Catchment-scale surface water-groundwater connectivity on China's Loess Plateau

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A B S T R A C T

Thick loess deposits (up to 200 m deep) and a large unsaturated zone (up to 100 m below the soil surface) complicate the interactions between surface water and groundwater in China’s Loess Plateau, especially in catchments characterized by tableland-gully topography in this region. In the Heihe watershed, electrical conductivity (EC), chloride (Cl) concentrations, and stable water isotope data (δD and δ18O), obtained during dry and wet seasons in the period of 2012–2014 are used to determine the relationship between surface water and groundwater. EC and Cl concentrations are found to be unsuitable for analyzing the relationship between surface water and groundwater. Stable water isotope data indicate a gaining surface water system, i.e., groundwater and gully runoff both recharge streamflow. Further, groundwater appears to dominate the hydrologic cycle in the watershed. Therefore, water resources management on China’s Loess Plateau should pay more attentions to groundwater protection.

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1. Introduction

Water shortages, including runoff reduction and groundwater depletion, have been observed worldwide (Milliman et al., 2008; Rodell et al., 2009; Wada et al., 2010; Xu et al., 2010). For effective management of water resources, it is fundamental to determine whether surface water-groundwater connectivity is present or not, and in what manner this connectivity exists (e.g., a connected – a gaining or losing surface water system – or disconnected system – completely disconnected system or a transitional state) (Banks et al., 2011; Brunner et al., 2011; Chiogna et al., 2014; Penna et al., 2014; Song et al., 2006; Woessner, 2000). Although important, this information is difficult to be obtained in some regions, especially for those with the complicated hydrologic system.

China’s Loess Plateau (CLP) is subject to severe soil erosion and water shortages due to intensive rainstorms, steep landscapes, low vegetation cover, highly erodible loess soil, and a semiarid to arid climate (Li et al., 2009). Over the past 50 years, the land surface condition has been substantially changed by the soil conservation measures (Sun et al., 2015), and the climate has become drier and warmer (Li et al., 2010). As a result, both streamflow and groundwater storage have been observed to decrease in most catchments (Gao et al., 2015; Gao et al., 2016; Zhang et al., 2008; Zhao et al., 2014). However, on the CLP, the relationships between streamflow reduction and groundwater depletion are still poorly understood.

The hydrological processes on CLP are complicated due to a very thick loess layer (up to 200 m) and a deep unsaturated zone (up to 100 m). For deep unsaturated zones at steady state with low water content, moisture movement is dominated by the upward movement of vapor, and groundwater recharge is negligible (Ross, 1984). Groundwater recharge on CLP in the form of piston flow is therefore limited due to low precipitation and the existence of dried soil layers with low water contents (Li, 1983). According to this assumption, the groundwater likely contributes little to surface water. However, hydrometric-based hydrograph separation shows that groundwater contributes more than 50% to streamflow (Dou et al., 2009; Zhu et al., 2010), suggesting strong surface water-groundwater connectivity. Importantly, however, the type of surface water-groundwater connectivity remains unclear.

CLP consists of two main landscapes: hilly-gully regions and tableland-gully regions, with different hydrologic systems. In the hilly-gully region, the steep slopes make rainfall discharge quickly into gullies; however, in the tableland-gully region, almost all rainfall infiltrates into soils on the flat tablelands. The differences in the hydrologic systems are likely to cause different interactions between surface water and groundwater (Liu et al., 2010; Song et al., 2009; Su et al., 2009). In the hilly-gully region, observations have revealed significant surface water-groundwater interactions, with fluctuating stable water isotope concentrations of groundwater in the middle reaches due to varying water sources including precipitation, direct surface runoff, isotopically-enriched surface water, and/or lateral recharge of adjacent...
groundwater (Liu et al., 2010). However, it is unclear about the interactions (if any) between groundwater and surface water in the tableland-gully region.

