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## Groundwater storage trends in the Loess Plateau of China estimated from streamflow records

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**Abstract:** The catchments in the Loess Plateau in China have experienced significant land use change since the 1950s with a great number of soil conservation measures such as revegetation being implemented. Such soil conservation measures and climate variability have had considerable impacts on the annual streamflow from these catchments. However, much less is known about changes in groundwater storage as the period of direct groundwater storage measurements is too short to reliably infer groundwater storage trends. For this study, annual values of groundwater storage from 38 catchments in the Loess Plateau were estimated from daily streamflow records based on groundwater flow theory. It was found that over the period of record (viz. 1955 to 2010), statistically significant ( $p < 0.1$ ) downward trends have been identified in 20 selected catchments with an average reduction of  $-0.0299$  mm per year, mostly located in the northern part of the Loess Plateau. Upward groundwater storage trends were observed in 10 catchments with an average increase of  $0.00467$  mm per year; these upward trends occurred in southern parts of the study area. Groundwater storage showed no statistically significant trends in 8 out of the 38 selected catchments. Soil conservation measures implemented in the Loess Plateau such as large-scale revegetation may have contributed to the estimated groundwater storage trends. Changes in sea surface temperature in the tropical Pacific Ocean, as indicated by shifts in climate variability modes such as El Niño-Southern Oscillation and the Pacific Decadal Oscillation, appear to have also contributed to the decreasing trends in groundwater storage in this region.



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**Professor Andras Bárdossy,**  
Editor-in-Chief, Journal of Hydrology

14/8/2015

Ref: "Groundwater storage trends in the Loess Plateau of China estimated from streamflow records" by Zhaoliang Gao, Lu Zhang, Lei Cheng, Xiaoping Zhang, Tim Cowan, Wenju Cai and Wilfried Brutsaert.

Dear Professor Bárdossy,

Thank you for the opportunity to revise the above manuscript. As you requested, we have made all necessary changes to address the reviewers' concern and have detailed how the points raised by the reviewers have been accommodated. From the changes made in the revised manuscript and response provided, I hope you are convinced that we have adequately addressed the reviewers' concern and made the paper stronger.

I am looking forward to your response.

Best regards,

A handwritten signature in black ink, appearing to be the name "Lu Zhang" written in a stylized, cursive script.

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## Research Highlights:

- ✓ Groundwater storage in the Loess Plateau were estimated from daily streamflow data
- ✓ Most catchments showed significant downward trends in annual groundwater storage
- ✓ Storage trends were related to changes in land cover and sea surface temperature

1 **Groundwater storage trends in the Loess Plateau of**  
2 **China estimated from streamflow records**

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3

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15 **Abstract:** The catchments in the Loess Plateau in China have experienced significant land use  
16 change since the 1950s with a great number of soil conservation measures such as  
17 revegetation being implemented. Such soil conservation measures and climate variability have  
18 had considerable impacts on the annual streamflow from these catchments. However, much  
19 less is known about changes in groundwater storage as the period of direct groundwater  
20 storage measurements is too short to reliably infer groundwater storage trends. For this study,  
21 annual values of groundwater storage from 38 catchments in the Loess Plateau were estimated  
22 from daily streamflow records based on groundwater flow theory. It was found that over the  
23 period of record (viz. 1955 to 2010), statistically significant ( $p < 0.1$ ) downward trends have  
24 been identified in 20 selected catchments with an average reduction of  $-0.0299$  mm per year,  
25 mostly located in the northern part of the Loess Plateau. Upward groundwater storage trends  
26 were observed in 10 catchments with an average increase of  $0.00467$  mm per year; these  
27 upward trends occurred in southern parts of the study area. Groundwater storage showed no  
28 statistically significant trends in 8 out of the 38 selected catchments. Soil conservation  
29 measures implemented in the Loess Plateau such as large-scale revegetation may have  
30 contributed to the estimated groundwater storage trends. Changes in sea surface temperature  
31 in the tropical Pacific Ocean, as indicated by shifts in climate variability modes such as El  
32 Niño-Southern Oscillation and the Pacific Decadal Oscillation, appear to have also  
33 contributed to the decreasing trends in groundwater storage in this region.

34

35 **Keywords:** Base flow, groundwater storage, climate change, trends, land use change

## 36 **1 Introduction**

37 Changes in hydrological cycles have been shown to occur over a range of scales with  
38 climate variability and land use change identified as the main drivers (Milly et al., 2005;  
39 Zhang et al., 2008; Petrone et al., 2010; Zhao et al., 2010; Zhang et al., 2011). Most  
40 investigations of these changes have focused on surface hydrology, more specifically  
41 evapotranspiration and streamflow under different climate scenarios (Christensen and  
42 Lettenmaier, 2007; Chiew et al., 2009). These studies enhanced our understanding of  
43 potential impacts on surface water hydrology and provided useful information for water  
44 resources managers. Yet, there are only a few studies that deal with climate change impacts on  
45 groundwater storage mainly due to limited reliable records of groundwater observations  
46 (Brutsaert 2008; Goderniaux et al., 2009; Green et al., 2011; Zhang et al., 2014). This is also  
47 reflected in the most recent Intergovernmental Panel on Climate Change (IPCC) report, which  
48 stated that detection of changes in groundwater systems and attribution to climatic change are  
49 difficult due to a lack of appropriate observational data and detailed studies (Jiménez Cisneros  
50 et al., 2014). Groundwater is an important source of water supply and accounts for about 50%  
51 of domestic water supply globally (Zektser and Everett, 2004). A better understanding of  
52 groundwater storage trends can assist in the development of sustainable water resources plans  
53 as groundwater storage is often crucial for maintaining ecosystem health (Bertrand et al., 2012;  
54 Todd and Mays, 2005).

55 During prolonged dry periods, low flows in natural streams are sustained mostly by  
56 releases from groundwater storage. This means that it is possible to derive information on  
57 groundwater storage from daily streamflow records and one such a method was developed by  
58 Brutsaert (2008) based on groundwater flow theory. This method has been successfully  
59 applied to a number of catchments under different climatic and land use conditions (Brutsaert  
60 and Sugita, 2008; Brutsaert, 2010; Zhang et al., 2014). The advantages of the method are that

61 it provides catchment-scale estimates of groundwater storage only from daily streamflow data  
62 at the catchment outlet.

63 The Loess Plateau lies in the middle reaches of the Yellow River and has experienced  
64 large-scale land use changes over the past 50 years, resulting in reductions in annual  
65 streamflow (Zhang et al., 2008). For instance, Huang and Zhang (2004) and Mu et al. (2007)  
66 reported reductions of 20-45% in mean annual streamflow from the Jialu, Qiushui, Tuwei, and  
67 Yanhe catchments in this region following major soil water conservation measures. Apart  
68 from land use changes, the climatic variables such as precipitation and temperature have also  
69 changed (e.g. Wang et al., 2012). A number of studies have shown that both climate  
70 variability and land use change are responsible for the observed annual streamflow trends (Mu  
71 et al., 2007; Zhang et al., 2008; Gao et al., 2011). Impacts of land use change such as  
72 afforestation on streamflow in the Loess Plateau have been widely recognised, but the impacts  
73 on deep drainage and groundwater storage are still poorly understood. In addition, large-scale  
74 mining activities occurred more recently in the Loess Plateau are suspected of having  
75 modified the regional hydrology, especially groundwater storage. A better insight into how  
76 the groundwater systems in the Loess Plateau respond to changes in land use and climate will  
77 be critical in developing sustainable resources management plans. Accordingly, the  
78 objectives of this study are (1) to estimate long-term groundwater storage trends in the Loess  
79 Plateau from daily streamflow records using the method of Brutsaert (2008) and (2) to  
80 examine the impact of land use changes and climate variability on the estimated groundwater  
81 storage trends.

## 82 **2 Catchment description and data**

83 The study area is located in the middle of the Loess Plateau and covers an area about  
84  $1.4 \times 10^5$  km<sup>2</sup> (Figure 1). Seventeen catchments within the study area were selected and some  
85 features of these catchments are provided in Table 1. The average mean annual precipitation



86 (1957-2010) of the study area is 465 mm, but ranges from 544 mm in the south-east to 370  
87 mm in the north-west. The north-western region is relatively flat whilst the south-east is  
88 characterized by a heavily dissected landscape, with gully density varying from 2 to 8 km km<sup>-2</sup>  
89 (Tang and Chen, 1990; Ran et al., 2000). Loess soil was deposited over the study area to a  
90 depth exceeding 100 m during the Quaternary period (Liu, 1999). Coarser, sandier sediments  
91 are common in the northwest and finer, clay-rich sediments occur in the southeast. The  
92 dominant vegetation type for all except for four catchments is pasture, with the remainder  
93 predominantly covered by forest.

94 Daily streamflow data from 38 gauging stations were obtained from the Water Resources  
95 Committee of the Yellow River Conservancy Commission; most of the streamflow records  
96 cover the period of 1952-2010 with shorter records for some stations (Table 1). The annual  
97 precipitation and relevant meteorological data were obtained from the State Meteorology  
98 Bureau. The meteorological data were spatially averaged across the study area as described by  
99 Zhang (2007).

100 *Insert Figure 1 here.*

101

## 102 **3 Methods**

### 103 **3.1 Estimation of groundwater storage**

104 The baseflow from a catchment can be expressed as:

$$105 \quad Q = Q(t) \quad (1)$$

106 where  $Q$  is the rate of flow [ $L^3T^{-1}$ ] and  $t$  is the time [T]. For convenience,  $Q$  is generally  
107 expressed by  $y = Q / A$ , in which  $A$  is the catchment area. The most common equation for  
108 describing describe baseflow is of the exponential form, namely

109 
$$y = y_0 \exp(-t / K) \tag{2}$$

110 where  $K$  is the characteristic time scale of the catchment drainage process [T], and  $y_0$  is the  
 111 value of  $y$  at the selected time origin  $t = 0$ . Brutsaert (2005) showed that the “long-time”  
 112 solution of the linearized Boussinesq equation yields the following expression for the  
 113 characteristic drainage time scale

114 
$$K = 0.10n_e / (D_d^2 k_0 \eta_0) \tag{3}$$

115 where  $k_0$  [ $LT^{-1}$ ] is the hydraulic conductivity,  $n_e$  the drainable porosity,  $\eta_0$  is the average  
 116 vertical thickness [L] of the layer in the soil profile occupied by flowing water,  $D_d = L / A$  is  
 117 the drainage density, where  $L$  is the total length of upstream channels in the catchment.

