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ORIGINAL ARTICLE

Preliminary assessment of hydraulic connectivity between river water and shallow groundwater and estimation of their transfer rate during dry season in the Shidi River, China

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Abstract Understanding the relationship between surface water and groundwater is important for the integrated management of water resources in arid regions. In the present study, the connectivity of river water and shallow groundwater along the Shidi River, China is estimated using a connectivity index, as well as analyses of hydrochemistry and isotopic signature. The three approaches for hydraulic connectivity assessment were compared and discussed. An end member mixing analysis was performed to estimate the contribution ratios of local precipitation, river leakage and groundwater lateral inflow to the total groundwater recharge along the river. The results show that medium connectivity is identified in all reaches of the river (upstream, midstream and downstream). Water table depth and river channel sediments are the major factors responsible for the spatial variation of the hydraulic connectivity. The CI approach can be adopted to generate preliminary assessment results of hydraulic connectivity, while the physiochemical and isotopic approaches should be used as a tool for results validation and verification. Groundwater lateral inflow is the most important recharge source of groundwater along the river, while river leakage only accounts for 18.4–27.0 % of the total recharge. This study is meaningful in integrated water resources management in arid regions and the methods used in this study can be adopted by other scholars in similar studies.

Keywords Groundwater · River water · Surface water-groundwater interaction · Isotopic signature · Hydrochemistry · Human activity

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Introduction

Water resource is one of the most important natural resources for human survival and economic development (Li 2014). Demand for fresh water is increasing due to rapid population growth and economic development. However, the water resource is quite limited and the sustainable use of it requires an integrated management of surface water and groundwater (Kalbus et al. 2012; Raul et al. 2011), which requires a detailed understanding of the relationships between surface water and groundwater. The understanding of their relationships is especially meaningful in arid and semiarid regions which cover approximately 40 % of the earth's surface (Oyarzún et al. 2014), because these regions are facing severe climate change and intense human activities that may significantly influence the availability and quality of water resources. Surface water and groundwater relationships have been incorporated into water related legislation in Australia (Oyarzún et al. 2014). EU also calls for a sustainable management of coupled groundwater and surface water resources (Fleckenstein et al. 2010). Actually, understanding and managing the relationships between surface water and groundwater is important to all countries for the management of near-channel ground water and surface water (Woessner 2000), especially in regions where human activities are intense. For example, the mountaintop removal projects underway

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in China will alter surface water courses as well as aquifer structure and groundwater dynamics (Li et al. 2014a). The original relationships between surface water and groundwater will also be altered as a result. For sustainable development in these land creation areas, it is mandatory that research on surface water and groundwater interaction must be implemented.

During the past several decades, the surface water and groundwater interaction has been fully recognized and has received a lot of attention (Hu et al. 2009). A large amount of literatures can now be found in various journals or databases with respect to surface water and groundwater interaction. For example, Chen (2001) presented a method of using particle-tracking techniques to evaluate the transport of the leaked stream water in the nearby aquifers. Kalbus et al. (2009) simulated the impact of subsurface heterogeneity on the distribution of groundwater discharge through the streambed. Rodgers et al. (2004) investigated the groundwater and surface water exchanges in the main braided river, Scotland using a tracer based approach (the tracers are alkalinity and silica); Lamontagne et al. (2005) carried out a study on groundwater and surface water interaction by integrating piezometric surface monitoring and environmental tracers (Cl^-, δ^2H, and $\delta^{18}O$) in the riparian area of a large floodplain of Victoria for the purpose of designing effective salinity remediation strategies; Langhoff et al. (2006) found that the ratio which was defined as the width of the wet zone of the flood plain divided by the effective width of the stream could be indicative of the percentage of water entering the stream directly through the streambed. As hydrochemistry and isotopes have become effective tool in analyzing water cycle, many researches have been conducted to study the interaction between surface water and groundwater by analyzing hydrochemistry and isotopic signatures of waters (for example, Dor et al. 2011; King et al. 2014; Lambs 2004). Another widely used approach for investigating groundwater and surface water interaction is the numerical modeling approach (Chen and Chen 2003; Fleckenstein et al. 2010). Sulis et al. (2010) compared two physics-based numerical models for simulating surface–subsurface interactions. Cho et al. (2010) developed a DANSAT, MODFLOW and MT3D coupled dual-simulation scheme to study surface water and groundwater interaction. There are, of course, some other approaches that can be applied for analyzing groundwater and surface water interaction, such as heat tracer methods (Constantz and Stonestrom 2003; Schmidt et al. 2006) and experimental approaches (Chen 2007; Song et al. 2009). Becker et al. (2004) has recognized the importance and usefulness of temperature as a tracer for estimating stream/groundwater exchange over ten years ago. Kalbus et al. (2007) proposed a methodology for quantifying the spatial pattern and magnitude of mass fluxes at the stream-aquifer interface by mapping streambed temperatures. Keery et al. (2007) assessed the spatial and temporal variability of water fluxes at the river–groundwater interface using a temperature time series. Anibas and colleagues (Anibas et al. 2011, 2012; Dujardin et al. 2011, 2014; Vandersteen et al. 2015) carried out a set of theoretical and practical studies in the past several years in the research field of surface water and groundwater interaction. They proposed and used several approaches for estimating groundwater and surface water exchange, such as temperature–time series (Vandersteen et al. 2015), simple thermal mapping method (Anibas et al. 2011), high resolution satellite imagery (Dujardin et al. 2011), flux estimation techniques (Dujardin et al. 2014) and a hierarchical approach (Anibas et al. 2012). These studies provided useful references for similar research in groundwater-surface water interaction. What also deserves to be mentioned here is some review papers that have presented the state of the art in research of groundwater and surface water interaction (Dahl et al. 2007; Eslamian and Nekoueineghad 2009; Jolly et al. 2008; Kalbus et al. 2006; Newman et al. 2006; Sophocleous 2002). These review papers have provided comprehensive information about surface water and groundwater interaction to readers.

The Shidi River is situated in the Mideast of the Guanzhong Plain (also known as Weihe Basin). It is a tributary of the Weihe River which is one of the most seriously polluted rivers in China. As the main source of water for domestic, industrial and agricultural purposes, groundwater is heavily abstracted, inducing river leakage to shallow riverbank aquifers, deteriorating groundwater quality and risking human health (Li et al. 2014b). The Shidi River is also severely contaminated because of wastewater effluents from Shaanxi Fertilizer Production Plant (referred to as Shanhua hereafter) in the upstream. Contaminated river water flows northwards and finally runs into the Weihe River. However, whether the contaminated river water have close connection with groundwater and whether the river water will contribute to the groundwater recharge are still not clear. If they do have some connections, what is the contribution ratio of the river water to the groundwater? To answer these questions, a comprehensive investigation on groundwater and surface water interactions is required.

Therefore, the main aims of the present study are, on one hand, to characterize the connectivity between river water and groundwater using a connectivity index, hydrochemistry and isotopic signatures of water samples as well as cluster analysis, and on the other hand, to estimate the transfer rates of aquifer-river. The approaches and results presented in this study will be helpful for a better management of water resources and prevention of water pollution in this area and in other regions facing similar problems.

Study area

Location

The Shidi River is located in the middle of Hua County, Weinan City of Shaanxi province, China, 87 km east of Xi'an City (Fig. 1). The study area is a part of the Guanzhong Plain which is formed by the alluvial sediments of the Weihe River. The study area lies within east longitude 109°39′14″–109°49′02″ and north latitude 34°27′24″–34°36′37″. It stretches 13 km from south to north and 15 km from east to west, covering approximately 170 km^2. The Weihe River, the biggest river in this area, runs eastwards along the northern boundary. Shanhua, built in 1967, is the biggest pollutants producing factory in this area. Its industrial wastewater containing high content of nitrate and some other organic pollutants is discharged into the Shidi River every day, contaminating surface water and groundwater as well.