The use of hydrometric techniques is traditional but important for identifying the role of surface water or groundwater in the hydrologic system. Based on separation methods such as recession curve displacement technique (Rutledge and Daniel, 1994) and digital filter method (Arnold et al., 1995), the streamflow can be separated into groundwater and rainfall-induced runoff. However, the results from hydrometric methods have been challenged by the geochemical hydrograph separation technique; for example, stream discharge responds promptly to rainfall but with dominant flows comprised of water that can be years or decades old (Kirchner, 2003; McDonnell and Beven, 2014). The tracer-based methods, especially those using the stable isotopes of water, provide a useful technique for hydrograph separation. They can be used to qualitatively interpret or quantify the role of each component by mass balance methods (Brkić et al., 2016; Klaus and McDonnell, 2013; Liu et al., 2015; Srdoc et al., 1982).

The objective of this study is to determine the surface water-groundwater connectivity in the tableland-gully region of CLP. Specifically, several aspects will be analyzed and discussed: (i) How do the hydrochemical characteristics of the surface water and groundwater vary over space and time? (ii) What is the relationship between surface water and groundwater? (iii) What implications does the identified surface water-groundwater connectivity have for water resource management?

2. Materials and methods

2.1. Study area

The study site is the Heihe catchment in the southern region of CLP (Fig. 1). The catchment has an area of 1506 km². The annual mean precipitation is 571 mm with 55% falling in July through September, and the mean annual temperature is 9.4 °C (1961–2012). The annual mean runoff depth is 46.4 mm (1961–2012) accounting for 9% of the annual mean precipitation. Low flows occur from December to June, while high flows occur from July to September. The water table depth fluctuates between 30 and 100 m below the soil surface.

The tableland-gully region consists of two landforms, i.e. flat tablelands and gullies with steep slopes. On tablelands, almost all rainfall infiltrates into soils and recharges groundwater, and then groundwater discharges to gullies and the main channel. Rainfall falling in the gullies is directly converted to runoff due to the steep slopes (approximately 36% of the whole catchment has a slope gradient greater than 15°). As the main channel of the river cuts deeply below the bedrock of the tableland, it also obtains groundwater from confined aquifers. Therefore, streamflow in the main channel can obtain water from gully runoff and groundwater. However, it is not clear whether the streamflow in the main channel can also recharge groundwater.

The location of the tablelands and gullies in the Heihe catchment are unevenly spatially distributed. All the tablelands are located in the lower reach, while the upper reach is dominated by gullies. With a loess layer thicker than 150 m (Fig. 2), the tablelands have great potential for water storage; therefore, the spatial variation in terrain might have impacts on the water quantity from different sources.

The hydrogeological conditions are similar across the whole catchment (Fig. 2). The horizontal Neogene/Cretaceous mudstone and sandstone beds (N2 and KZ series) are covered by three layers of loess. The top layer is composed of Malan Loess (Q3, upper Pleistocene) with an approximate thickness of 15 m. The middle layer is composed of Lishi Loess (Q2, middle Pleistocene) with a thickness of 71–74 m, which forms an aquifer due to unconsolidated sediments of relatively high porosity. The third layer originates from Wucheng Loess (Q1, lower Pleistocene) with a thickness of 22–78 m, which forms an aquitard due to its low permeability.

2.2. Hydrochemical water sampling and data analysis

Samples for precipitation, runoff in the tributary gullies (hereafter referred to as gully runoff), groundwater along the main channel (referred to as groundwater), and streamflow in the main channel have been collected in the Heihe watershed. Precipitation was sampled on a daily basis from one site in the lower reach in 2005, 2010 and during the period 2012–2014. Streamflow, gully runoff and groundwater were sampled twice per year during the period 2013–2014 (see the sampling sites in Fig. 1). The first sampling campaign in June is representative of the dry season due to the greatest evapotranspiration and the lowest flow rates, while sampling campaigns during August to October are representative of the wet season due to the highest precipitation amounts and flow rates (Fig. 3). Groundwater samples were taken from both wells and springs. To investigate the impacts of rainfall on streamflow, we collected samples after four separate rainfall events (Table 1) in June 2012, August 2012, September 2013, and June 2014.