118 When groundwater recharge is negligible, the movable groundwater stored in a  
 119 catchment  $S$  is the volume of water over the area  $A$  of the catchment [L] that has not yet been  
 120 released as baseflow  $y$

121 
$$S = - \int_t^{\infty} y dt \tag{4}$$

122 Upon integration with equation **Error! Reference source not found.**, this yields a linear  
 123 relationship between groundwater storage and rate of flow,

124 
$$S = Ky \tag{5}$$

125 The groundwater storage  $S$  can be considered as the average thickness of water stored  
 126 above the zero-flow level of the water table over the catchment.

127

### 128 **3.2 The characteristic drainage timescale**

129 Estimating groundwater storage using Equation (5) requires a knowledge of the  
 130 characteristics drainage timescale  $K$ . In this study,  $K$  was determined from daily streamflow

131 data using the method of Brutsaert and Nieber (1977) by expressing  
132 **Error! Reference source not found.** in differential form:

$$133 \quad \frac{dy}{dt} = \varphi(y) \quad (6)$$

134 where  $\varphi(y)$  is a function that is characteristic for a given basin. Thus, in the case of equation  
135 **Error! Reference source not found.**, for the present purpose (6) becomes

$$136 \quad \frac{dy}{dt} = -\frac{y}{K} \quad (7)$$

137 Decrease in low flow from groundwater and soil moisture storage is generally assumed to  
138 be much slower than that of surface runoff generated directly from rainfall.  
139 Evapotranspiration tends to accelerate the decline of low flow, and thus result in a larger  
140  $|dy/dt|$ . This means that low flows during periods of minimal evapotranspiration can be  
141 associated with the smallest  $|dy/dt|$  for a given flow rate  $y$ . Equation (7) describes the low  
142 flow hydrograph from a catchment and requires identification of the streamflows that took  
143 place under low-flow conditions. For each catchment,  $K$  was determined by implementing  
144 the method of Brutsaert and Nieber (1977) considering the lowest envelope of a  $\log(-dy/dt)$   
145 versus  $\log(y)$  plot.

146 Only streamflow data that met stringent low flow criteria were used with (7), and all  
147 others were excluded; these criteria are based on the following considerations (e.g. Zhang et  
148 al., 2014). During a recession,  $-dy/dt$  is expected to decrease monotonically and a recession  
149 should last at least multiple days to contain useful information. Moreover, since concurrent  
150 precipitation data were available, in the present implementation of the procedure, careful  
151 scrutiny of these data allowed exclusion of any direct storm runoff on days of rainfall, and  
152 also a number of days (1 to 4 depending on the area of the catchment) after the rainfall event.  
153 After low flow data points were identified, they were plotted as  $\log(-dy/dt)$  versus  $\log(y)$

154 relationships for the selected catchments. A straight line lower envelope with unit slope was  
 155 fitted to the data from which  $K$  could be determined. Because the data points show scatter, the  
 156 determination of the exact position of the lower envelope is somewhat subjective. Therefore,  
 157 as suggested by Troch *et al.* (1993), the positions of the lower envelopes were determined  
 158 such that 5% of the plotted flow data points fell below the lower envelopes.

### 159 3.3 Trend analysis of annual groundwater storage

160 The Mann-Kendall rank correlation coefficient (Mann, 1945; Kendall, 1975) is  
 161 commonly used to assess the significance of trends in hydro-meteorological time series and  
 162 has been used in this study for estimating annual groundwater storage trends. The Mann-  
 163 Kendall test statistic ( $T$ ) is given by

$$164 \quad T = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (8)$$

$$165 \quad \text{and} \quad \begin{array}{ll} \text{if } \theta > 0, & \text{sgn}(\theta) = 1 \\ \text{if } \theta = 0, & \text{sgn}(\theta) = 0 \\ \text{if } \theta < 0, & \text{sgn}(\theta) = -1 \end{array}$$

166 where,  $n$  is the data set record length;  $x_j$  and  $x_k$  are the sequential data values.

167 The Mann-Kendall test has two parameters that are of importance to trend detection.  
 168 These parameters are the significance level, which indicates the trend's strength, and the slope  
 169 magnitude estimate, which indicates the direction as well as the rate of change. Under the null  
 170 hypothesis that there is no trend in the data, the distribution of  $S$  is then expected to have a  
 171 mean of zero and a variance of

$$172 \quad \text{var}(T) = \frac{n(n-1)(2n+5)}{18} \quad (9)$$

173 The normal  $Z$ -test statistic is calculated as

$$z = \begin{cases} \frac{T-1}{\sqrt{\text{Var}(T)}} & \text{if } T > 0 \\ 0 & \text{if } T = 0 \\ \frac{T-1}{\sqrt{\text{Var}(T)}} & \text{if } T < 0 \end{cases} \quad (10)$$

The null hypothesis is rejected at significance level of  $p$  if  $|Z| > Z_{(1-p/2)}$ , where  $Z_{(1-p/2)}$  is the value of the standard normal distribution with a probability of exceedance of  $p/2$ . A positive value of  $Z$  indicates an upward trend while a negative value represents a downward trend in the data.

If a linear trend is present, the magnitude of the trend,  $\beta$ , or the slope (change per unit time) is estimated using a non-parametric method proposed by Sen (1968) and extended by Hirsch et al. (1982):

$$\beta = \text{Median} \left[ \frac{X_j - X_k}{j - k} \right] \quad \text{for all } k < j \quad (11)$$

where  $1 < k < j < n$ . In other words, the slope estimator  $\beta$  is the median of all possible combinations of pairs for the whole data set.

## 4 Results and Discussion

### 4.1 Characteristic drainage time scale

The values of the catchment drainage time scale  $K$  estimated by means of the method described in the previous section are listed in Table 1. For the 38 selected gauging stations, the drainage time scale  $K$  varies between 12 and 83 days with an average value of 30 days and standard deviation of 15 days. Figure 2 shows examples for the Qingjian River catchment at Yanchuan station and Shiwang River catchment. All the catchments have  $K$  values smaller than 45 days, except for Gaojiabao, Zhaoshiyao, and Hanjiamao stations. These three stations are located in the northwest part of the study area with lower annual precipitation. However, the areas have flat landscape with coarser and sandier sediments, resulting higher groundwater recharge (Wang et al., 1990). The groundwater tables in these catchments are shallower

196 (Office of Land and Resources of Shaanxi Province, 2008) with much higher baseflow index  
197 (i.e. the ratio of average annual baseflow to the total average annual streamflow) compared to  
198 the rest of the catchments (Zhu et al., 2010). As a result, these catchments sustain higher  
199 baseflow rates and show slower flow recession during dry periods. The south-eastern part of  
200 the study area is characterized by a heavily dissected landscape with high gully density and  
201 deep loess soil, exceeding 200 m in many locations. The groundwater recharge is limited in  
202 this region and the surface water is weakly coupled with the groundwater system, resulting in  
203 quick flow recession. In a different approach, Zhu et al., (2010) estimated the catchment  
204 drainage time scale in the Loess Plateau and showed that it varied from 5 to 16 days across the  
205 catchments. In their estimation of the drainage time scale, the master recession curve approach  
206 was used. Xu et al., (2010) analysed isotopic characteristics of rainfall, soil moisture, and  
207 groundwater samples taken from the Yangou catchment located in the south of the Loess  
208 Plateau and showed that the time lags between rainfall and groundwater discharge are about  
209 35 days. Although obtained by a different method, in general, the  $K$  values obtained in the  
210 present study are similar with the results of Xu et al. (2010), but larger than the estimates of  
211 Zhu et al. (2010). However, the average  $K$  value for the catchments in the Loess Plateau is  
212 smaller than those reported by Brutsaert (2008, 2010) for US catchments and Zhang et al.  
213 (2014) for Australian catchments, where it was found that  $K$  is on average 46 days, with an  
214 uncertainty of less than 15 days. Studies show that the loess soils in the Loess Plateau are  
215 highly permeable with saturated hydraulic conductivity values ranging from 1.1 m/day to 7.2  
216 m/day (Jiang and Huang, 1986). Moreover, as noted earlier, the region is highly dissected  
217 with drainage densities varying from roughly 2 to 8 km/km<sup>2</sup> (Tang and Chen, 1990; Ran et al.,  
218 2000). These rather large hydraulic conductivity values and large drainage density values  
219 indicate that water drains faster from the catchments implying smaller  $K$  values. Actually, this

220 can also readily be seen in the theoretical expression **Error! Reference source not found.**,  
221 where larger values of  $k_0$  and  $D_d$  result in smaller values of  $K$ .

222 *Insert Figure 2 here.*

223

## 224 **4.2 Annual groundwater storage trends**

225 In this study the annual lowest 7-day flows were used to represent  $y$  in (5) to determine  
226 the annual groundwater storage with estimates of drainage time scale  $K$ , obtained as indicated  
227 in the previous section. Then annual groundwater storage trends were estimated using the  
228 Mann-Kendall and Sen's slope method described above. The results are listed in Table 1 for  
229 the periods of record. Actually, several other characteristics of baseflow could be used to  
230 represent  $y$  in (5). The lowest 7-day flow was specifically chosen because it represents the  
231 lowest groundwater storage level in each year, which is carried over to the next year, so that it  
232 can be used to track its long-term evolution. Moreover, the lowest 7-day flow is a common  
233 and robust variable used in drought statistics (Smakhtin, 2001), which can be readily  
234 determined as the lowest value of the 7-day running averages for each year of record.

235 As examples of the results presented in Table 1, Figure 3 shows groundwater storage  
236 trends over the periods of record from three selected catchments. The Tuwei River catchment  
237 at Gaojiabao station in the northwest of the study area exhibited the strongest downward trend  
238 (i.e.  $-0.2612$  mm/year) (Figure 3a), while the Yanhe River catchment showed an upward  
239 trend in groundwater storage of  $0.0010$  mm/year. The Wuding River catchment at  
240 Qingyangcha station shows stable groundwater storage (i.e. no statistically significant trend)  
241 over the period of 1959 to 2005 (Figure 3c). Over the period of record, which varies from 39  
242 to 57 years, 30 catchments show statistically significant trends at least at the 0.1 significance  
243 level (Table 1). Among them, 20 catchments, i.e. the majority, showed statistically significant

244 downward trends ranging from -0.0002 to -0.2612 mm per year with an average value of -  
245 0.0299 mm per year (Table 1). The downward trends in groundwater storage are similar to  
246 those of the South Atlantic-Gulf region in the US (Brutsaert, 2010), of the Kherlen River  
247 basin in Mongolia (Brutsaert and Sugita, 2009), and of the Australian catchments studied by  
248 Zhang et al. (2014) over a similar period. The reductions in groundwater storage in these  
249 catchments are consistent with the annual streamflow and baseflow trends reported by Gao et  
250 al. (2015). There are 10 catchments where groundwater storage exhibited upward trends  
251 ranging from 0.0011 to 0.0119 mm per year with an average value of 0.0047 mm per year  
252 (Table 1). These groundwater trends are opposite to the annual streamflow trends obtained by  
253 Gao et al. (2015), but consistent with their annual baseflow trends. The baseflow trends of  
254 Gao et al. (2015) provide an independent measure of the groundwater storage trends as  
255 baseflow is a result of groundwater discharge and the good agreement between the two  
256 estimates suggests that the method used in our study is appropriate for estimating groundwater  
257 storage trends. It should also be noted that the magnitudes of the upward trends in  
258 groundwater storage are similar to those of the Souris-Red-Rainy and the Missouri regions  
259 reported by Brutsaert (2010).