Climate and hydrology

The study area lies within the semi-humid continental monsoon climate zone, and has a warm spring, hot summer, rainy autumn and a cold winter. According to the weather data from the weather station of Hua County, the average annual temperature here is 13.4 °C, and the extreme maximum temperature in history is 43 °C which was recorded on June 19, 1966, while the extreme minimum temperature is −16.5 °C that was observed on January 30, 1997 (Wu and Sun 2015). Monthly averages for precipitation, temperature and evaporation are shown in Fig. 2. The average annual rainfall is 581.2 mm, with about 50 % of it being concentrated from July to September. Evaporation in this area is moderately

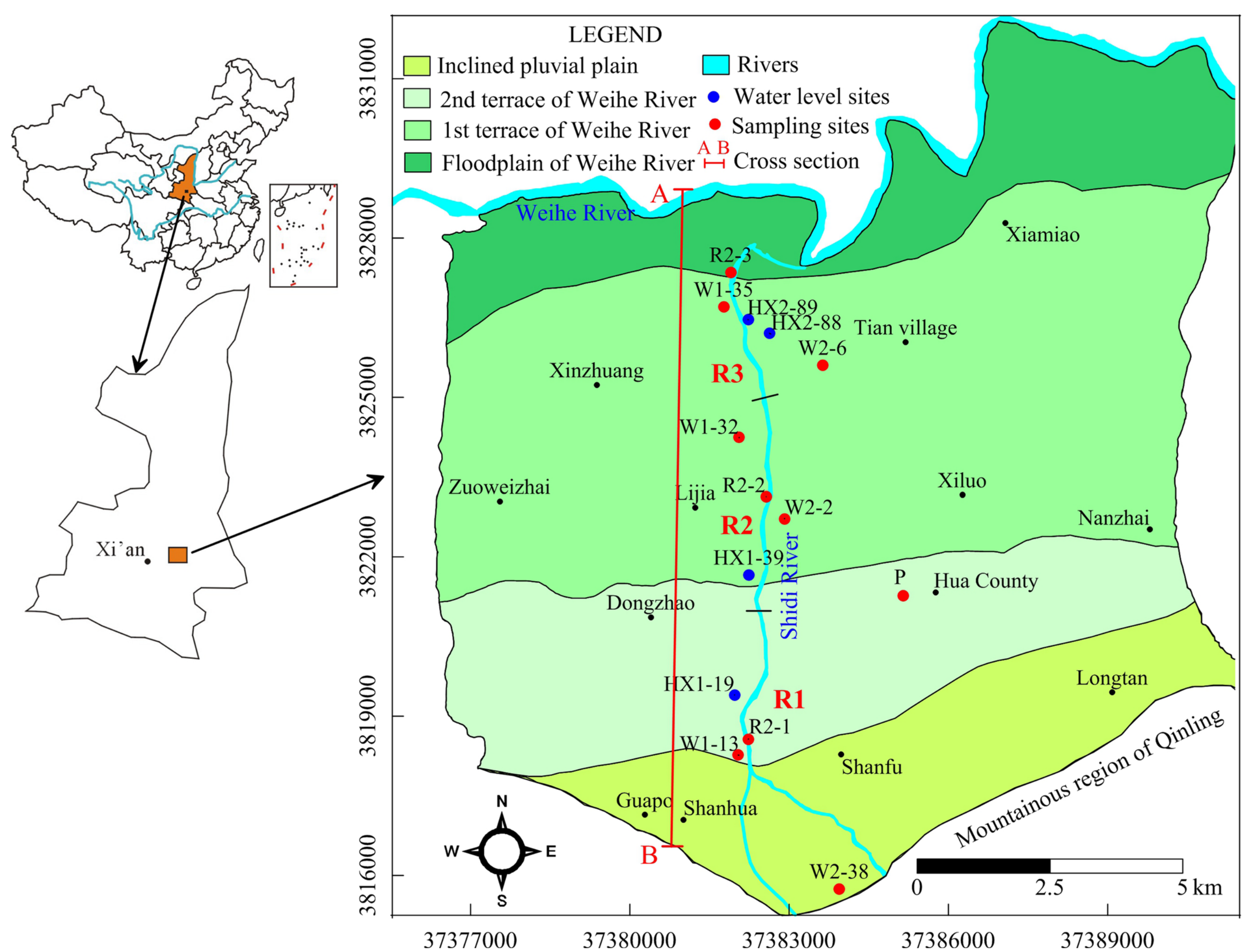


Fig. 1 Location and sampling sites of the study area. R1 represents upstream, R2 denotes midstream and R3 indicates downstream

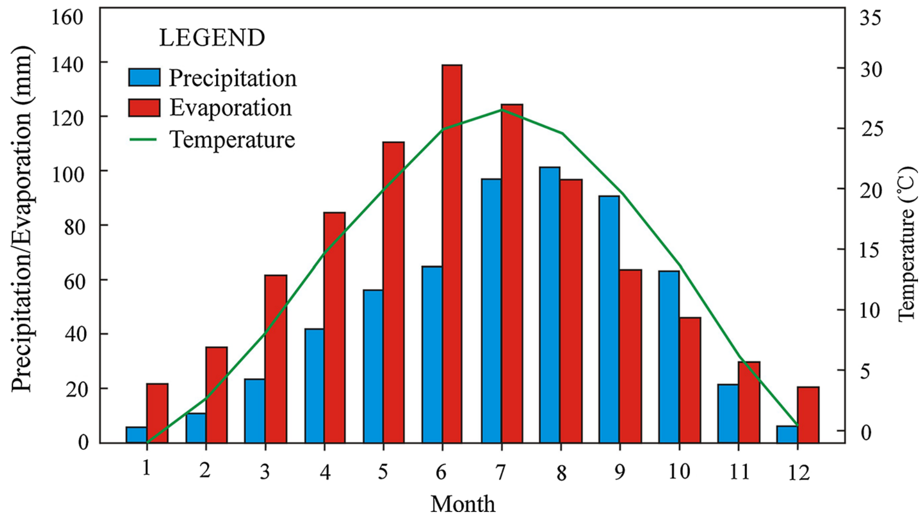


Fig. 2 Annual precipitation, evaporation and temperature in the study area

intensive, and the annual rate of evaporation is 830.7 mm, with 66.6 % observed in April to August (Zhang 2014; Wu and Sun 2015).

The Weihe River is the biggest river in this area. According to the data released by the hydrological station of Hua County from 1951 to 2006, the average annual flow of the Weihe River is 219 m^3/s (Zhang 2014). It transports almost 0.38 billion ton of sediments annually and has a salinity ranging from 68 to 1050 mg/L. The Shidi River originates in the southern mountainous region. It flows northwards through the middle of the study area, and finally runs into the Weihe River. It is 37 km long, and the average annual flow is 0.872 m^3/s (Zhang 2014). Physiochemical analyses show that the Shidi River is severely contaminated by fluoride (F^-), nitrogen (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), and chemical oxygen demand (COD).

Geology and hydrogeology

Landforms in the study area begin with an inclined pluvial plain in the south, which transits to a pluvial–alluvial plain, as the Weihe River is approached (Wu and Sun 2015). The Quaternary deposits in the region are mainly loose deposits formed by river, lake and flood (Zhang 2014). The geologic cross-section of A–B is shown in Fig. 3. According to field investigation, the Holocene alluvium (Q_4^{al}) is mainly distributed over the floodplain and terraces of the Weihe River. The upper part of it (Q_4^{2al}), mainly observed over the floodplain, is composed of sand and fine sand, while the lower part (Q_4^{1al}) which is widely distributed over the 1st terrace consists of sand, gravel and silty clay. The Late Pleistocene deposits underneath the floodplain and terraces (Q_3^{al}) consist of pale yellow medium sand imbedded by silty clay. The Middle Pleistocene alluvium (Q_2^{al}) is widely distributed over the study area, consisting of medium to coarse sand and fine sand imbedded by sandy clay. The Early Pleistocene deposits in the area are formed by lakes (Q_1^{l}). This layer consists of brown, yellow, and gray-green powder sand, silty clay and clay, imbedded by yellow fine sand, coarse sand, and sometimes gravels (Zhang 2014).