For all samples, with the exception of rainfall samples, EC, pH, and temperature were measured in-situ using a portable instrument,
SevenGo Duo pro™ SG78 (Mettler Toledo). Stable water isotope compositions ($\delta D$ and $\delta^{18}O$) of all water samples were determined by the LCR IWA-4SEP water-vapor isotope analyzer with a precision of 0.2‰ for $\delta D$ and 0.03‰ for $\delta^{18}O$ for liquid water. Cl concentrations of samples taken in 2014 were obtained using a DIONEX ICS-1100 Ion Chromatography System.

The spatiotemporal EC, Cl, and stable water isotope ($\delta D$ and $\delta^{18}O$) data were analyzed to give insights into the water exchange among the streamflow, gully runoff and groundwater. As Cl was only determined for 2014, and it had similar spatiotemporal variability as EC (described in the Results), EC instead of Cl was analyzed in detail.

3. Results

3.1. Spatial variation in hydrochemical indices

The 2012–2014, catchment-averaged EC, $\delta D$, and $\delta^{18}O$ data were shown in Table 2. EC is the lowest in the streamflow, the highest in the groundwater, and intermediate in gully runoff. As Cl was only determined for the streamflow samples in 2014, the values were not presented; however, they showed good agreement with EC.

There is some spatial variation in hydrochemistry (Fig. 4). EC and Cl concentrations in streamflow are relatively uniform throughout the catchment, albeit with a slight increase in concentration with distance downstream. By comparison, gully runoff and groundwater exhibit greater spatial variability through the catchment, and both are relatively uniform in the upper reach and generally increasing in the lower reach. Like EC and Cl, the $\delta D$ of streamflow is also relatively uniform throughout the catchment, with the exception of those samples collected following rainstorms (e.g. June 2012). The $\delta D$ of gully runoff and groundwater both become more depleted with distance downstream.

3.2. Temporal variation in hydrochemical indices

The seasonal averages (separated by dry season and wet season) of EC, $\delta D$, and $\delta^{18}O$ data for streamflow, gully runoff and groundwater were calculated to determine the overall seasonal differences (Table 2). The hydrochemical data for groundwater appear temporally-invariant since they remain largely constant during the different seasons. By comparison, the isotopic composition of streamflow and gully runoff in dry seasons is more depleted (more negative) than in wet seasons. For example, streamflow has a $\delta D$ of $-64.7$‰ and $-63.7$‰ for the dry and wet seasons respectively, while gully runoff has the corresponding values of $-68.3$‰ and $-66.7$‰. This seasonal difference in isotopic composition conflicts with what we would have expected; due to limited water inputs and strong evaporation, we would have expected that the dry season samples would be more enriched (more positive) than those in the wet season.

The seasonal difference was further investigated by comparing samples from different years and different seasons (Fig. 4). EC and $\delta D$ of

![Fig. 2. Hydrogeological profiles of the study area.](image)

![Fig. 3. Mean monthly precipitation (P), potential evapotranspiration (ET0) and runoff (R) in the Heihe watershed.](image)

### Table 1

<table>
<thead>
<tr>
<th>Sampling day</th>
<th>Antecedent rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>Amount, mm</td>
</tr>
<tr>
<td>2012-06-30</td>
<td>2012-06-29</td>
</tr>
<tr>
<td>2012-08-27</td>
<td>2012-08-26</td>
</tr>
<tr>
<td>2013-06-29</td>
<td></td>
</tr>
<tr>
<td>2013-09-01</td>
<td>2012-08-28</td>
</tr>
<tr>
<td>2014-06-24</td>
<td>2013-06-19</td>
</tr>
<tr>
<td>2014-10-17</td>
<td></td>
</tr>
</tbody>
</table>
streamflow during dry seasons typically are more positive and more enriched, respectively, than those in wet seasons. However, it is apparent that they are influenced by antecedent rainfall events. For example, a rainfall with the amount of 23.5 mm occurred before the June 2012 sampling, which coincided with EC and δD of streamflow being much depleted in comparison to those in August 2012. Gully runoff and groundwater do not exhibit clear seasonal variation, with the δD of groundwater, especially, being very similar across all seasons. This suggests that gully runoff and groundwater are less sensitive to rainfall than streamflow, which might indicate different water sources.