260 Spatial patterns of the groundwater storage trends in the Loess Plateau are shown in  
261 Figure 4. The catchments with significant downward trends in groundwater storage are  
262 mostly those located in the northern part of the study area, where the landscape tends to be  
263 flatter with more sandy soils and shallower groundwater tables. The baseflow index in this  
264 region is also higher than that of the catchments in the southern part of the study area (Zhu et  
265 al., 2010). Upward groundwater storage trends occurred mostly in the Beluo River basin  
266 located in the southern part of the Plateau (Figure 4).

267 *Insert Figure 3 and Figure 4 here.*



268 The observed groundwater storage trends in the Loess Plateau are probably caused  
269 mostly by land use changes and climate variability. Indeed, over the period of 1959 to 2006,  
270 the catchments reported in this study experienced major land use changes including the  
271 establishment of sediment check dams and revegetation (Zhang et al. 2008). A number of  
272 studies have shown that the soil conservation measures implemented in this region since the  
273 1950s contributed to marked reductions in annual streamflow (Huang and Zhang, 2004; Mu  
274 et al., 2007, Zhang et al., 2008). The observed downward groundwater storage trends may be  
275 at least partly explained by the soil conservation measures as they can reduce runoff and  
276 increase evapotranspiration. Huang and Pang (2010) examined the effects of land use  
277 changes in the Loess Plateau using a chloride mass balance approach and their results indicate  
278 that conservation measures such as afforestation have considerably reduced groundwater  
279 recharge through increased transpiration. Also, large scale open coal mining activities  
280 commenced recently in parts of the study area (Lei et al., 2013; Jiang et al., 2010) appear to  
281 have affected water balance components and reduced groundwater storage. Other studies have  
282 demonstrated that revegetation can enhance evapotranspiration and reduced streamflow  
283 (Zhang et al., 2001; Brown et al., 2005) and that revegetation can also improve soil conditions  
284 and result in higher infiltration capacity (Wilcox et al., 1988; Bartley et al., 2006).

285 Groundwater storage is affected by a number of factors, including soil hydraulic  
286 properties, riparian aquifer characteristics, stream network, land scape topography, and  
287 evapotranspiration (Brutsaert 2005). Land use changes can affect these factors and result in  
288 changes in groundwater storage. The selected catchments in this study have experienced  
289 considerable land use change such as revegetation and it is expected that these changes will  
290 affect evapotranspiration and infiltration. In the case of the catchments located in the northern  
291 part of the study area, increases in vegetation cover led to greater infiltration of rainfall into  
292 the soil, but the additional water stored in the soil was used by vegetation, resulting decreases

293 in groundwater storage. The effect of the soil conservation measures on groundwater storage  
294 was exacerbated by large scale open coal mining commenced more recently in the northern  
295 parts of the study area (Lei et al., 2013; Jiang et al., 2010). For the catchments in the south-  
296 western part of the study area, increases in groundwater storage may be partly attributed to  
297 enhanced infiltration following land use change as the region is highly dissected with a high  
298 gully density and drainage density, and focused recharge is potentially an important process.  
299 This means that infiltrated water can quickly escape the root zone and recharge groundwater  
300 storage before being used by vegetation.

301 The Loess Plateau has experienced slight downward trends in annual precipitation over  
302 the period of 1957 to 2010, albeit mostly in its southern half (Wang et al., 2012, Figure 5).  
303 This is also illustrated for several catchments in Figure 5, where it can be seen that the number  
304 of years with below average annual precipitation has increased over time; this may at least  
305 partly explain the downward trends in groundwater storage. However, the upward  
306 groundwater storage trends in the south of the study area cannot be explained by the  
307 downward precipitation trends, where the precipitation decreases are most pronounced. This  
308 should perhaps not be surprising because, according to the water budget equation, beside  
309 evaporation and runoff, precipitation is related to the change in storage, rather than to storage  
310 itself; as a result, groundwater storage is a more slowly changing hydrologic variable, and its  
311 correlation with concurrent precipitation cannot be expected to be very strong over short time  
312 scales. It should be acknowledged that groundwater storage is a complex process and many  
313 factors can influence the ability of water to flow in or out of the storage. Price (2011) argued  
314 that little is known about baseflow or groundwater storage responses to land use change in  
315 large and complex systems and called for more studies investigating the relative influences of  
316 these factors. Our study provided useful information on changes in groundwater storage  
317 following large scale land use change. However, it is difficult to attribute the groundwater

318 storage change to individual factors due to limited data available on land use change,  
319 especially their spatial distribution. Further studies are needed to explore how specific land  
320 use change affects groundwater storage by combining data analysis with modelling.

321 Hanson et al. (2004) analysed time series of streamflow, base flow, and groundwater  
322 levels and showed that these hydrological variables were strongly correlated over longer time  
323 scales, namely with temporal variability in the Pacific Ocean, as manifested by the Pacific  
324 Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO) indices. The PDO  
325 represents a pattern of Pacific climate variability involving interdecadal fluctuations in sea  
326 surface temperatures (SSTs). Its regional climate signatures are similar to those associated  
327 with ENSO, which is one of strongest ocean-atmosphere coupled modes of variability.  
328 Typically, PDO phases last for 2–3 decades, much longer than ENSO phases of 6 to 18  
329 months. Brabets and Walvoord (2009) investigated streamflow trends in the Yukon River  
330 basin of Alaska and Canada and found changes in streamflow patterns correlated with a PDO  
331 regime shift. More recently, Brutsaert (2012) found that the PDO and ENSO affected  
332 groundwater storage in four desert regions of North America. It is of interest to put these  
333 findings in context for the Loess Plateau.

334 The evolution of the PDO can be represented as an index, defined as the leading principal  
335 component of monthly sea surface temperature (SST) anomalies over the North Pacific region  
336 (Mantua et al. 1997). For this study, we utilised the PDO index calculated in Mantua et al.  
337 (1997), based on Version 1 and 2 of Reynolds's Optimally Interpolated SST product  
338 (Reynolds and Smith 1994). A 13-year running average was applied to the PDO index as a  
339 low-pass filter, similar to how the closely related inter-decadal Pacific Oscillation is  
340 calculated (Parker et al. 2007). Positive PDO index values reflect the warm phase associated  
341 with anomalously cool central-North Pacific SSTs and warm SST anomalies in the eastern  
342 tropical Pacific. When the PDO index is negative (i.e. cold phase), the anomalous SST

343 patterns are reversed, with warming in the central-North Pacific and cooling along the  
344 equatorial Pacific. The changes in distribution of cold and warm ocean water masses alter the  
345 path of the jet stream responsible for storm delivery.

346 *Insert Figure 5 here.*

347 The inter-decadal relationship between PDO, ENSO and China rainfall has been  
348 addressed in a number of studies (e.g., Chan and Zhou, 2005; Yoon and Yeh 2010) with focus  
349 on both boreal winter and summer monsoon rainfall over East Asia (Kim et al. 2014; Feng et  
350 al. 2014). The consensus is that the influence of ENSO on East Asian rainfall is either  
351 enhanced or damped by the decadal phases of the PDO. For example, during the peak ENSO  
352 season (December-February), there is a tendency for SSTs along the subtropical and tropical  
353 eastern Pacific to warm during positive PDO, which causes an anomalous zonal circulation  
354 response that strengthens the west Pacific subtropical high (Yu et al. 2014). This restricts  
355 moisture transport into northern China, but increases the moisture transport into the Yangtze  
356 River Valley region (southeastern China). Many studies have documented the fact that when  
357 the state of ENSO is in phase with the PDO this can strongly influence rainfall totals over  
358 South China (Chan and Zhou 2005), and northeast China during the summer monsoon (Yoon  
359 and Yeh 2010).

360 For the purpose of this study, we define ENSO using the NINO3.4 index, defined as areal  
361 averaged SST anomalies over 5°N-5°S and 170°-120°W. The association between ENSO and  
362 groundwater storage averaged across all study catchments in the Loess Plateau is statistically  
363 significant at the 95% confidence level (negative correlation exceeds -0.53 based on 12  
364 degrees of freedom) for most of the positive warm PDO phase (1977-2002), as shown in  
365 Figure 6. As the PDO trends towards the negative cool phase (i.e. mid 1990s), the ENSO-  
366 ground water storage association becomes weak and insignificant on interannual time-scales.  
367 What this suggests is that during the warm PDO phase, annual precipitation across catchments

368 decreases (*increases*) during an El Niño (*La Niña*) event, with flow-on effects for runoff  
369 generation and groundwater storage.

370 ***Insert Figure 6 here.***

371 To help better understand how the variability in the Pacific might explain changes in  
372 groundwater storage over the Loess Plateau, we focus on the atmospheric circulation  
373 differences over the northern Pacific between the positive [1977-2002] and negative [1950-  
374 1976] PDO phases (i.e. circulation averaged over positive PDO index years [1977-2002]  
375 minus circulation averaged over negative PDO index years [1950-1976]; see Figure 7). The  
376 change in the circulation is represented by mean sea level pressure (colour), 500-mb vertical  
377 velocity (contour) and near-surface (850-mb) winds (vectors) based on output from the  
378 National Centers for Environmental Prediction (NCEP) and the National Center for  
379 Atmospheric Research (NCAR) Reanalysis dataset (Kalnay et al. 1996). The circulation  
380 difference between PDO phases merely reflects the long-term trends in circulation over the  
381 Asia and the North Pacific (not shown).