The long geological history has produced thick loose deposits in the area, providing good spaces for groundwater storage. Generally, two types of aquifers can be classified in the area within the Quaternary deposits: phreatic aquifer and confined aquifer (Wu and Sun 2015). The unconfined aquifer is comprised of alluvial sands and coarse sands deposited during the Late Pleistocene and Holocene (Q_3^{al} and Q_4^{al}), while the confined aquifer consists of sands, fine sands and thin clayey layers formed during the Early and Middle Pleistocene of Quaternary. Due to the great depth of confined aquifer, only phreatic aquifer is possible to have direct connection with surface water, thus is considered in the present study. The phreatic aquifer located in the floodplain, usually 42–51 m in thickness, is composed of medium and fine sand with good sorting and high permeability. The average hydraulic conductivity of the unconfined aquifer in this region is 25.26 m/d and the precipitation infiltration coefficient is 0.25, which is advantageous for the infiltration of precipitation and river water. The unconfined aquifer in terraces, generally 38–51 m in thickness, is composed of medium to coarse sand and fine sand. It also has a good sorting and high permeability. The hydraulic conductivity varies from 19.5 to 24.5 m/d, and the precipitation infiltration coefficient is 0.22 (Wu and Sun 2015). The aquitard between the phreatic and confined aquifers is composed of sandy clay and silt with a thickness of 6.7-12 m. The vertical hydraulic conductivity of the aquitard is 0.0002 m/d (Qian et al. 2014a). Groundwater flows basically from south to north, but is influenced to some degree by rivers in areas

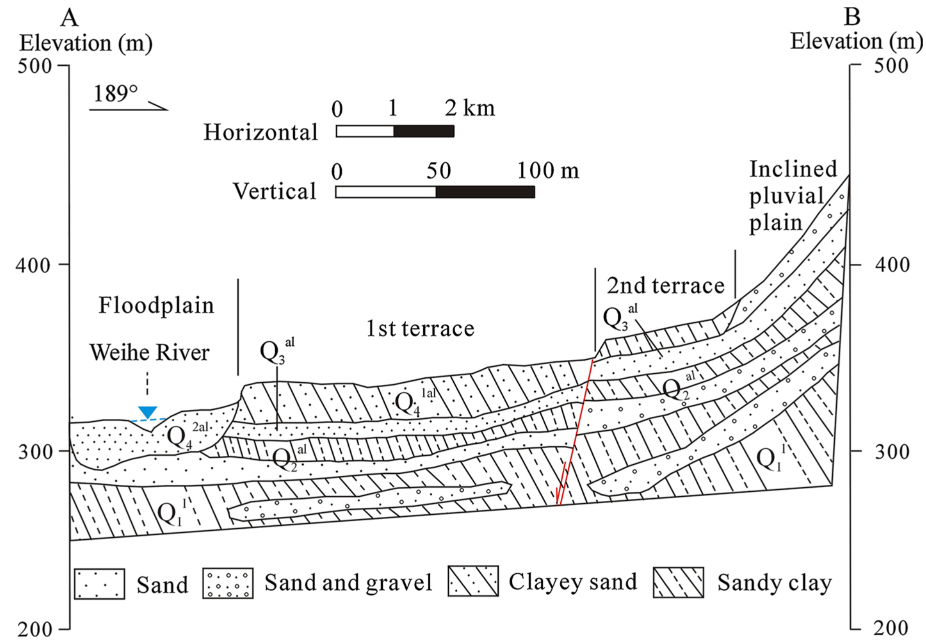


Fig. 3 Geologic cross-section of A–B

adjacent to the rivers. Water level depth varies a lot over the study area. It may be 4–10 m over the floodplain, but can be over 15 m in the pluvial plain. Groundwater is recharged mainly by lateral inflow, precipitation infiltration, river leakage, and irrigation infiltration, while discharged by artificial abstraction and evaporation as well as lateral outflow (Qian et al. 2014a; Zhang 2014). According to the water balance calculated for the period of April 2012 to March 2013, lateral inflow accounts for 43.40 % of the total recharge, and the ratios of recharge from precipitation infiltration, irrigation infiltration and river leakage are 19.81, 19.47 and 17.32 %, respectively. The water balance calculated also shows that over 90 % of the groundwater is discharged through artificial abstraction, and evaporation and lateral outflow accounts only small proportions of the total discharge, being 6.51 and 1.42 %, respectively (Wu and Sun 2015). Serious groundwater pollution is also observed. Similar to surface water, F^-, NH_4^+, NO_3^-, NO_2^- and COD are main pollutants in groundwater, which may be indicative of connections between river water and groundwater.

Methodology

Sample collection and analysis

Five groundwater samples (W1-13, W1-32, W1-35, W2-2, and W2-6) and 3 river water samples (R2-1, R2-2 and R2-3) were collected in April 2013 (dry season) at several sites along the Shidi River (Fig. 1). A background groundwater sample (W2-38) was also collected at the foot of mountainous region for the end member mixing analysis. The rain water (P) used in the end member mixing analysis was collected from the Meteorological Bureau of Hua County which is very close to the Shidi River. Groundwater samples were collected from shallow wells (less than 30 m) providing domestic and agricultural water for local communities. River water samples were obtained at three locations representing upstream, midstream and downstream of the area. Sampling locations were recorded using a potable GPS.

At each site, a 5-L bottle was filled for chemical analysis and another 500-mL bottle for isotopic analysis. The pH and EC were measured in situ using portable meters. Physiochemical analyses were carried out at the Laboratory of Shaanxi Institute of Geological Engineering Investigation. Analyzed parameters include major ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-}), total dissolved solids (TDS), total hardness (TH), F^-, chemical oxygen demand (COD), free carbon dioxide (CO_2), ammonia nitrogen (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-). The analyses were carried out following the methods and procedures in *Standard methods for the examination of water and wastewater*, 20th edition (Clesceri et al. 1999). Isotopic analyses of ^{18}O and ^{2}H were performed at the State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry of Chinese Academy of Sciences using the Liquid Water Isotope Analyzer (Los Gatos Research, USA). QA/QC was performed by introducing duplicates in the analytical procedure. Isotopic ratios are expressed in per mil (‰):

$$\delta(‰) = \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \times 1000 \quad (1)$$

where R is the ratio of $^2H/^1H$ or $^{18}O/^{16}O$ for a sample or the standard. In the present study, the VSMOW standard was adopted for both $\delta^{18}O$ and δ^2H.

Connectivity index

The connectivity index was proposed by Ransley et al. (2007). It is a simple method to assess the connectivity between surface water and groundwater, and it considers four factors: water table depth, river channel sediments, geology, and geomorphology. Each factor is assigned a score according to different conditions (Table 1). A weight is assigned to each parameter and the connectivity index can finally be calculated according to the followings (Oyarzún et al. 2014):

$$\text{CI} = 3D + 5S + 5G + 2GM \quad (2)$$

where CI is the connectivity index, D is water table depth, S is river channel sediments, G represents geology, and GM denotes geomorphology. In the present study, water table depths were determined by measurement at wells located along the river, which were situated within 500 m from the river. This distance is regarded suitable for the analyses of the stream-aquifer connectivity in this study. River channel sediments were determined by field investigation and laboratory granulometric analysis. Geology information (lithology) was obtained from field observation and previous geology maps, and geomorphology features were obtained from Google Earth and topography maps. As the entire study area is the Quaternary alluvial plain of the Weihe River, it therefore is considered as a depositional environment. According to Oyarzún et al. (2014), the specific criteria for CI classification are as follows: $-78.5 < \text{CI} < -24$, low connectivity, $-24 < \text{CI} < 53$, medium connectivity, and $53 < \text{CI} < 75$, high connectivity.