3.3. Dual isotope comparison

Dual isotope (δD and δ18O) comparison was used to provide information about water sources and identify the relationships between different water components (Fig. 5). The volume-weighted precipitation isotopic composition anchors most data points of streamflow, gully runoff, and groundwater, which implies that the water source of this watershed is predominantly precipitation (Fig. 5a); however, the intersection point of the evaporation line (EL) and local meteoric water line (LMWL) also suggests other water sources, which will be subsequently interpreted.

The isotopic composition of streamflow in dry seasons spans a wider range than that in the wet season (Fig. 5b), implying that the isotopic composition in wet seasons is more homogeneous. The differences are perhaps caused by different flow velocities through the catchment. Low flows in the dry season are subject to more and stronger evaporation. As a result, its isotopic composition becomes more positive with distance downstream, than it would do in the wet season when high flows accelerate the movement of water downstream. For streamflow data, the slope of the EL is 4.81 and its intersection with the LMWL is more positive in dual isotope space than the volume-weighted precipitation, which implies that streamflow originates from direct

Table 2

Spatiotemporal variations in electrical conductivity (EC) and stable water isotopic compositions of streamflow, gully runoff and groundwater.

<table>
<thead>
<tr>
<th></th>
<th>Streamflow</th>
<th>Runoff</th>
<th>Groundwater</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EC (μS/cm)</td>
<td>δD (%)</td>
<td>δ18O (%)</td>
</tr>
<tr>
<td></td>
<td>EC (μS/cm)</td>
<td>δD (%)</td>
<td>δ18O (%)</td>
</tr>
<tr>
<td></td>
<td>EC (μS/cm)</td>
<td>δD (%)</td>
<td>δ18O (%)</td>
</tr>
<tr>
<td>Spatial variations, averaged over both dry and wet seasons</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whole</td>
<td>628 -64.2</td>
<td>-9.0</td>
<td>636 -67.5</td>
</tr>
<tr>
<td>Upper reach</td>
<td>627 -63.7</td>
<td>-9.1</td>
<td>544 -65.0</td>
</tr>
<tr>
<td>Lower reach</td>
<td>630 -64.7</td>
<td>-8.9</td>
<td>736 -70.3</td>
</tr>
<tr>
<td>Temporal variations, averaged over the whole watershed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry season</td>
<td>643 -64.7</td>
<td>-8.9</td>
<td>587 -68.3</td>
</tr>
<tr>
<td>Wet season</td>
<td>580 -63.7</td>
<td>-9.1</td>
<td>675 -66.7</td>
</tr>
<tr>
<td>Temporal variations, averaged over different reaches</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper reach Dry</td>
<td>640 -63.5</td>
<td>-8.9</td>
<td>471 -66.4</td>
</tr>
<tr>
<td>Wet reach</td>
<td>558 -63.6</td>
<td>-9.1</td>
<td>625 -62.7</td>
</tr>
<tr>
<td>Lower reach Dry</td>
<td>642 -66.0</td>
<td>-8.8</td>
<td>714 -71.3</td>
</tr>
<tr>
<td>Wet reach</td>
<td>605 -63.8</td>
<td>-9.0</td>
<td>722 -70.0</td>
</tr>
</tbody>
</table>

Units: EC, μS/cm; δD and δ18O, ‰.
Fig. 5. Dual isotope comparison of streamflow, gully runoff and groundwater (panel b, c and d use the same legend. The equations represent the LMWL in a; and EL in b, c and d).

Fig. 6. Comparison of electrical conductivity in streamflow, gully runoff and groundwater.
precipitation and surface runoff from precipitation but is subject to strong evaporation.