382 The composite difference captures anomalous easterlies along the equatorial Pacific and  
383 an anti-cyclonic flow flanking the anomalous low pressure cell over the extratropical Pacific –  
384 this reflects the conditions during the warm PDO phase with El-Niño-like conditions. Over  
385 the Loess Plateau region lies an anomalously high mean sea level pressure center, directing  
386 anomalous northerlies to the region, along with downward motion as represented by the  
387 positive vertical velocity at 500-mb. The circulation over the Loess Plateau suggests that local  
388 convection/divergence is much stronger during the PDO warm phase and plays an important  
389 role in precipitation variability. The strong tendency for large El Niño episodes to  
390 predominate during the positive PDO phase (e.g., 1982/83, 1997/98) would result in a  
391 dynamical set-up that involves anomalous northerlies and subsidence conducive to a reduction  
392 in precipitation and thus groundwater storage over the Loess Plateau. This may partially

393 explain the decline in precipitation and storage in many of the catchments to the north of the  
394 Loess Plateau over the late 20<sup>th</sup> century, however it fails to explain increases in groundwater  
395 storage in several catchments located in the south. As the ENSO-Loess Plateau precipitation  
396 teleconnection breaks down during the negative PDO phase (i.e. post-2002), variations in  
397 ENSO show no control on precipitation and ground water storage over the catchments.  
398 Variations in precipitation, runoff and groundwater storage during the cool PDO phase would  
399 more likely be associated with changes in local atmospheric conditions, related to the strength  
400 of summer and winter monsoons.

401 *Insert Figure 7 here.*

402

## 403 **5 Conclusions**

404 Annual values of groundwater storage from 38 catchments in the Loess Plateau of China  
405 were derived from daily streamflow data using the method proposed by Brutsaert (2008). The  
406 method can be considered reliable for estimating catchment scale groundwater storage as  
407 shown in several studies (e.g. Brutsaert, 2008; Zhang et al., 2014). The selected catchments in  
408 this study have at least 39 years of continuous daily streamflow data with catchment area  
409 ranging from 327 to 29662 km<sup>2</sup>. These catchments are representative of the hydro-climatic,  
410 and hydro-geologic conditions of the Loess Plateau and have been under the influence of both  
411 climate variability and human activities.

412 The analysis showed that the drainage time scale  $K$  varied between 12 and 83 days with  
413 an average value of 30 days. The  $K$  values obtained in this study are similar with results of Xu  
414 et al. (2010), but smaller than those reported by Brutsaert (2008, 2010) for US catchments and  
415 Zhang et al. (2014) for Australian catchments. Over the period of record, 20 catchments  
416 showed statistically significant ( $p < 0.1$ ) downward trends ranging from -0.0002 to -0.2612 mm

417 per year with an average value of -0.0299 mm per. In 10 catchments groundwater storage  
418 exhibited upward trends ranging from 0.0011 to 0.0119 mm per year with an average value of  
419 0.00467 mm per year. Groundwater storage showed no statistically significant trends in 8 out  
420 of the 38 selected catchments. The groundwater storage trends are consistent with changes in  
421 annual streamflow and baseflow reported in other studies. Soil conservation measures  
422 implemented in the Loess Plateau such as large-scale revegetation may have contributed to the  
423 observed groundwater storage trends. Changes in sea surface temperature in the Pacific Ocean,  
424 as indicated by variations in ENSO and phase shifts of the PDO, appear to have also affected  
425 longer term rainfall patterns and hence contributed to decreasing trends in groundwater  
426 storage, predominantly through the 1990s.

427

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435

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**Table 1. Characteristics of selected catchments in the Loess Plateau. Also shown are estimates of drainage time scale ( $K$ ), average groundwater storage ( $S$ ), and groundwater storage trends over the period of records estimated from daily streamflow.**

Catchment	Gauging station	Area (km <sup>2</sup> )	Slope (‰)	Rainfall (mm yr <sup>-1</sup> )	Runoff (mm yr <sup>-1</sup> )	Period of streamflow record	Drainage time scale $K$ (days)	Average groundwater storage (mm)	Groundwater storage trend (mm yr <sup>-1</sup> ) <sup>a</sup>
1 Kuye	Xinmiao	1527	4.89	385	60.9	1966 – 2005	31	0.1886	-0.0050**
	Wangdaohengt a	3839	4.88	437	49.0	1959 – 2005	34	0.3174	-0.0099***
	Wenjiachuan	8645	4.28	425	67.4	1953 – 2010	36	0.3888	-0.0100***
2 Tuwei	Gaojiabao	2095	4.93	444	130.4	1966 – 2005	83	16.1245	-0.2612***
	Gaojiachuan	3253	3.87	444	106.1	1955 – 2010	41	4.6855	-0.1214***
3 Jialu	Shenjiawan	1121	6.28	401	55.0	1957 – 2010	19	0.5113	-0.0165***
4 Wuding	Dianshi	327	10.62	370	41.2	1958 – 2005	24	0.5531	-0.0049
	Mahuyu	371	7.10	457	42.9	1962 – 2005	18	0.2276	-0.0040***
	Qingyangcha	662	7.94	457	38.8	1959 – 2005	29	0.5375	-0.0027
	Lijiahe	807	5.03	457	41.6	1959 – 2005	16	0.1232	-0.0012
	Hengshan	2415	4.01	370	28.5	1957 – 2005	42	0.9013	-0.0282***
	Hanjiamao	2452	3.7	401	35.1	1957 – 2005	189	2.5959	-0.0353***
	Zhaoshiyao	15325	2.72	407	35.8	1954 – 1990	61	2.3234	0.0027
	Dingjiagou	23422	2.04	407	38.0	1959 – 2005	33	0.7654	-0.0243***
	Baijiachuan	29662	1.80	458	38.7	1956 – 2010	24	0.4355	-0.0160***
5 Qingjian	Zichang	913	6.22	494	45.0	1958 – 2005	21	0.1918	0.0058***
	Yanchuan	3468	8.37	494	41.1	1954 – 2010	25	0.3325	0.0052**
6 Yanhe	Yan'an	3208	3.53	484	39.7	1965 – 2005	16	0.0916	0.0010

	Ganguyi	5891	3.26	484	35.8	1952 – 2010	20	0.1846	0.0022*
7 Yunyan	Linzhen	1121	5.7	544	17.8	1959 – 2005	16	0.1144	–0.0013
	Xinshihe	1662	5.2	544	19.7	1966 – 2010	17	0.1500	–0.0013 <sup>+</sup>
8 Shiwang	Dacun	2141	11.41	544	34.1	1959 – 2010	30	0.3974	–0.0083**
9 Beiluo	Zhidan	774	5.86	502	38.5	1964 – 2009	18	0.1253	0.0015*
	Huangling	2266	4.96	543	46.8	1967 – 2009	25	0.7664	0.0119*
	Wuqi	3408	3.27	377	27.6	1963 – 2009	30	0.2123	0.0057***
	Zhangcunyi	4715	3.88	523	22.7	1958 – 2009	28	0.2400	0.0054**
	Liujiathe	7325	2.17	432	32.3	1958 – 2009	33	0.4778	0.0062***
	Jiaokouhe	17180	2.06	512	25.9	1952 – 2009	28	0.3930	0.0017*
	Zhuangtou	25154	1.98	524	25.4	1957 – 2009	27	0.2353	–0.0041
10 Pianguan	Pianguan	1915	6.52	411	17.9	1957 – 2010	24	0.2505	–0.0126***
11 Lanyi	Kelan	476	9.6	467	49.4	1959 – 2010	42	1.0183	–0.0086
12 Weifen	Xingxian	650	9.73	488	42.3	1956 – 2010	14	0.0188	–0.0003***
13 Qiushui	Linjiaping	1873	6.51	487	39.4	1953 – 2010	21	0.0747	–0.0002**
14 Sanchuan	Gedong	749	9.69	487	65.0	1960 – 2004	46	1.8402	–0.0256***
	Houdacheng	4102	4.70	468	53.8	1953 – 2010	23	1.2281	–0.0135*
15 Quchan	Peigou	1023	8.12	503	31.8	1962 – 2010	15	0.1008	0.0011*
16 Xinshui	Daning	3992	9.35	518	33.4	1955 – 2010	20	0.1829	–0.0034***
17 Zhouchuan	Jixian	436	15.2	500	34.8	1959 – 2010	12	0.2435	–0.0012 <sup>+</sup>

Notes: <sup>a</sup> the symbols indicate different significance levels: \*\*\* when  $p < 0.001$ , \*\* when  $p < 0.01$ , \* when  $p < 0.05$  or + when  $p < 0.1$ .

Figure 1. Location map of the selected catchments in the Loess Plateau in China. The numbers represent the river basins listed in Table 1.

Figure 2. Relationships between  $\log(-dy / dt)$  and  $\log(y)$  for (a) the Qingjian River and (b) the Shiwang River. The lower envelope line has a unit slope and the estimate of the characteristic drainage timescale ( $K$ ) is 25 and 30 days, respectively.

Figure 3. Evolution of the annual lowest groundwater storage for (a) Tuwei River catchment, (b) Yanhe River catchment, and (c) Qingyangcha River catchment. The groundwater storage is expressed in millimetre above the zero-flow level over the period of records.

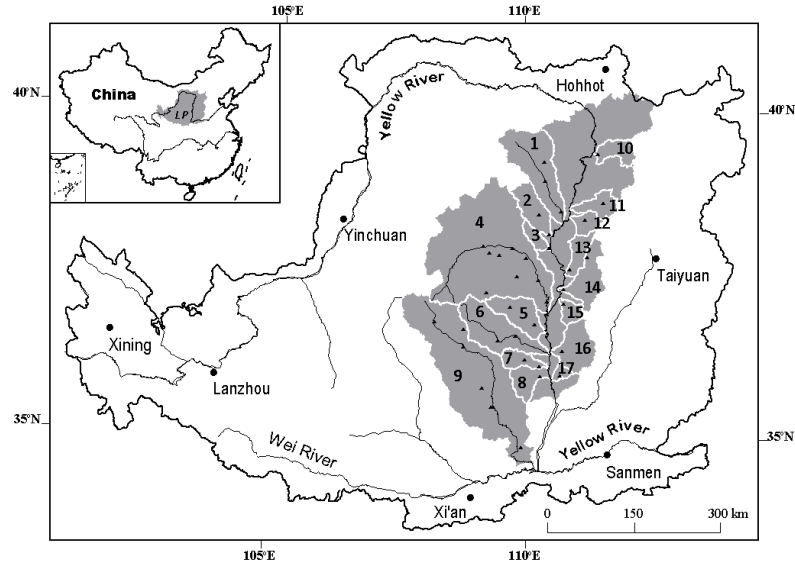
Figure 4. Spatial patterns of the annual lowest groundwater storage trends in the Loess Plateau. Red circles represent downward trends and blue circles indicate upward trends.

Figure 5. Evolution of the annual rainfall anomalies over the period of 1957-2010 for (a) Tuwei River, (b) Sanchuan River, (c) Yanhe River, (d) Kuye River, (e) Wuding River, and (f) Beiluo River.