Table 1 Factors, classes and scores for calculating the connectivity index (after Oyarzún et al. 2014)

Parameter	Class	Score
Water table depth	<10 m	5
	10–20 m	3
	>20 m	0.5
River channel sediment	Sand/gravel	5
	Sandy loam/silty loam	3
	Silt/clay loam	−1
	Clay	−4
Geology	Gravel/sand	5
	Clay/sand	3
	Clay	−4
Geomorphology	Erosional environment	5
	Depositional environment	1
	Hill top	0

Hydrochemical and isotopic assessment

Hydrochemical and isotopic parameters are useful in understanding the water cycle, the variation of water environment and interactions between different water bodies (Li et al. 2013; Qian et al. 2013, 2014b). They have been used by many researchers in assessing the connectivity of surface water and groundwater (for example, Cook 2013; Dor et al. 2011; Liu et al. 2004; Liu and Yamanaka 2012; Oyarzún et al. 2014; Smith et al. 2010). If surface water and groundwater are highly connected, they would hopefully possess similar hydrochemical characteristics and isotopic signatures, while under disconnected conditions, the compositions of the surface water and groundwater will be more likely different.

In the present study, the classification criteria proposed by Oyarzún et al. (2014) were adopted to classify the connectivity into three levels: low, medium and high. These criteria are proved reasonable through a comparative study conducted by Oyarzún et al. (2014), although they are defined arbitrarily. It is considered that a difference less than 20 % in major ions between surface water and groundwater located in the same river reach will indicate high connectivity, a difference between 20 and 40 % represents a medium connectivity, while that larger than 40 % will characterize low connectivity between the surface water and groundwater. Based on stable isotopes, similar classification criteria (20 and 40 % differences) are used, which will results in thresholds ±0.7 and ±1.4 ‰ for ^{18}O and ±4 and ±9 ‰ for ^2H (Oyarzún et al. 2014).

Hydrochemical and isotopic methods may produce different classification results which are difficult to be used in water resources management. In the present study, the most repeated category is kept for major ion (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, and SO_4^{2-}) based classification of the stream, and if the classifications of a reach based on hydrochemistry, ^2H and ^{18}O differ, a medium category will be assigned to this reach (Oyarzún et al. 2014). Additionally, in case a reach includes more than one groundwater sample (for example, W1-32 and W2-2 in the midstream, and W1-35 and W2-6 in the downstream), the two closest river water and groundwater samples are considered for the classification.

Cluster analysis

Cluster analysis is a data classification technique that can group samples or indices with similar characteristics (Wu et al. 2014). It can generally be divided into two modes: Q mode cluster that is usually used to highlight spatial relationships among sample points, and R mode cluster which is able to classify the parameters into groups based on their similarity with each other (Banoeng-Yakubo et al. 2009; Wu et al. 2014). This technique has already been widely applied in various fields, such as hydrology, geology, meteorology, mining science, industry, agriculture, and environmental science (for example, Cloutier et al. 2008; King et al. 2014; Li et al. 2014c; Yidana et al. 2010). In the present study, Q mode hierarchical cluster analysis (HCA) was performed with SPSS 20.0 integrating hydrochemical parameters (pH, TDS, TH, F^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^-, HCO_3^-, COD, CO_2 and NO_2^-) and isotopes (^2H and ^{18}O).

There are several cluster techniques that can be used practically such as the furthest neighbor, nearest neighbor, centroid clustering, and the Ward's method (Wu et al. 2014). As the Ward's method is proved effective in determining clusters in hydrology and water resources (Oyarzún et al. 2014), it was adopted in the present study. The squared Euclidean distance measurement was considered to calculate the distance factor. Z-score transformation was performed to all data before they are used for cluster analysis to eliminate the impacts of unit and scale on the results.

End member mixing analysis (EMMA)

A three end member (i.e. precipitation, lateral inflow and river leakage) EMMA was performed in the study, because these three end members are the main recharge sources of groundwater during dry season in the area. The EMMA was proposed by Christophersen et al. (1990) and Hooper et al. (1990), and it follows the following assumptions (Liu and Yamanaka 2012): (1) the concentrations of substances from end member solutions are fixed; (2) the mixing process is linear; (3) the substances are conservative tracers; and (4) the mixing effects of solutions revealed by Qian and Li (2011, 2012), and Chen et al. (2013) are neglected. The concentrations of $\delta^{18}O$, δ^2H and Cl^- were used to estimate the contribution ratio of the potential sources in the present study following the three end member model proposed by Liu and Yamanaka (2012).

$$R_r = \frac{(\delta_s - \delta_i)(c_p - c_i) - (c_s - c_i)(\delta_p - \delta_i)}{(\delta_r - \delta_i)(c_p - c_i) - (c_r - c_i)(\delta_p - \delta_i)} \quad (3)$$

$$R_p = \frac{(\delta_s - \delta_i)(c_r - c_i) - (c_s - c_i)(\delta_r - \delta_i)}{(\delta_p - \delta_i)(c_r - c_i) - (c_p - c_i)(\delta_r - \delta_i)} \quad (4)$$

$$R_i = 1 - R_r - R_p \quad (5)$$

where R is the contribution ratio, δ is the value of ^{18}O or ^2H, c is the concentration of Cl^-, and the subscripts s, i, p and r represent, respectively, the sampled water at each site, groundwater from lateral inflow (sample W2-38), local precipitation (sample P) and river water at the upstream (sample R2-1). In case that the plots of some samples fall outside of the model domain defined by the three end members, the contribution ratios of the outliers can be estimated following the geometrical approach described by Liu et al. (2004).

Results and discussion

Characterization of groundwater and river water chemistry

The geochemical data of the collected groundwater and river water samples were analyzed statistically to reveal their general geochemical characteristics and judge preliminarily the hydraulic relationships between them. The results are shown in Table 2.

As shown in Table 2, the concentrations of K^+ and Na^+ in river water range from 17.80 to 27.70 mg/L and from 65.10 to 141.00 mg/L, respectively, which is a little higher than those in groundwater. This may be due to the pollution from human activities. The concentrations of Ca^{2+} and Mg^{2+} in groundwater along the river, however, are higher than those in river water, which is probably attributed to carbonate mineral dissolution, as carbonate minerals such as calcite and dolomite are prevalent in the alluvial plain of the Weihe River (Li et al. 2014b). The abundances of cations in river water and groundwater, based on their mean values, are $Na^+>Ca^{2+}>K^+>Mg^{2+}$ and $Ca^{2+}>Na^+>Mg^{2+}>K^+$, respectively.

Regarding major anions, HCO_3^- is the most prevalent one in both river water and groundwater, followed by SO_4^{2-} and Cl^-. The similar order of abundances for anions in river water and groundwater indicates, to some degree, a close connection between river water and groundwater. However, the concentrations of SO_4^{2-} and Cl^- in river water are higher than those in groundwater, which is indicative of strong effect of evaporation and concentration that may have significant impacts on the concentrations of SO_4^{2-} and Cl^-.

TDS, TH, NO_2^-, NH_4^+, and NO_3^- are important parameters of water quality. In the present study, TDS ranges from 572.00 to 820.00 mg/L, while that in groundwater ranges within 348.00-788.00 mg/L. TH in river water varies from 292.80 to 327.80 mg/L, with a mean of 306.13 mg/L, and that in groundwater ranges from 270.20 to 558.00 mg/L, with an average of 373.82 mg/L. The concentrations of TDS and TH in both river water and groundwater are very close, respectively, indicating again the connection between river water and groundwater.

