{up} - Q_{dn}$' and 'Q_{gr}' of Table 8. Results show that groundwater discharge to the river segment occurs during all seasons in the upstream mountain region. In the midstream oasis region, groundwater is recharged by river during the

Table 7 | Mean difference between precipitation (Q_{pr}) and evaporation (Q_{evp}) in the upstream, midstream, and downstream segments of the Heihe River for different irrigation periods during 2004–2008 (unit 10^8 m^3)

	Major-irrigation period (Jun–Sept)			Medium-irrigation period (Apr–May, Oct–Nov)			Minor-irrigation period (Dec–next Mar)		
River reach	Q_{pr} **(1)**	Q_{evp} **(2)**	$Q_{pr} - Q_{evp}$ **(2) − (1)**	Q_{pr} **(1)**	Q_{evp} **(2)**	$Q_{pr} - Q_{evp}$ **(2) − (1)**	Q_{pr} **(1)**	Q_{evp} **(2)**	$Q_p - Q_{evp}$ **(2) − (1)**
Upstream	0.02	0.03	−0.01	0	0.02	−0.02	0	0.01	−0.01
Midstream	0.02	0.20	−0.18	0.01	0.17	−0.16	0	0.07	−0.07
Downstream	0.04	0.69	−0.65	0.01	0.76	−0.75	0.01	0.30	−0.29

Table 8 | Volumetric difference between the upstream inflow and the downstream outflow ($\sum Q_{up} - Q_{dn}$), mean water volume diverted (Q_{wd}), and mean river–groundwater exchange (Q_{gr}) in the upstream, midstream, and downstream segments of the Heihe River for different irrigation periods during 2004–2008 (unit 10^8 m^3)

	Major-irrigation period (Jun–Sept)			Medium-irrigation period (Apr–May, Oct–Nov)			Minor-irrigation period (Dec–next Mar)		
Segment	$\sum Q_{up} - Q_{dn}$	Q_{wd}	Q_{gr}	$\sum Q_{up} - Q_{dn}$	Q_{wd}	Q_{gr}	$\sum Q_{up} - Q_{dn}$	Q_{wd}	Q_{gr}
Upstream	−3.10	0	1.27	−0.97	0	0.57	−0.79	0	0.73
Midstream	7.18	6.18	−7.20	1.79	3.41	−0.23	−2.53	0.45	2.24
Downstream	1.52	0.55	−6.67	0.75	0.30	−1.36	1.88	0.04	−2.36

1. Volumetric difference between inflow and outflow $\sum Q_{up} - Q_{dn}$ is calculated by multiplying the difference between upstream inflow and downstream outflow by the irrigation time period.
2. Positive value of river–groundwater exchange Q_{gr} means groundwater discharge to the river, and negative values for Q_{gr} seepage from the river to the ground.
3. Annual river–groundwater exchange by summing Q_{gr} in all months: upstream 2.57×10^8 m^3, midstream -5.29×10^8 m^3, downstream -10.39×10^8 m^3.

major-irrigation and medium-irrigation periods, while groundwater discharges to the river in minor-irrigation periods. This shows that human activities significantly affect the river–groundwater interaction in the midstream oasis region, which results in less outflow than inflow in the midstream river reach. As a result, it reduces the river inflow to the downstream river reach. In the downstream desert region, the seepage flow of the river to the aquifer is found for all seasons, which is opposite to the river–groundwater exchange in the upstream mountain region.

DISCUSSION

In the upstream mountain region of the Heihe River basin, an extensive area of forest and grass growing on sandy loam or loam textured soils can help hold moisture in soils or recharge aquifers when a certain amount of precipitation falls in the form of rain or snow. Furthermore, relatively steeper slopes exist along and across the river channel in the mountain area. On the one hand, a river segment with a steep gradient will have a faster flow velocity and, as a result, the river water quickly moves along the channel and hardly percolates into the aquifer through overlying unsaturated materials. On the other hand, due to the high altitude and steep slope of the Qilian mountainous area, abundant groundwater, driven by gravity, moves away from recharge areas in the mountain to the adjacent valley and consequently converted into river water. Thus, the upstream river segment gains water from groundwater (a positive value of Q_{gr}) regardless of the irrigation period. In addition, a large quantity of precipitation (over 70% of annual precipitation) falls and alpine glaciers melt in summer seasons, which contributes to a rise in the groundwater table in the unconfined aquifer and, consequently, results in more water flowing into the river (Cai *et al.* 2014a). This can explain why 49.4% of the groundwater discharge to the river is found as about 1.27×10^8 m^3 in major-irrigation periods whereas it is 22.2% in medium-irrigation periods and 28.4% in minor-irrigation periods, for the upstream river channel. It is, therefore, indicated that the characteristics of river–groundwater interaction are mainly controlled by geophysical settings and precipitation.

Compared with the upstream region, the midstream oasis region comprises relatively flat terrain and wide river channels, which decreases the velocity of river water. Hence, the slow-moving river water has time to move downwards to groundwater when the groundwater level is lower than the water level in the river. The midstream region is mainly veneered with loam textured soil of medium permeability, which is beneficial to water exchange between the river and groundwater. The high evaporation area (e.g., Gobi, desert, and bare land) and the human activity area (e.g., agricultural and urban land) accounts for 41.85% and 16.65% of the midstream region, respectively. The large-scale groundwater withdrawals for irrigation and domestic use and high evaporation rates give rise to low groundwater-level elevation. The groundwater level may vary due to the seasonal changes, such as agricultural irrigation and precipitation in the farming regions (Chen *et al.* 2003; Cai *et al.* 2014b). In major- or medium-irrigation periods, a large amount of groundwater is withdrawn for irrigating crops, which decreases greatly the groundwater level. Meanwhile, due to the precipitation recharge in the upstream mountain area, the river flow increases and, as a result, the water level rises in the midstream river channels. Thus, the groundwater level is lower than the water level in the river channels and, consequently, the river channel loses water to the adjacent groundwater aquifer in the midstream oasis region during regular irrigation months from April to November. In minor-irrigation periods with little precipitation, the runoff from the mountain area decreases significantly, which leads to a very low water level in the channels. However, owing to the irrigation return flows and few groundwater withdrawals, a rise in the groundwater level is maintained during winter months. Hence, the groundwater level is usually higher than the river water level and the river–groundwater interaction can be described generally as groundwater discharging to river channels in the midstream reach of the Heihe River during minor-irrigation periods. Notwithstanding the water flow direction during the river–groundwater exchange varying with irrigation period, the river–groundwater interaction in the midstream region is dominated by human activities, such as groundwater withdrawals and agricultural irrigation, as well as precipitation.