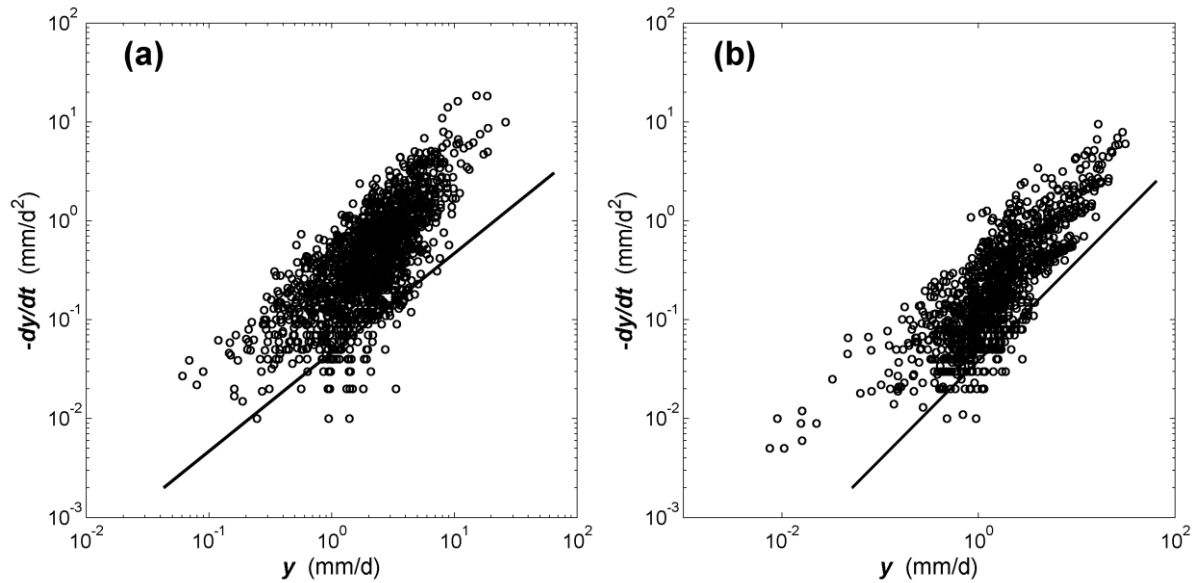
Figure 6. Time series showing 13-year sliding window correlation between annual groundwater storage and ENSO over the period 1957-2009 (blue), for the catchments in the Loess Plateau. Also shown in a time-series of the PDO (green) smoothed using a 13-year running mean.

Figure 7. Map showing the difference in circulation anomalies between the positive and negative phases of the PDO for mean sea level pressure (mb; colour), 500-mb vertical velocity (Pa/s; contour) and 850-mb winds (m/s; vectors). The positive phase of the PDO covers 1977-2002, while the negative phase covers 1950-1976. The stippling represents mean sea level pressure values are that are statistically significant based on  $t$ -test comparing the difference of two means. The white rectangle indicates the approximate location of the Loess Plateau.

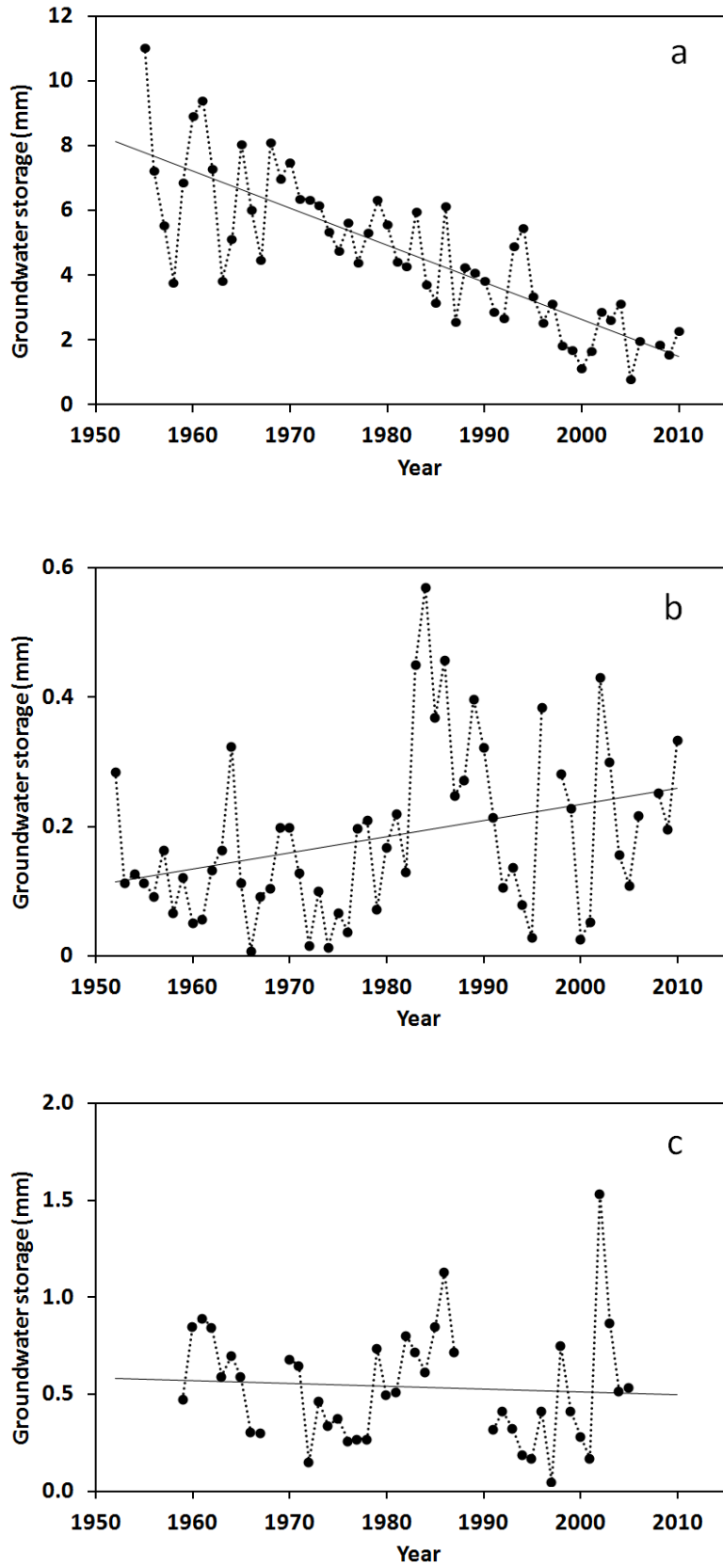




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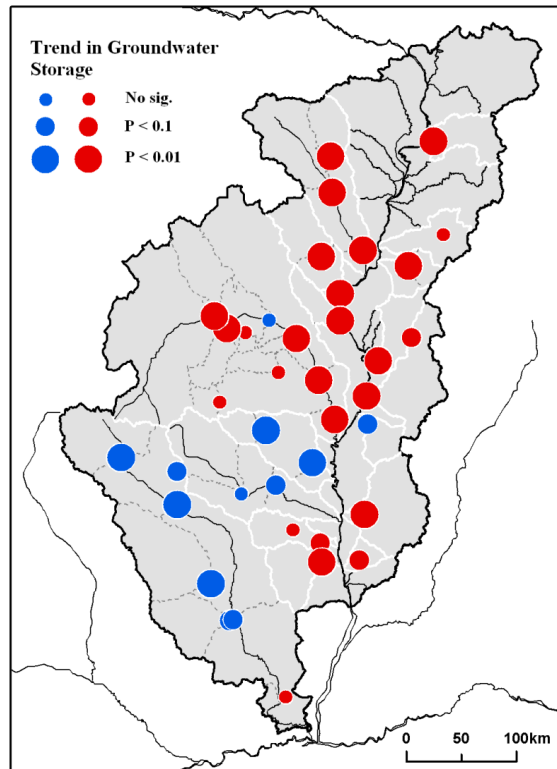