Table 2 Statistical analysis of physiochemical parameters of river water and groundwater

Index	Shidi River water				Groundwater along the Shidi River			
	Min	Max	Mean	SD	Min	Max	Mean	SD
K^+	17.80	27.70	22.10	4.14	1.84	10.36	6.02	3.48
Na^+	65.10	141.00	94.90	33.06	12.10	35.90	26.88	9.52
Ca^{2+}	91.20	97.20	94.20	2.45	82.20	158.30	114.02	24.68
Mg^{2+}	13.40	22.50	17.23	3.85	12.20	39.50	21.64	9.67
Cl^-	86.90	124.10	101.07	16.43	19.50	53.20	39.70	11.58
SO_4^{2-}	98.50	259.40	160.93	70.46	55.20	142.20	91.04	35.02
HCO_3^-	180.00	350.90	248.17	73.93	271.50	369.20	325.86	43.36
F^-	0.98	1.95	1.52	0.40	0.39	0.63	0.47	0.09
TDS	572.00	820.00	686.67	102.10	348.00	788.00	513.60	147.67
pH	7.95	8.07	8.00	0.05	7.86	8.30	8.11	0.14
TH	292.80	327.80	306.13	15.46	270.20	558.00	373.82	97.32
NO_2^-	28.33	65.60	52.98	17.43	0.00	0.38	0.12	0.14
NH_4^+	3.96	29.59	13.08	11.70	0.03	0.10	0.05	0.03
NO_3^-	16.80	35.68	29.08	8.69	2.50	135.33	31.29	52.20
COD	10.90	16.70	14.63	2.64	0.80	1.20	1.02	0.15

SD standard derivation

NO_2^-, NH_4^+, and NO_3^- are indicators of anthropogenic pollution (Wu et al. 2013), and they can transform into each other under proper conditions. In this study, river water has higher NO_2^- and NH_4^+ but lower NO_3^- than groundwater. This means that shallow aquifers are under an oxidative condition, and NO_2^- and NH_4^+ have been transformed into NO_3^- during and after leaching into groundwater. Higher concentration of COD in river water but lower concentration of it in groundwater indicates that organic matter has been degraded in the oxidative condition of the shallow aquifers.

Connectivity index

The connectivity of each reach determined by CI is shown in Table 3. This method yields a medium connectivity conditions in all reaches, but these reaches receive different scores of factors. The upstream receives the highest river channel sediment score, because the sediment in upstream is mainly gravels and sands. The midstream and downstream receive relatively smaller channel sediment scores, as river channel sediment transits to sandy loam and/or silty loam with the river flows downstream. As the river flows away from the Qinling Mountains, groundwater level depth decreases, resulting in the increase of water level depth scores from upstream to downstream. In upstream, groundwater level depth is greater than 10 m, and the two upstream wells receive a score of 3, while all wells in the midstream and downstream, except HX1-39, show shallower water depth, receiving a score of 5.

It should be noted that the distance of water level measurement well to the river can be an uncertain factor impacting the final category, because water level in a well will alter as the well approaches the river. In the research conducted by Oyarzún et al. (2014), a distance of less than 1000 m from the river is considered suitable for the analysis. However, we believe that wells situated closer to the river will provide more accurate information on the connectivity. In the present study, all water level measurement wells are situated less than 500 m from the river. Besides, we hold the belief that more than one well along the river should be measured for water level information, as more wells may probably help to reduce uncertainty of connectivity assessment, even though water level depth receives a smaller weight (3) than geology and river channel sediment which receive a weight of 5 each. This is especially true when information about geology and river channel sediment keeps the same across the entire study area, just as the situation in the present study.

Although the overall connectivity assessed by CI is medium along the Shidi River, it is meaningful and important to describe the spatial variation in more detail. A figure was generated to show the spatial distribution of CI along the Shidi River in Fig. 4. As shown in Fig. 4, the whole river can be divided into three subsections based on the calculation results of CI. The upstream of the river (R1) comprises the first subsection (indicated by pink line in Fig. 4) which has a CI value of 51, the biggest value among the three subsections. This is because the river channel sediments and geology in the upper stream of the river is mainly sand/gravel that has great hydraulic conductivity.

Table 3 Degree of connectivity calculated by CI for each river reach

Reach	Water level measurement well	Distance of well to the river (m)	Water level depth (m)	Water table depth score	River channel sediment score	Geology score	Geomorphology score	CI	Connectivity category
Upstream	W1-13	201	11.58	3	5	3	1	51	Medium
	HX1-19	247	13.61	3	5	3	1	51	Medium
Midstream	HX1-39	266	13.595	3	3	3	1	35	Medium
	W2-2	354	8.02	5	3	3	1	41	Medium
Downstream	W1-35	160	5.585	5	3	3	1	41	Medium
	HX2-88	460	5.43	5	3	3	1	41	Medium
	HX2-89	91	6.031	5	3	3	1	41	Medium

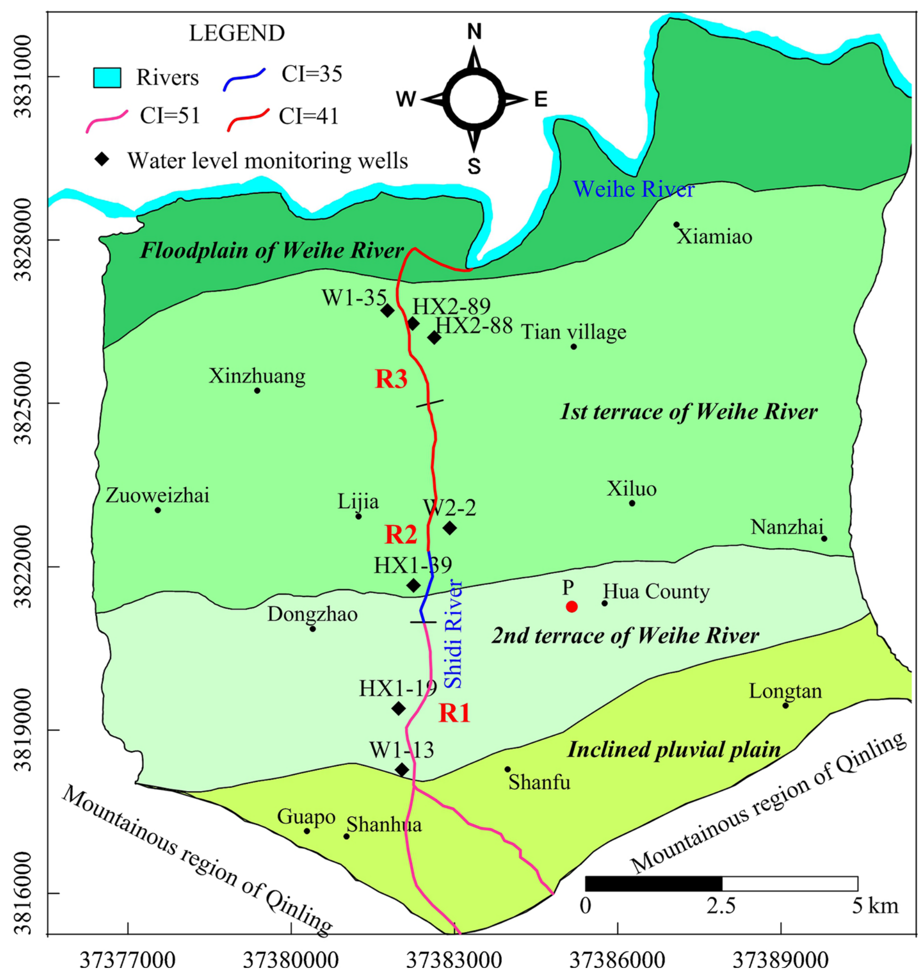


Fig. 4 Spatial variation of connectivity based on CI

However, in the upper stream of the river, water level depth is great, making river water difficult to infiltrate into groundwater. The middle reaches of the river (R2) can be divided into two subsections. According to our field investigation, river channel sediment in the southern subsection of R2 is mainly sandy loam/silty loam, which constrains the infiltration of river water to groundwater. The water level depth in this subsection is also great, resulting in the least CI (CI = 35) value among the three subsections. Although the northern subsection of R2 has the same river channel sediment as the southern subsection, it has a greater CI value (CI = 41) than the southern subsection, because the northern subsection of R2 has shallower water level depth than the southern subsection. The lower reaches of the Shidi River (R3) has the same CI value as the northern subsection of R2.