Different to the upstream and midstream regions, the downstream region receives very little precipitation all year round, which makes groundwater difficult to be recharged from rainfall. Furthermore, over 65% of the downstream region is covered by high-evaporation lands such as Gobi, desert, and bare land. Little precipitation and high evaporation results in a continued low groundwater level. As a consequence, the groundwater level is lower than the river water level in the downstream region, whatever the irrigation period. The river and groundwater, therefore, interact through groundwater recharge from the river in the downstream region. In addition, groundwater pumping for agricultural irrigation can affect the water exchange between the river and the groundwater. It can explain why the river–groundwater water exchange in major- and medium-irrigation periods is much greater than that in minor-irrigation periods. The interaction between the river and groundwater is significantly governed by evaporation and human activities, which agrees with the work of Wang *et al.* (2014). It may also be affected by geological heterogeneity, as discussed by Fleckenstein *et al.* (2006).

Given the inherent non-linearity and complexity of hydrological processes at any scale (Wu *et al.* 2014), the research community at times has to rely on simplistic empirical formulae as used in this study. Equations (2)–(4) have been effectively used in hydrology and water resources research and applications. GIS spatial analysis tool has been used to analyze high-resolution GIS data and produce the appropriate runoff coefficient distribution map (Figure 12) based on the table given by Browne (1990). This increases the reliability of the result from the empirical runoff equation. For evaporation and precipitation water volume estimations, no empirical coefficients exist in the equations. Channel width and length are obtained by GIS spatial analysis of high resolution GIS data, which would result in reliable data for estimating precipitation and evaporation water volume by the empirical equations.

Through comparisons among all terms in the balance equation, it is indicated that large water diversion and groundwater recharge from the river channels lead to a reduction of the river flow in the middle and downstream regions and, as a result, the blanking of lower reaches arises frequently and even some river channels have dried up or are drying up. For protecting the ecological environment in the Heihe River basin, particularly in its downstream region, it is suggested that the area of cultivated land should not be expanded further in the basin. Moreover, some ways to save water, such as sprinkling and drip irrigation, should be taken instead of surface flood irrigation. As well as this, it is essential to establish the related computational models to effectively manage the exploitation and utilization of water resources in the Heihe River basin.

CONCLUSIONS

Characteristics of river and groundwater interactions in the Heihe River basin have been investigated for the upstream mountain region, midstream oasis region, and downstream desert area. A river water balance equation was modified to represent the natural features and human activities of the Heihe River, and to estimate the water exchange between the river and groundwater. Through the analysis of geophysical characteristics, meteor-hydrological characteristics, and water balance in the river reaches, results show that the tempo-spatial characteristics of river–groundwater exchanges vary geographically along the Heihe River from the upstream mountain region to midstream agriculture area, and the downstream desert region during different seasons. This study intended to study the regional contrast in surface water–groundwater interactions on an annual and seasonal basis. Therefore, the methodology presented here was deemed appropriate to achieve the objectives of the study. Furthermore, given the spatio-temporal scale of the problem in hand, some deviations in the selected empirical coefficients should not effect our findings.

In the upstream mountain region, the river channel gains water from the ground in all seasons during the year, with a groundwater inflow of approximately 2.57×10^8 m^3 per year. With the net groundwater inflow to the river, outflow is larger than inflow in the upstream river reach. Physiographic mountain features and precipitation are the major factors controlling the groundwater flow to the river. Steep watershed slopes (about 20 degrees) across the river result in the higher groundwater table in the watershed, and produces the gravity gradient driving groundwater flow into the river.

In the midstream oasis region, the mild lateral slope across the river in the watershed is about 2 degrees. Human activities of water withdrawal during different agricultural irrigation seasons significantly affect the river–groundwater interaction. During the middle-major irrigation period from spring to autumn seasons (April to November), river–groundwater interaction is characterized by the net river water leaks into the ground (about 7.43×10^8 m^3 per year), which results in less river outflow than the inflow in the river reach. However, during the minor-irrigation period in the winter (December to March), there is a net groundwater inflow to the river (about 2.24×10^8 m^3 per year).

The downstream desert area is characterized by the low precipitation, high evaporation, and near-flat lateral slope of about 1.77 degrees. Opposite to the upstream region, the river–groundwater interaction in the downstream desert area is characterized by the net leakage flow, with the annual net loss about 10.39×10^8 m^3, from the river to the ground during all seasons. Generally, several factors contribute to the leakage of river water to the ground in the downstream desert area, including near-flat watershed, poor land cover with high evaporation, and water withdrawal activities. The large water diversion and groundwater recharge from the midstream oasis region result in a notable decrease of river inflow in the downstream desert region. In order to protect the ecological environment against desertification in the downstream desert region, adopting water-saving irrigation techniques in the midstream oasis region is important to reduce the leakage of river flow to the ground so as to increase the river inflow to the downstream desert area.

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