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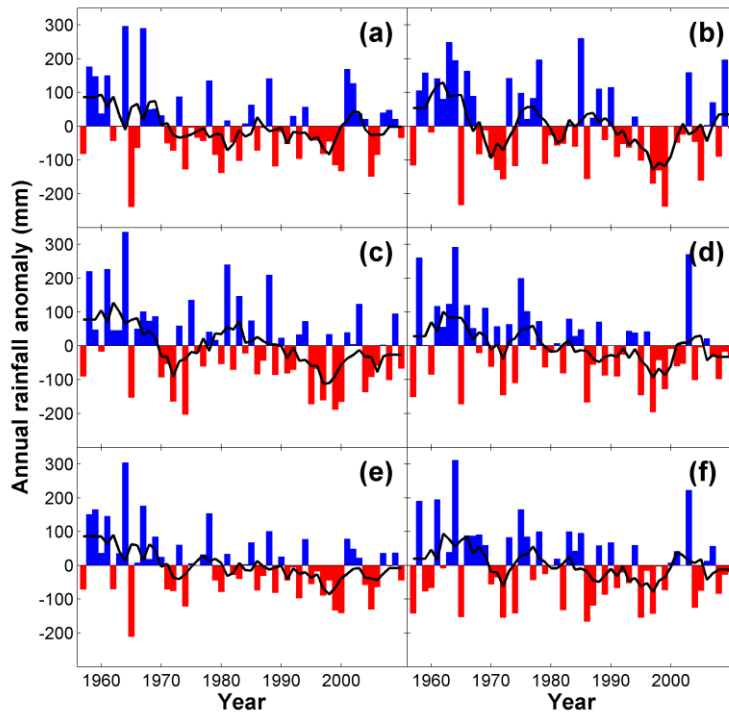
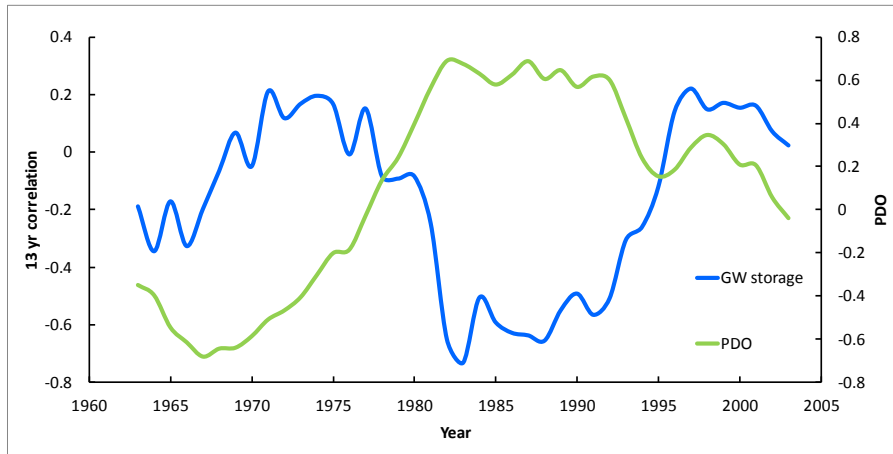
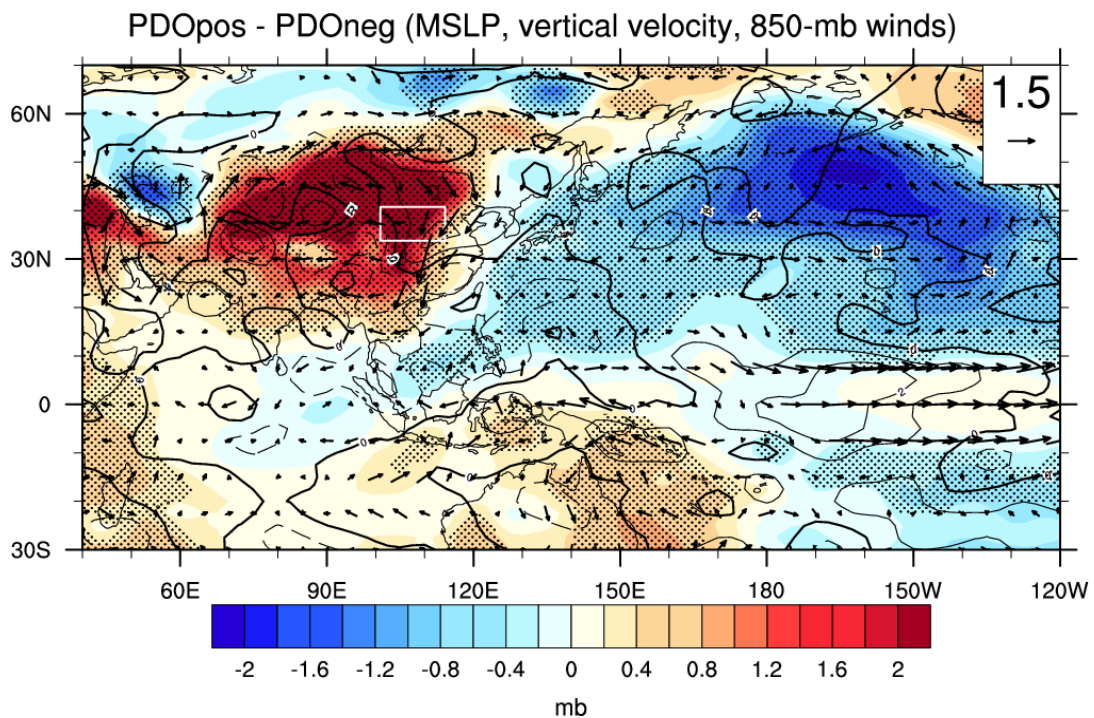


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Dear Dr. Zhang,

I can now inform you that the reviewers and editor have evaluated the manuscript "Groundwater storage trends in the Loess Plateau of China estimated from streamflow records" (Dr. Lu Zhang). As you will see from the comments below and on <http://ees.elsevier.com/hydrol/>, moderate revision has been requested.

Please consider the reviews to see if revision would be feasible. Should you wish to resubmit you should explain how and where each point of the reviewers' comments has been incorporated. For this, use submission item "Revision Notes" when uploading your revision. Also, indicate the changes in an annotated version of the revised manuscript (submission item "Revision, changes marked"). Should you disagree with any part of the reviews, please explain why. To facilitate further review, add line numbers in the text of your manuscript.

Please strictly follow the formatting requirements as presented in the Guide for Authors.

Given that the requested revisions are moderate the new version is required within 1 month.

To submit a revision, go to <http://ees.elsevier.com/hydrol/> and log in as an Author. You will find your submission record under Submission(s) Needing Revision.

When resubmitting, please present any figures, tables etc. as separate files. See the Artwork Guidelines on the home page right menu for further file naming conventions and format issues.

Please note that this journal offers a new, free service called AudioSlides: brief, webcast-style presentations that are shown next to published articles on ScienceDirect (see also <http://www.elsevier.com/audioslides>). If your paper is accepted for publication, you will automatically receive an invitation to create an AudioSlides presentation.

I hope that you will find the comments to be of use to you and am looking forward with interest to receiving your revision.

PLEASE NOTE: The journal would like to enrich online articles by visualising and providing geographical details described in Journal of Hydrology articles. For this purpose, corresponding KML (GoogleMaps) files can be uploaded in our online submission system. Submitted KML files will be published with your online article on ScienceDirect. Elsevier will generate maps from the KML files and include them in the online article.

Journal of Hydrology features the Interactive Plot Viewer, see: <http://www.elsevier.com/interactiveplots>. Interactive Plots provide easy access to the data behind plots. To include one with your article, please prepare a .csv file with your plot data and test it online at <http://authortools.elsevier.com/interactiveplots/verification> before submission as supplementary material.

Thank you for submitting your work to this journal.

With kind regards,

Andras Bardossy, Dr-Ing  
Editor  
Journal of Hydrology

.....  
COMMENTS FROM EDITORS AND REVIEWERS

.....  
Associate editor Alon Rimmer: Five reviewers evaluated this manuscript this time.  
Moderate revisions are still required, especially to the comments of Reviewer #4  
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Reviewer #1: Having served as the original reviewer of this manuscript, I will focus my comments on the revisions. In general, I think the authors did a reasonable and satisfactory revision on most of the issues except for one concern that was raised by all reviewers: why different trends in groundwater storage (GS) between north and south?

In your rebuttal, you explained the upward GS trend in the south is due to enhanced infiltration as a result of increased vegetation coverage and/or other land use changes. However, the same land use change also occurred in the north. Increased vegetation cover will not only results in enhanced infiltration but also more interception and more transpiration, both of which lead to less water coming to/retaining in the soil. Plus, the large scale climate effect has led to a decreased trend in precipitation in the region, which makes the upward GS trend in the south even more unreasonable. (If your analyses were correct, at least the statement that GS trend in the LP is related with sea surface temperature, the PDO and the ENSO is no longer stand).

Response: We found increasing trends in groundwater storage in several catchments located in the south and these increasing trends are not intuitive given the land use changes occurred. Other studies also reported increasing trends in base flow in these catchments (Gao et al., 2015 and Liu et al., 2014). The question is why upward trends in groundwater storage and baseflow occurred. We agree with the reviewer that increased vegetation cover will not only result in enhanced infiltration but also more interception and transpiration. It appears that enhanced infiltration contributed more to groundwater storage in these catchments due to their high gully and drainage density as we explained in the paper. We acknowledge that this hypothesis needs to be further tested with additional data ideally from small experimental catchments, but this is beyond the scope of our current paper. As for the impact of climate on groundwater storage, we qualified our statement in the revised manuscript.

Liu et al., (2014). Influences of shrubs-hers-arbor vegetation cover on the runoff based on remote sensing data in the Loess Plateau. ACTA GEOGRAPHICA SINICA, Vol 69(11), 1595-1603  
Gao, Z.L., Zhang, L., Cheng, L., Zhang, X.P., Potter, N., Cowan, T., Cai, Wenju, (2015). Long-term streamflow trends in the middle reaches of the Yellow River Basin: detecting drivers of change (submitted to Hydrological Processes)

I suggest the authors to examine the trend in annual runoff during the non-flood period, as base flow is a result of groundwater discharge, and should provide an independent measure of GS trend in the region. However, I am not very positive about the outcome. Our previous analyses in the same region shows that annual Q, runoff coefficient of both flood and non-flood seasons all exhibited a decreasing trend during 1961~2009 (for example, the Beiluo basin where your GS trend shows the most obvious upward trend).

Response: Thank you for the suggestion. In a separate study by Gao et al. (2015), they estimated trends in annual total streamflow, surface runoff, and baseflow for these catchments. The reductions in groundwater storage in our study are consistent with the annual streamflow and

baseflow trends reported by Gao et al. (2015). There are 10 catchments where groundwater storage exhibited upward trends ranging from 0.0011 to 0.0119 mm per year with an average value of 0.0047 mm per year. These groundwater trends are opposite to the annual streamflow trends obtained by Gao et al. (2015), but consistent with their annual baseflow trends. The baseflow trends of Gao et al. (2015) provide an independent measure of the groundwater storage trends obtained in this study and the good agreement between them suggests that the method used in our study is appropriate for estimating groundwater storage trend.

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Reviewer #2: Review of  
Groundwater storage trends in the Loess Plateau of China estimated from streamflow records

By  
Ismail Chenini and Abdallah Ben Mammou

Manuscript Number: HYDROL19571

I recommend that the paper be published with some revisions.  
First, in manuscript should be describe the characteristic drainage time scale (K) that different between the results of this study and other research and how to explain uncertainty of K in this case study.

Response: We described the method for estimating the characteristic drainage time scale and compared our estimates with results obtained by other scientists for the region. We also discussed uncertainty in estimating K using our method (see line 184 – 217).

Second, I suggested the authors should showed the groundwater level near streamflow gauging stations. I think that can explain the trends of groundwater storage.

Response: We agree with the reviewer that it would be useful to compare the estimates groundwater storage trends with direct groundwater level observations. However, we were unable to obtain groundwater monitoring data for the region.

Finally, In this study using lowest 7-day flow to determine the annual groundwater storage trends. I think that only represents the lowest groundwater storage. The title of this paper should be to add "lowest" groundwater storage trends? To conclusions, it seems to me that the paper is mature for publication in Journal.

Response: We have made it clear in the paper that the groundwater storage obtained in this study represents lowest groundwater storage. However, it would be unnecessary and confusing to add "lowest" to the title of the paper because we are not dealing with the lowest groundwater storage trends.

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Reviewer #3: The extended explanation and discussion of review comments have been addressed, therefore, I think that the paper has been greatly improved and meets the publication requirement.

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Reviewer #4: The authors "do not agree with comments and criticism" and do not really deal with my comments. This starts with the little and formal things: Instead of dimensions of the different variables, the actually used units should be indicated.

Of course, groundwater storage can be expressed as a thickness (height or depth) with the dimension [L] and the unit mm. However, then it is not a volume (Lines 118-119, Eq.4). These things must be clear.

Response: Thanks for the comment. Changes have been made to indicate that it is the volume of water over the area  $A$  of the catchment.

There is some confusion with the "groundwater storage trends".