The isotopic composition of gully runoff (Fig. 5c) and groundwater (Fig. 5d) both span a large range. The EL slopes are 6.09 and 5.55, respectively, and the intersections of EL and LWML are more negative in dual isotope space than the volume-weighted precipitation, suggesting that they are not only sourced from direct precipitation and rapid runoff of precipitation, but also from some other water with more negative isotopic composition.

3.4. Interactions between surface water and groundwater

The EC and δD of streamflow, gully runoff, and groundwater for each sampling campaign were plotted together (EC: Fig. 6; δD: Fig. 7) to interpret the potential interactions between surface water and groundwater. The EC data of gully runoff and groundwater typically are lower than those of streamflow in the upper reach, while higher than those of streamflow in the lower reach (Fig. 7). Cl concentrations show a similar spatial pattern to EC. According to mass balance, water with higher values of EC or Cl should be the sink of that water with smaller values of EC or Cl. Accordingly, gully runoff and groundwater appear to recharge streamflow in the upper reach, while the opposite is true in the lower reach, where streamflow appears to recharge gully runoff and groundwater.

However, these findings demonstrated by the EC and/or Cl concentrations are not supported by the isotope mass balance (Fig. 7). In most cases, streamflow is more enriched (more positive values for δD) than gully runoff, which in turn is more enriched than groundwater. Therefore, it is unlikely that the groundwater, whose δD isotope composition is depleted, is recharged by the streamflow with more positive isotopic composition.

4. Discussion

4.1. Appropriate hydrochemical indices for hydrologic systems in depositional environments

For the Heihe catchment in the CLP region, the focus of this study, different hydrochemical indices suggest differing flow paths and directions of recharge. While EC and Cl concentrations suggest flow from surface water to groundwater, the isotopic data indicate flow from groundwater and runoff to streamflow. These disparate flow path results highlight the importance of using the appropriate index/indices to interpret hydrological processes.

Theoretically, the stable isotopes of water should more accurately indicate hydrological processes and flow paths, since they are components of the water molecule and inherent labels. By comparison, ion concentration can be influenced by myriad factors, such as chemical weathering, and atmospheric and anthropogenic inputs. With a long formation period, the thick loess deposits have higher ion concentration with depth due to a gradual decrease in chemical weathering (Chen et al., 2001; Nie et al., 2015). Accordingly, the high EC or Cl concentration in groundwater is perhaps not due to recharge from surface water but from the temporal evolution of the loess deposits. Therefore, if the soil information is taken into account, the flow path interpreted from EC and Cl concentrations is also from groundwater and gully runoff to streamflow, which is in agreement with that revealed by the isotopic data.

The above results imply that the ion concentrations in water from deep loess layers are not suitable for approaches that use mass balance equations. This conclusion is supported by the results of Xiao et al. (2016) and Chen et al. (2005). From river water sampling across the CLP, Xiao et al. (2016) found that the total dissolved solids (TDS) were

Fig. 7. Comparison of isotopic compositions in streamflow, gully runoff and groundwater (dashed lines stand for the isotopic compositions of rainfall before sampling, details can be found in Table 1; rainfall before the sampling in June 2012 was not sampled).
much higher than the global average and other large rivers in China. The dissolved solutes were mainly derived from rock weathering, but with minor anthropogenic and atmospheric inputs. Further, for the period 1958–2000, an increased trend in TDS was detected for the CLP and the change trend coincided with a significant decrease in water discharge (Chen et al., 2005). The decrease in streamflow was attributed to increasing regulations of reservoirs, substantial conversion from farmland to forest and grassland, and intensive water withdrawal, as well as many other anthropogenic processes (Zhang et al., 2008; Zhao et al., 2014). Therefore, although human activities play a minor role in directly increasing dissolved solutes, they can indirectly influence the ion concentration by altering the streamflow.