Theoretically, the grain size of the river sediments becomes smaller as the river runs over, and the infiltration capacity becomes weaker. Water level, however, becomes much shallower in the lower reaches of the river, resulting in a bigger CI value than the southern subsection of R2. In the present study, geology and geomorphology are the same for all reaches of the river, which means that geology and geomorphology have the same effect on CI values of the three reaches.

Hydrochemical assessment

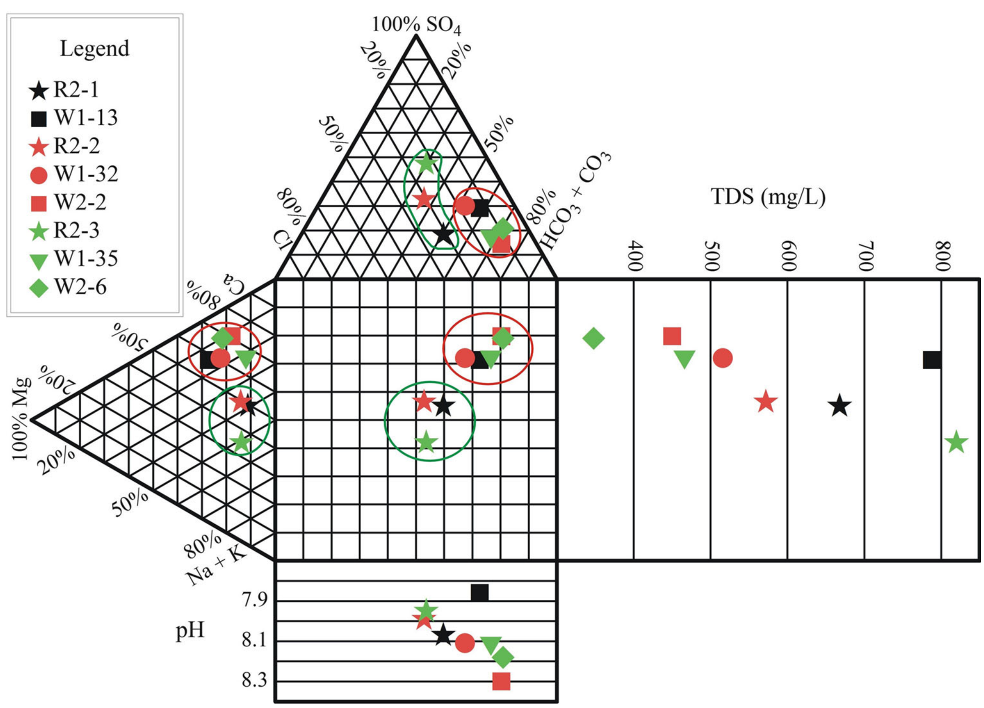
Durov diagram (Fig. 5) was used in the present study for the hydrochemical interpretation of the difference between surface water and groundwater along the river. Figure 5 shows that two main groups can be recognized with regard to cations and anions, as well as hydrochemcial types indicated in the square zone of the Durov diagram.

Group 1 includes all groundwater samples (W1-13 from the upstream, W1-32 and W2-2 from the midstream and W1-35 and W2-6 from the downstream), while group 2 is composed of only surface water (R2-1, R2-2 and R2-3 from the upstream, midstream and downstream, respectively). In group 2, an increasing trend for the concentration of SO_4^{2-} and a decreasing trend for that of HCO_3^- in the direction of river water flow can be recognized. A decreasing trend of pH in river water is also observed. For the concentrations of Ca^{2+} and Na^+ in samples of group 2, a notable decrease of Ca^{2+} and an increase of Na^+ can be distinguished from the midstream to downstream, while the transitions from the upstream to midstream are not observed. This indicates that strong effect of evaporation and concentration, which is responsible for the increase of SO_4^{2-} and Na^+ and the decrease of HCO_3^- and Ca^{2+}, has occurred in surface water. Groundwater in group 1 generally possesses higher concentrations of Ca^{2+} and HCO_3^- and lower Na^+ than surface water in group 2, because the effect of evaporation and concentration of groundwater is much weaker than surface water considering the great groundwater level depth in this area.

Given the different hydrochemical groups that the surface water and groundwater samples are classified into in this study, it is evident that the connectivity between surface water and groundwater is not high. However, judged from the triangular regions of the Durov diagram, it is obvious that the differences of major ions between surface water and groundwater in the same reach generally fall within 20–40 %, indicating a medium connectivity condition in general.

HCA produces similar results as hydrochemical interpretation. The dendrograms (Fig. 6) show that two main clusters can be obtained (C1 and C2). The first cluster includes groundwater samples, while the second cluster includes river water. The HCA results indicate again that groundwater and surface water in the study area may not have high connectivity. The Stiff diagrams below the dendrograms show that HCO_3^- and Ca^{2+} are the dominant anion and cation, respectively, in groundwater, while HCO_3^- is the most important anion in surface water, followed by SO_4^{2-}. Ca^{2+} and Na^+ are both presented in high

Fig. 5 Durov diagram of water samples



proportions in surface water. The differences in hydrochemcial compositions of surface water and groundwater, revealed by Stiff diagrams, prove that the connectivity between surface water and groundwater in the area is not high.

Two important conclusions can be drawn from above analyses. First, the distinguished groups recognized from the Durov diagram and the dentrograms of HCA indicates that the connectivity between river water and groundwater in the study area is not very high, and the connectivity can be determined simply by the differences of major ions indicated in the square zone of the Durov diagram. Second, HCA is a useful tool to classify water samples that possess different chemical compositions and evolution mechanisms, and it can act as a strong support for understanding the results obtained from the Durov diagram. However, it is helpless in determining the connectivity between river water and groundwater.

Stable isotopes

Isotopic signature of river water and groundwater was presented in Fig. 7. The global meteoric water line (GMWL) and local meteoric water line (LMWL) were also added for analysis. The GMWL was established by Craig (1961), and is expressed as Eq. (6). The LMWL determined by Qin et al. (2005) for precipitation in Xi'an, a very close place to the study area, is expressed as Eq. (7). The regression lines for sampled groundwater and river water are expressed as Eqs. (8) and (9) with squared correlation coefficients (r^2) being 0.942 and 0.999, respectively.

$$\delta^2H = 8^{18}O + 10 \quad (6)$$

$$\delta^2H = 7.5^{18}O + 6.1 \quad (7)$$

$$\delta^2H = 7.49^{18}O + 2.12 \quad r^2 = 0.942 \quad (8)$$

$$\delta^2H = 3.92^{18}O - 26.52 \quad r^2 = 0.999 \quad (9)$$

As shown in Fig. 7, all water samples plot below the GMWL and LMWL and the slops of the regression lines of the sampled groundwater and river water are lower than that of GMWL and LMWL, indicating significant evaporation processes in the area. However, the slop of the regression line of sampled river water is lower than that of groundwater, which indicates that the evaporation process of groundwater is much weaker than the river water. Furthermore, the regression line of groundwater is quite close to LMWL determined by Qin et al. (2005), which means that local precipitation is an important recharge source of groundwater in the area.