Chapter 3.1 deals obviously with baseflow recession with the objective to obtain  $K$ -values, while in 4.2 the trend of annual active storage depths is described.

Response: Thanks for the comments. Changes have been made to eliminate the confusion. In the revised manuscript, it is clear that section 3.1 deals with the estimation of groundwater storage and section 3.3 describes the Mann-Kendall method for estimating trends in annual groundwater storage.

In 3.1: The authors assume that baseflow (outflow) is proportional to storage (Eq. 5). This is the model of the linear reservoir (Maillet, 1905). Eq. 3 is not used? Omit.

Response: Equation (3) is the theoretical basis for the characteristic drainage time scale and it is useful for understanding the  $K$  values and how they relate to aquifer properties.

Line 125ff: "temporal trend of groundwater storage"; this is recession and  $K$  is the retention or reservoir-constant, not a "drainage timescale" (3.2).

Response: Changes have been made (see our response above).

3.3 Trend analysis: This is used for the "annual groundwater storage trends" (4.2) or also for the  $K$ -values?

Response: We have changed the subheading to "Trend analysis of annual groundwater storage" to avoid any confusion.

4.2 It seems a practical idea to use annual 7-day low flows. Average values for every gauging station should be given in Table 1.

Response: We have included average annual groundwater storage for every gauging station in Table 1 and it is the product of annual 7-day low flows and the characteristic time scale (see Equation (5)).

Lines 223-224 appear however doubtful. It is not the  $dS/dt$  of Eq. 6 "temporal trend", what is determined here but the long time trend. Apparently, annual lowest storage  $S_l$  was calculated from annual 7-day low flow  $y_l$  by multiplication with  $K$ , thus  $S_l = K * y_l$ , Eq. 5, right? Authors insist that they used Eq. 6 and that "clearly  $y$  is a variable in the equation". However, the variable is not " $y$ " but " $dy$ "; that is a difference! Authors seemed annoyed, that I proposed trend analyses for time series of annual low flows. Figure 3 shows the trends of low flows multiplied by the respective  $K$ -value.

Response: Thanks for the comments. We have made necessary changes to more clearly describe the methods for estimating groundwater storage (section 3.1) and its trends (section 3.3).

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Reviewer #5: After addressing the comments of all the reviewers the article appears to be in pretty good shape for publication. I think there are still some serious questions about the hypotheses regarding the causes of the changes in the storage in the watersheds, but I believe that without additional data it will not be possible to completely test those hypotheses, and instead at this point a tentative conclusion about what is happening over time in the watersheds seems appropriate.

Response: Thanks for the comments and we hope we will be able to obtain additional data to further investigate this problem in a separate study.



The authors need to read the paper carefully since there are still some problems with the grammar; missing words, etc. I am not able to go through and mark all of these omissions; it will be up to the publishing staff.

Response: [We went through the paper and made some editorial changes.](#)

1 **Groundwater storage trends in the Loess Plateau of China**  
2 **estimated from streamflow records**

---

3  
4 **Zhaoliang Gao<sup>a</sup>, Lu Zhang<sup>b,\*</sup>, Lei Cheng<sup>b</sup>, Xiaoping Zhang<sup>a</sup>, Tim Cowan<sup>c</sup>, Wenju Cai<sup>c</sup>,**  
5 **Wilfried Brutsaert<sup>d</sup>**

6  
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8 Agriculture and Forest University, Chinese Academy of Sciences, Yangling, Shaanxi,  
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13

14 \*Corresponding author: [Lu.Zhang@CSIRO.au](mailto:Lu.Zhang@CSIRO.au)

15 **Abstract:** The catchments in the Loess Plateau in China have experienced significant land use  
16 change since the 1950s with a great number of soil conservation measures such as revegetation  
17 being implemented. Such soil conservation measures and climate variability have had  
18 considerable impacts on the annual streamflow from these catchments. However, much less is  
19 known about changes in groundwater storage as the period of direct groundwater storage  
20 measurements is too short to reliably infer groundwater storage trends. For this study, annual  
21 values of groundwater storage from 38 catchments in the Loess Plateau were estimated from  
22 daily streamflow records based on groundwater flow theory. It was found that over the period  
23 of record (viz. 1955 to 2010), statistically significant ( $p < 0.1$ ) downward trends have been  
24 identified in 20 selected catchments with an average reduction of  $-0.0299$  mm per year, mostly  
25 located in the northern part of the Loess Plateau. Upward groundwater storage trends were  
26 observed in 10 catchments with an average increase of  $0.00467$  mm per year; these upward  
27 trends occurred in southern parts of the study area. Groundwater storage showed no statistically  
28 significant trends in 8 out of the 38 selected catchments. Soil conservation measures  
29 implemented in the Loess Plateau such as large-scale revegetation may have contributed to the  
30 estimated groundwater storage trends. Changes in sea surface temperature in the tropical Pacific  
31 Ocean, as indicated by shifts in climate variability modes such as El Niño-Southern Oscillation  
32 and the Pacific Decadal Oscillation, appear to have also contributed to the decreasing trends in  
33 groundwater storage in this region.

34

35 **Keywords:** Base flow, groundwater storage, climate change, trends, land use change

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38 **1 Introduction**

39 Changes in hydrological cycles have been shown to occur over a range of scales with  
40 climate variability and land use change identified as the main drivers (Milly et al., 2005; Zhang  
41 et al., 2008; Petrone et al., 2010; Zhao et al., 2010; Zhang et al., 2011). Most investigations of  
42 these changes have focused on surface hydrology, more specifically evapotranspiration and  
43 streamflow under different climate scenarios (Christensen and Lettenmaier, 2007; Chiew et al.,  
44 2009). These studies enhanced our understanding of potential impacts on surface water  
45 hydrology and provided useful information for water resources managers. Yet, there are only a  
46 few studies that deal with climate change impacts on groundwater storage mainly due to limited  
47 reliable records of groundwater observations (Brutsaert 2008; Goderniaux et al., 2009; Green  
48 et al., 2011; Zhang et al., 2014). This is also reflected in the most recent Intergovernmental  
49 Panel on Climate Change (IPCC) report, which stated that detection of changes in groundwater  
50 systems and attribution to climatic change are difficult due to a lack of appropriate observational  
51 data and detailed studies (Jiménez Cisneros et al., 2014). Groundwater is an important source  
52 of water supply and accounts for about 50% of domestic water supply globally (Zektser and  
53 Everett, 2004). A better understanding of groundwater storage trends can assist in the  
54 development of sustainable water resources plans as groundwater storage is often crucial for  
55 maintaining ecosystem health (Bertrand et al., 2012; Todd and Mays, 2005).

56 During prolonged dry periods, low flows in natural streams are sustained mostly by  
57 releases from groundwater storage. This means that it is possible to derive information on  
58 groundwater storage from daily streamflow records and one such a method was developed ~~by~~  
59 ~~Brutsaert (2008)~~ based on groundwater flow theory. This method has been successfully applied  
60 to a number of catchments under different climatic and land use conditions (Brutsaert and Sugita,  
61 2008; Brutsaert, 2010; Zhang et al., 2014). The advantages of the method are that it provides

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65 catchment-scale estimates of groundwater storage, only from daily streamflow data at the  
66 catchment outlet.

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67 The Loess Plateau lies in the middle reaches of the Yellow River and has experienced  
68 large-scale land use changes over the past 50 years, resulting in reductions in annual streamflow  
69 (Zhang et al., 2008). For instance, Huang and Zhang (2004) and Mu et al. (2007) reported  
70 reductions of 20-45% in mean annual streamflow from the Jialu, Qiushui, Tuwei, and Yanhe  
71 catchments in this region following major soil water conservation measures. Apart from land  
72 use changes, the climatic variables such as precipitation and temperature have also changed (e.g.  
73 Wang et al., 2012). A number of studies have shown that both climate variability and land use  
74 change are responsible for the observed annual streamflow trends (Mu et al., 2007; Zhang et al.,  
75 2008; Gao et al., 2011). Impacts of land use change such as afforestation on streamflow in the  
76 Loess Plateau have been widely recognised, but the impacts on deep drainage and groundwater  
77 storage are still poorly understood. In addition, large-scale mining activities occurred more  
78 recently in the Loess Plateau are suspected of having modified the regional hydrology,  
79 especially groundwater storage. A better insight into how the groundwater systems in the Loess  
80 Plateau respond to changes in land use and climate will be critical in developing sustainable  
81 resources management plans. Accordingly, the objectives of this study are (1) to estimate long-  
82 term groundwater storage trends in the Loess Plateau from daily streamflow records using the  
83 method of Brutsaert (2008) and (2) to examine the impact of land use changes and climate  
84 variability on the estimated groundwater storage trends.

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## 85 **2 Catchment description and data**

86 The study area is located in the middle of the Loess Plateau and covers an area about  
87  $1.4 \times 10^5$  km<sup>2</sup> (Figure 1). Seventeen catchments within the study area were selected and some  
88 features of these catchments are provided in Table 1. The average mean annual precipitation  
89 (1957-2010) of the study area is 465 mm, but ranges from 544 mm in the south-east to 370 mm

92 in the north-west. The north-western region is relatively flat whilst the south-east is  
93 characterized by a heavily dissected landscape, with gully density varying from 2 to 8 km km<sup>-2</sup>  
94 (Tang and Chen, 1990; Ran et al., 2000). Loess soil was deposited over the study area to a depth  
95 exceeding 100 m during the Quaternary period (Liu, 1999). Coarser, sandier sediments are  
96 common in the northwest and finer, clay-rich sediments occur in the southeast. The dominant  
97 vegetation type for all except for four catchments is pasture, with the remainder predominantly  
98 covered by forest.

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99 Daily streamflow data from 38 gauging stations were obtained from the Water Resources  
100 Committee of the Yellow River Conservancy Commission; most of the streamflow records  
101 cover the period of 1952-2010 with shorter records for some stations (Table 1). The annual  
102 precipitation and relevant meteorological data were obtained from the State Meteorology  
103 Bureau. The meteorological data were spatially averaged across the study area as described by  
104 Zhang (2007).