Severe soil erosion on the CLP is thought to have greatly influenced nutrient loss (such as organic matter, nitrogen and phosphorus) and enriched eroded sediment (Zheng et al., 2005); thereby increasing the ion concentration in runoff. If this is the case for this study, the potential perturbation could have caused surface water to have a higher ion concentration than groundwater; however, this is not true since EC of groundwater is much higher than that of surface water in the Heihe watershed. Indeed, despite dry or wet seasons, the water samples have little sediment due to the substantial soil conservation practices implemented since the 1950s (Li et al., 2009). According to an evaluation for a small watershed (the Nanxiaohe catchment) on the CLP, approximately half of the total transported water and 94.8% of the total transported soil and nutrients have been locally retained in the selected catchment by the soil conservation practices (Xu et al., 2012). Therefore, the potential impacts of soil loss and sediment on ion concentration can be neglected.

Considering the impacts of depositional environments and human activities, the use of ion concentration for interpreting the hydrological cycle in thick depositional environments should be treated with caution. Otherwise, the conclusion about water flow in a watershed (the Nanxiaohe catchment) on the CLP, approximately half of the total transported water and 94.8% of the total transported soil and nutrients have been locally retained in the selected catchment by the soil conservation practices (Xu et al., 2012). Therefore, the potential impacts of soil loss and sediment on ion concentration can be neglected.

4.2. Surface water-groundwater connectivity

The isotopic composition of surface water, i.e. streamflow and gully runoff, is spatially variable (Fig. 4). The streamflow in the lower reach and the upstream gully runoff is more variable in terms of its isotopic composition. Temporally, the isotopic composition of streamflow in dry seasons is more positive than that in wet seasons; however, no obvious seasonal pattern is detected for gully runoff. The isotopic composition of groundwater is likely to be stable over space and time.

The spatiotemporal variations in the isotopic composition of gully runoff and groundwater are very similar, especially for those in the lower reach, but different from those of streamflow. In most cases, the isotopic composition of gully runoff and groundwater are more negative than that of streamflow, (although the opposite situation occurs when large rainstorms prior to sampling are detected) (Fig. 7). However, even with large rainstorms, the isotopic composition of gully runoff and groundwater does not change vastly when compared with those samples without antecedent rainfall (Fig. 4). Therefore, the surface water-groundwater connectivity system is likely to be a gaining surface water system, i.e. groundwater and runoff to streamflow.

This conclusion of gaining surface water system is consistent with the flow regime in Fig. 3. In the first half of the year (January to June), streamflow did not significantly change despite increasing monthly precipitation. This was due to low antecedent soil water content and high evapotranspiration, which implies that streamflow originates from groundwater in the dry season. In the second half of the year (July to December), although the streamflow was sensitive to rainfall inputs (Fig. 3), the isotopic compositions in streamflow are more negative than rainfall and more positive than groundwater (Tables 1 & 2), which suggests that groundwater still greatly contributes to streamflow. Especially, though the precipitation in November to December is similar as that in the first half of the year, the larger streamflow is caused by the delayed groundwater discharge.

4.3. Role and sources of groundwater

The surface water-groundwater connectivity system is closely related to the topography. The stream channel cuts deeper than the bedrock of the tablelands and is at the smallest surface elevation of the region. Therefore, it is not surprising that the gully runoff will flow into the stream channel. However, interestingly, the stable isotopic composition of groundwater is always more depleted than that of streamflow, which suggests that groundwater only flows to streamflow and not vice versa. Some of the groundwater samples are from springs with higher elevation than streamflow, which are unlikely to obtain recharge from streamflow. Many groundwater samples are from wells in aquifers near the stream channel, which should be completely connected to streamflow; however, they have stable isotopic compositions more depleted than those of streamflow even without antecedent rainfall. These results imply that even the groundwater in aquifers near the stream channel cannot be recharged by streamflow. Overall, therefore, the groundwater in the tableland-gully region of the CLP is highly likely to dominate the hydrologic system since surface water hinges on it.