During the sampling period, $\delta^{18}O$ and δ^2H for groundwater ranged from −8.54 to −7.48 ‰ and from −62.42 to −54.02 ‰, respectively. The $\delta^{18}O$ and δ^2H for river water ranged from −8.19 to −7.15 ‰ and from −54.60 to −58.67 ‰, respectively. The plot of R2-1 overlaps some groundwater samples, which suggests that river water

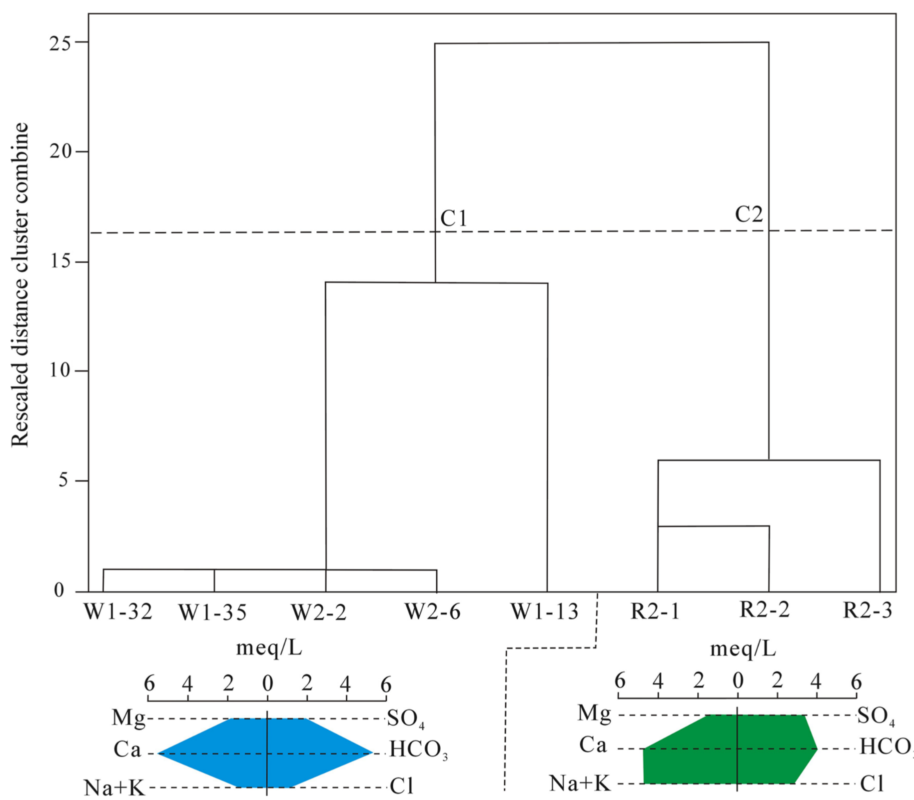


Fig. 6 Clusters obtained from HCA and the Stiff diagrams based on the mean concentrations of major ions in each cluster

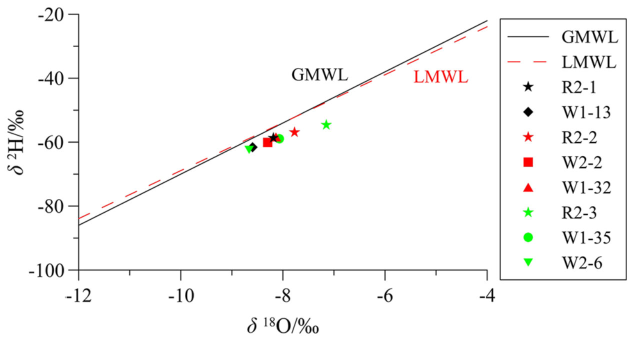


Fig. 7 Plots of δ^{18}O and δ^{2}H

represented by R2-1 is a significant recharge source of local groundwater. The connectivity estimated by δ^{18}O and δ^{2}H was shown in Table 4. Generally, a medium connectivity is recognized in the three reaches of the river, but in the midstream, the estimation result of δ^{2}H (high connectivity) is different from that of hydrochemistry and δ^{18}O (both medium connectivity), thus it is assigned a medium connectivity arbitrarily. Considering the uncertainty of isotopic analysis, it is acceptable to carry out such an arbitrary assignment.

It can be seen from Table 4 that the results obtained by different methods are quite similar, which indicates that the estimation results are reasonable, and thus can be used in future water resources management. The CI approach which considers river channel sediment, geology and geomorphology represent the long term conditions, while the results from hydrochemistry and isotope represent short term conditions (Oyarzún et al. 2014). These methods can be used at a basin scale, providing fast assessment for the surface water and groundwater relationships in a given watershed system. There are, however, some uncertainties to some degree.

Comparison of the three approaches

There are two important results obtained from the above analysis. First of all, the results from CI, hydrochemistry and isotopes all indicate that the three reaches of the Shidi River are moderately connected. This conclusion is helpful for the rational management of water resources in this area. Second, the methods using CI, hydrochemistry and isotope to estimate the connectivity of surface water and groundwater are suitable, which can be adopted in various studies to estimate the relationships between surface water and groundwater, as well as groundwater recharge.

However, it is interesting to discuss further the merits and drawbacks of each of the three approaches. The formulas and theories of CI are easy to understand and it can provide preliminary results of hydraulic connectivity assessment easily. It doesn't require any physicochemical and isotopic analyses, thus saving time and money for water sampling, preservation, pretreatment, and lab analysis. However, calculation of CI requires an overall understanding of the hydrological, geological, hydrogeological, and geomorphological conditions of the area to be assessed. The information regarding geological, hydrogeological and geomorphological conditions of the area, however, is sometimes difficult to obtain, and sometimes the information collected has hardly enough resolution (Information has to be deduced from large scale geological and geomorphological maps), which results in the low accuracy of connectivity assessment for small scale regions. Besides, the CI approach considers only four factors, three of which, except water level depth, cannot be representative of short term hydrodynamic variations. This further reduces the accuracy of the assessment results.

Hydrochemical and isotopic approaches can reveal short term variation of hydrogeological and hydrodynamic conditions. They, especially the isotopic approach, can provide a more precise measurement of hydraulic connectivity between surface water and groundwater. However, water sampling, preservation, transportation and lab analysis all require additional time and money, which may constrain the number of samples to be sampled and thus limit the accuracy of the assessment. This is especially true for isotopic analysis, because the number of laboratories that can perform qualified isotopic analysis is rather limited in China and even in the world.

Considering the expense, accuracy and workload, it is wise to adopt the three methods simultaneously in the hydraulic connectivity assessment. The CI approach can be used for a preliminary assessment, while hydrochemcial and isotopic approaches are used for results validation and verification. The number of samples for physiochemical analysis can be a little big, while that for isotopic analysis can be small, because physiochemical analysis is much simple and cheaper than isotopic analysis.

Table 4 Comparison of connectivity between river water and groundwater estimated by different approaches

Reach	CI	Hydrochemistry	δ^{18}O	δ^{2}H	Final connectivity category
Upstream	Medium	Medium	Medium	Medium	Medium
Midstream	Medium	Medium	Medium	High	Medium
Downstream	Medium	Medium	Medium	Medium	Medium

Contribution ratio estimation

The calculation of transfer rate between surface water and groundwater is as important as the assessment of connectivity. Whereas, the connectivity estimation can only provide information on to which extent the river water is connected with groundwater. In this section, the contribution ratios of three groundwater recharge sources will be calculated using the EMMA. Figure 8 shows the relationships of Cl^- with $\delta^{18}O$ and δ^2H, respectively. As can be seen from Fig. 8a, all sampled groundwater and river water, except sample R2-3, falls within the triangular region (EMMA model domain) defined by local precipitation (sample P, denoting precipitation recharge), upstream groundwater (W2-38, representing lateral groundwater inflow) and upstream river water (R2-1, representing river leakage), which indicates that groundwater and river water along the Shidi River is recharged mainly by the three sources. The contribution ratios can be calculated by Eqs. (3) to (5). As sample R2-3 falls out of the model domain (Fig. 8a), the geometrical approach described by Liu et al. (2004) was applied to estimate the transfer rate for this sample. Similarly, the model domain defined in Fig. 8b can also be used to calculate the contribution ratios