The different spatiotemporal patterns of isotopic composition suggest that the water sources of streamflow are different from those of gully runoff and groundwater, which can be further confirmed by the dual isotope comparison. The water sources (inferred by the intersection of the EL and LWML) of gully runoff and groundwater have more depleted isotopic compositions than that of the volume-weighted precipitation (Fig. 5), which implies that they are not only from precipitation but also from water with a more depleted isotopic composition. According to our earlier study (Cheng et al., 2014), the isotopic composition of unconfined groundwater falls on the LMWL and is very similar to that of precipitation during August and September. However, the precipitation in the past several centuries had a more depleted stable isotopic composition (Tan et al., 2014), and the deep confined groundwater is mostly from ancient water with more depleted isotopic signature than local modern precipitation (Li et al., 2015). This suggests that the gully runoff and groundwater are from the confined water with more depleted isotopic composition.

4.4. Implications for water resource management

The gaining surface water system identified here is quite different from that in the hilly-gully region on CLP. The isotopic composition of surface water and groundwater in a watershed located in a hilly-gully region indicated groundwater recharge by surface water during the rainy season (Liu et al., 2010). The surface water-groundwater interaction is a two-way connected system in the hilly-gully region, while a one-way connected system in the tableland-gully region. This highlights the importance of protecting groundwater in the tableland-gully region on CLP.

Considering the regional differences in groundwater storage, the groundwater in tablelands should be of high priority for water resource management. Due to the thick vadose zone with porous loess, the groundwater storage in tablelands is very large. However, the high water demands on tablelands, which are increasing due to a large, growing population and land use change, is causing greater groundwa-
5. Conclusion

Hydrochemical indices in streamflow, gully runoff and groundwater were analyzed to interpret the surface water-groundwater connectivity in a watershed with a depositional environment on China’s Loess Plateau. Stable water isotope data appear to be a better tool for analysis in a watershed with a depositional environment on China’s Loess Plateau. The water and isotopic compositions of the Loess Plateau are spatiotemporally invariant, especially in the lower reach. In most cases, the isotopic composition of groundwater is the most depleted for streamwater, adjustment of land structure and groundwater, and especially groundwater, should be cautious. Otherwise, the revegetation will exceed the sustainable water resource limits, and further cause conflicting demands for water between the ecosystem and humans (Feng et al., 2016).

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References


Table 3


<table>
<thead>
<tr>
<th>Types</th>
<th>Area (hm²)</th>
<th>1995</th>
<th>2000</th>
<th>2005</th>
<th>2010</th>
</tr>
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<tr>
<td>Farmland</td>
<td>90,230</td>
<td>90,544</td>
<td>88,883</td>
<td>86,509</td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>7163</td>
<td>7981</td>
<td>8439</td>
<td>8480</td>
<td></td>
</tr>
<tr>
<td>Grassland</td>
<td>57,243</td>
<td>55,800</td>
<td>56,788</td>
<td>59,099</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>25</td>
<td>25</td>
<td>31</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>Built-up land</td>
<td>1272</td>
<td>1583</td>
<td>1738</td>
<td>1760</td>
<td></td>
</tr>
<tr>
<td>Unused land</td>
<td>0</td>
<td>0</td>
<td>54</td>
<td>54</td>
<td></td>
</tr>
</tbody>
</table>

Meanwhile, groundwater recharge has been affected by substantial land use change (Table 3). According to four land use maps during 1995–2010, the three land use types, i.e. farmland, grassland and forest, accounted for approximately 99% of the whole watershed. However, compared with 1995, farmland in 2010 decreased by 3721 hm², while forest and grassland increased by 1317 and 1856 hm², respectively. The conversion from farmland to grassland and forest will certainly increase actual evapotranspiration and further alter the other hydrological processes. For example, many farmlands on tablelands have been converted to fruiting trees with higher water requirement, which greatly prevents soil water movement and decreases groundwater recharge (Huang et al., 2013; Wang et al., 2015). Therefore, to protect the water resources and especially groundwater, adjustment of land structure should be cautious. Otherwise, the revegetation will exceed the sustainable water resource limits, and further cause conflicting demands for water between the ecosystem and humans (Feng et al., 2016).