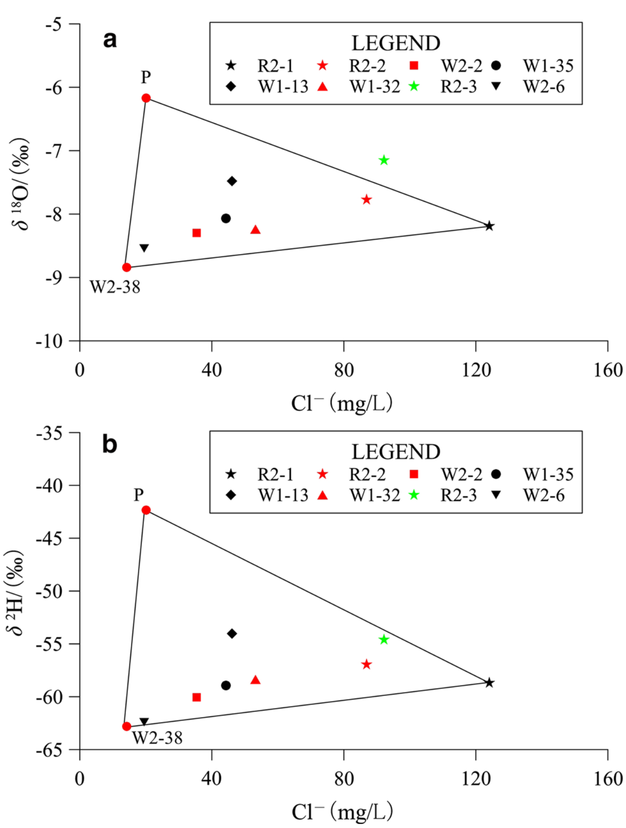


Fig. 8 End member mixing models established based on the relationships of Cl^- with **a** $\delta^{18}O$ and **b** δ^2H

of the recharge sources. The results are interpreted in Fig. 9.

Sample R2-3 can be identified with basically two recharge sources: precipitation and river water from upstream. The contribution ratios of the two sources ranged from 26.1 to 40.5 and from 59.5 to 69.6 %, respectively. All groundwater samples are plotted in the inner of the trilinear diagram in Fig. 9, which indicates that the three sources (precipitation, river recharge and groundwater lateral inflow) all contributed to some degree to the groundwater along the river. According to the calculation, the contribution ratios of precipitation, river recharge and groundwater lateral inflow in the upstream ranged from 35.5 to 44.4, 26.6 to 27.0 and from 28.9 to 35.5 %, respectively. The contribution ratios of the three sources in the midstream ranged from 9.6 to 15.8, 18.4 to 18.8 and 65.7 to 71.6 %, respectively, and those in the down streams were 13.6 to 22.6, 26.2 to 26.7 and 51.3 to 59.8 %, respectively. The contribution ratio of river leakage to groundwater shows a basically decreasing trend in the direction of river flow, as the river channel sediment particles tapers. Overall, groundwater lateral inflow contributes the most to the groundwater along the entire river, especially in the midstream and downstream, and then followed by river leakage and precipitation. Again as previously discussed, a medium connectivity between river water and shallow groundwater can be identified, as the river water and groundwater samples separate from each other in the diagrams and the contribution ratios of river leakage to groundwater is not high.

It should be noted that groundwater lateral inflow discussed above includes the portion from irrigation return flow, although there is no irrigation during the dry season (from December to the first half of April). The study area is a part of the agricultural zone of Guanzhong Basin. Groundwater is usually abstracted for irrigation purpose in the second half of April or May every year. A portion of irrigated water will then infiltrate into shallow aquifer. This portion becomes a part of groundwater lateral inflow that flows towards the river. Another important issue that deserves to be mentioned here is that the contribution ratios calculated in the present study is relative. Numerical modeling of groundwater flow can be carried out to calculate the absolute amount of each recharge source, which is obviously the concern of future studies.

Conclusions

This paper used connectivity index, hydrochemical interpretation, stable isotope techniques and cluster analysis to assess the connectivity between river water and shallow groundwater. End member mixing models based on the

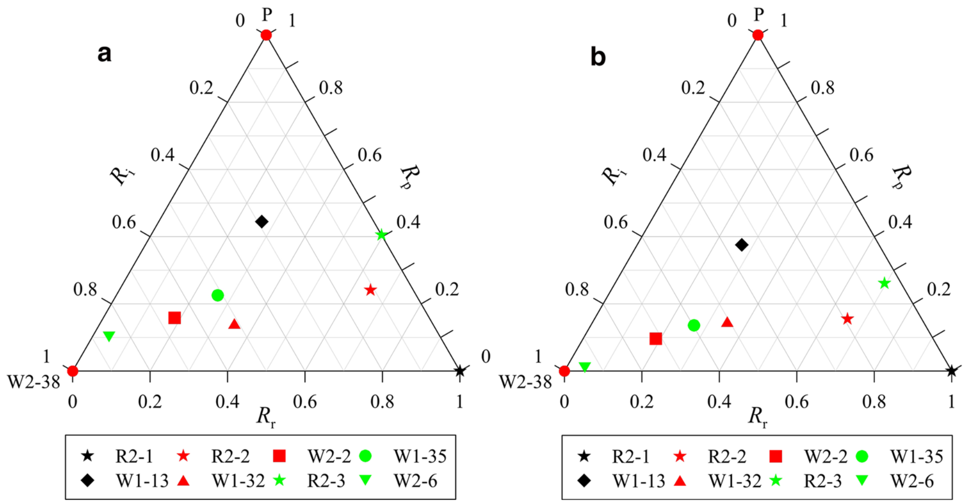


Fig. 9 Contribution ratios by the three end-member models (P in the upper angle is local precipitation, W2-38 in the lower left angle represents groundwater inflow, and the sample R2-1 located in the lower right denotes river water) established based on the relationships of Cl^- with **a** $\delta^{18}O$ and **b** δ^2H

relationships of Cl^- with $\delta^{18}O$ and δ^2H were used to estimate the contributions of local precipitation, river leakage and lateral inflow to the total groundwater recharge. Main conclusions can be drawn as follows.

- Statistical analysis of hydrochemical data reveals certain similarities between river water and groundwater along the river. Especially, the major contaminants such as TDS, TH, NO_2^-, NH_4^+, and NO_3^- indicate certain connections between river water and groundwater along the river.
- The CI approach yields a medium connectivity conditions in all reaches of the Shidi River. The CI approach considers water table depth, river channel sediments, geology and geomorphology which, except water level depth, represent stable conditions derived from long term geological and morphological transitions. Geology and geomorphology have the same effect on CI values of the three reaches of the river, while water table depth and river channel sediments are responsible for the spatial variation of the connectivity.
- The distinguished groups recognized from the Durov diagram and the dentrograms of HCA determine a medium degree of connectivity for all reaches of the river. Isotopic signature analysis produces similar results as hydrochemistry. Based on the assessment results from hydrochemistry and isotopes, it is determined that the relationship between river water and shallow groundwater is moderately connected.
- The contribution ratios estimated using the EMMA indicate that groundwater lateral inflow is the most important recharge source to the groundwater along the Shidi river, especially in the midstream and downstream. The contribution of groundwater lateral inflow ranges from 28.9 to 71.6 %. The contribution of river leakage ranges from 18.4 to 27.0 %, representing moderate recharge intensity, and it shows a basically decreasing trend in the direction of river flow.
- Hydraulic connectivity assessment based on CI requires a good understanding of some information that is sometimes difficult to obtain, such as the hydrological, hydrogeological, geological, and geomorphological conditions of the assessed regions, while physiochemical and isotopic approaches will cost additional expenses and time for water sampling, preservation and analysis. Therefore, the CI approach can be adopted for the preliminary assessment of hydraulic connectivity, while the physiochemical and isotopic approaches can be used as a tool for results validation and verification.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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