105 *Insert Figure 1 here.*

106

### 107 3 Methods

#### 108 3.1 Estimation of groundwater storage

109 The baseflow from a catchment can be expressed as:

$$110 \quad Q = Q(t) \quad (1)$$

111 where  $Q$  is the rate of flow [L<sup>3</sup>T<sup>-1</sup>] and  $t$  is the time [T]. For convenience,  $Q$  is generally  
112 expressed by  $y = Q/A$ , in which  $A$  is the catchment area. The most common equation for  
113 describing describe baseflow is of the exponential form, namely

$$114 \quad y = y_0 \exp(-t/K) \quad (2)$$

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117 where  $K$  is the characteristic time scale of the catchment drainage process [T], and  $y_0$  is the  
 118 value of  $y$  at the selected time origin  $t = 0$ . Brutsaert (2005) showed that the “long-time”  
 119 solution of the linearized Boussinesq equation yields the following expression for the  
 120 characteristic drainage time scale

$$121 \quad K = 0.10n_e / (D_d^2 k_0 \eta_0) \quad (3)$$

122 where  $k_0$  [ $LT^{-1}$ ] is the hydraulic conductivity,  $n_e$  the drainable porosity,  $\eta_0$  is the average  
 123 vertical thickness [L] of the layer in the soil profile occupied by flowing water,  $D_d = L / A$  is  
 124 the drainage density, where  $L$  is the total length of upstream channels in the catchment.

125 When groundwater recharge is negligible, the movable groundwater stored in a catchment  
 126  $S$  is the volume of water over the area  $A$  of the catchment [L], that has not yet been released as  
 127 baseflow  $y$

$$128 \quad S = - \int_t^{\infty} y \, dt \quad (4)$$

129 Upon integration with equation Error! Reference source not found., this yields a linear  
 130 relationship between groundwater storage and rate of flow,

$$131 \quad S = Ky \quad (5)$$

132 The groundwater storage  $S$  can be considered as the average thickness of water stored  
 133 above the zero-flow level of the water table over the catchment.

### 135 3.2 The characteristic drainage timescale

136 Estimating groundwater storage using Equation (5) requires a knowledge of the  
 137 characteristics drainage timescale  $K$ . In this study,  $K$  was determined from daily streamflow  
 138 data using the method of Brutsaert and Nieber (1977) by expressing  
 139 Error! Reference source not found. in differential form:

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Deleted: (2)

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Deleted: Based on equation (5), the temporal trend of groundwater storage can be determined from the temporal trend in the base flow as follows:

$$Deleted: \frac{dS}{dt} = K \frac{dy}{dt}$$

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150 
$$\frac{dy}{dt} = \varphi(y)$$

151 where  $\varphi(y)$  is a function that is characteristic for a given basin. Thus, in the case of equation

152 **Error! Reference source not found.**, for the present purpose (6) becomes

153 
$$\frac{dy}{dt} = -\frac{y}{K}$$

154 Decrease in low flow from groundwater and soil moisture storage is generally assumed to  
155 be much slower than that of surface runoff generated directly from rainfall. Evapotranspiration  
156 tends to accelerate the decline of low flow, and thus result in a larger  $|dy/dt|$ . This means that  
157 low flows during periods of minimal evapotranspiration can be associated with the smallest  
158  $|dy/dt|$  for a given flow rate  $y$ . Equation (7) describes the low flow hydrograph from a  
159 catchment and requires identification of the streamflows that took place under low-flow  
160 conditions. For each catchment,  $K$  was determined by implementing the method of Brutsaert  
161 and Nieber (1977) considering the lowest envelope of a  $\log(-dy/dt)$  versus  $\log(y)$  plot.

162 Only streamflow data that met stringent low flow criteria were used with (7), and all others  
163 were excluded; these criteria are based on the following considerations (e.g. Zhang et al., 2014).  
164 During a recession,  $-dy/dt$  is expected to decrease monotonically and a recession should last  
165 at least multiple days to contain useful information. Moreover, since concurrent precipitation  
166 data were available, in the present implementation of the procedure, careful scrutiny of these  
167 data allowed exclusion of any direct storm runoff on days of rainfall, and also a number of days  
168 (1 to 4 depending on the area of the catchment) after the rainfall event. After low flow data  
169 points were identified, they were plotted as  $\log(-dy/dt)$  versus  $\log(y)$  relationships for the  
170 selected catchments. A straight line lower envelope with unit slope was fitted to the data from  
171 which  $K$  could be determined. Because the data points show scatter, the determination of the  
172 exact position of the lower envelope is somewhat subjective. Therefore, as suggested by Troch

(6)

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179 *et al.* (1993), the positions of the lower envelopes were determined such that 5% of the plotted  
180 flow data points fell below the lower envelopes.

### 181 3.3 Trend analysis of annual groundwater storage

182 The Mann-Kendall rank correlation coefficient (Mann, 1945; Kendall, 1975) is commonly  
183 used to assess the significance of trends in hydro-meteorological time series and has been used  
184 in this study for estimating annual groundwater storage trends. The Mann-Kendall test statistic  
185 ( $T$ ) is given by

$$186 \quad T = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (8)$$

187 and

$$\begin{aligned} & \text{if } \theta > 0, & \text{sgn}(\theta) &= 1 \\ & \text{if } \theta = 0, & \text{sgn}(\theta) &= 0 \\ & \text{if } \theta < 0, & \text{sgn}(\theta) &= -1 \end{aligned}$$

188 where,  $n$  is the data set record length;  $x_j$  and  $x_k$  are the sequential data values.

189 The Mann-Kendall test has two parameters that are of importance to trend detection. These  
190 parameters are the significance level, which indicates the trend's strength, and the slope  
191 magnitude estimate, which indicates the direction as well as the rate of change. Under the null  
192 hypothesis that there is no trend in the data, the distribution of  $S$  is then expected to have a mean  
193 of zero and a variance of

$$194 \quad \text{var}(T) = \frac{n(n-1)(2n+5)}{18} \quad (9)$$

195 The normal  $Z$ -test statistic is calculated as

$$196 \quad z = \begin{cases} \frac{T-1}{\sqrt{\text{Var}(T)}} & \text{if } T > 0 \\ 0 & \text{if } T = 0 \\ \frac{T-1}{\sqrt{\text{Var}(T)}} & \text{if } T < 0 \end{cases} \quad (10)$$

197 The null hypothesis is rejected at significance level of  $p$  if  $|Z| > Z_{(1-p/2)}$ , where  $Z_{(1-p/2)}$  is the  
198 value of the standard normal distribution with a probability of exceedance of  $p/2$ . A positive

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202 value of  $Z$  indicates an upward trend while a negative value represents a downward trend in the  
203 data.

204 If a linear trend is present, the magnitude of the trend,  $\beta$ , or the slope (change per unit time)  
205 is estimated using a non-parametric method proposed by Sen (1968) and extended by Hirsch et  
206 al. (1982):

$$207 \quad \beta = \text{Median} \left[ \frac{X_j - X_k}{j - k} \right] \quad \text{for all } k < j \quad (11)$$

208 where  $1 < k < j < n$ . In other words, the slope estimator  $\beta$  is the median of all possible  
209 combinations of pairs for the whole data set.

## 210 4 Results and Discussion

### 211 4.1 Characteristic drainage time scale

212 The values of the catchment drainage time scale  $K$  estimated by means of the method  
213 described in the previous section are listed in Table 1. For the 38 selected gauging stations, the  
214 drainage time scale  $K$  varies between 12 and 83 days with an average value of 30 days and  
215 standard deviation of 15 days. Figure 2 shows examples for the Qingjian River catchment at  
216 Yanchuan station and Shiwang River catchment. All the catchments have  $K$  values smaller than  
217 45 days, except for Gaojiabao, Zhaoshiyao, and Hanjiamao stations. These three stations are  
218 located in the northwest part of the study area with lower annual precipitation. However, the  
219 areas have flat landscape with coarser and sandier sediments, resulting higher groundwater  
220 recharge (Wang et al., 1990). The groundwater tables in these catchments are shallower (Office  
221 of Land and Resources of Shaanxi Province, 2008) with much higher baseflow index (i.e. the  
222 ratio of average annual baseflow to the total average annual streamflow) compared to the rest  
223 of the catchments (Zhu et al., 2010). As a result, these catchments sustain higher baseflow rates  
224 and show slower flow recession during dry periods. The south-eastern part of the study area is  
225 characterized by a heavily dissected landscape with high gully density and deep loess soil,

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227 exceeding 200 m in many locations. The groundwater recharge is limited in this region and the  
228 surface water is weakly coupled with the groundwater system, resulting in quick flow recession.  
229 In a different approach, Zhu et al., (2010) estimated the catchment drainage time scale in the  
230 Loess Plateau and showed that it varied from 5 to 16 days across the catchments. In their  
231 estimation of the drainage time scale, the master recession curve approach was used. Xu et al.,  
232 (2010) analysed isotopic characteristics of rainfall, soil moisture, and groundwater samples  
233 taken from the Yangou catchment located in the south of the Loess Plateau and showed that the  
234 time lags between rainfall and groundwater discharge are about 35 days. Although obtained by  
235 a different method, in general, the  $K$  values obtained in the present study are similar with the  
236 results of Xu et al. (2010), but larger than the estimates of Zhu et al. (2010). However, the  
237 average  $K$  value for the catchments in the Loess Plateau is smaller than those reported by  
238 Brutsaert (2008, 2010) for US catchments and Zhang et al. (2014) for Australian catchments,  
239 where it was found that  $K$  is on average 46 days, with an uncertainty of less than 15 days.  
240 Studies show that the loess soils in the Loess Plateau are highly permeable with saturated  
241 hydraulic conductivity values ranging from 1.1 m/day to 7.2 m/day (Jiang and Huang, 1986).  
242 Moreover, as noted earlier, the region is highly dissected with drainage densities varying from  
243 roughly 2 to 8 km/km<sup>2</sup> (Tang and Chen, 1990; Ran et al., 2000). These rather large hydraulic  
244 conductivity values and large drainage density values indicate that water drains faster from the  
245 catchments implying smaller  $K$  values. Actually, this can also readily be seen in the theoretical  
246 expression Error! Reference source not found., where larger values of  $k_0$  and  $D_d$  result in  
247 smaller values of  $K$ .

248 *Insert Figure 2 here.*

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## 4.2 Annual groundwater storage trends

In this study the annual lowest 7-day flows were used to represent  $y$  in (5) to determine the annual groundwater storage with estimates of drainage time scale  $K$ , obtained as indicated in the previous section. Then annual groundwater storage trends were estimated using the Mann-Kendall and Sen's slope method described above. The results are listed in Table 1 for the periods of record. Actually, several other characteristics of baseflow could be used to represent  $y$  in (5). The lowest 7-day flow was specifically chosen because it represents the lowest groundwater storage level in each year, which is carried over to the next year, so that it can be used to track its long-term evolution. Moreover, the lowest 7-day flow is a common and robust variable used in drought statistics (Smakhtin, 2001), which can be readily determined as the lowest value of the 7-day running averages for each year of record.

As examples of the results presented in Table 1, Figure 3 shows groundwater storage trends over the periods of record from three selected catchments. The Tuwei River catchment at Gaojiabao station in the northwest of the study area exhibited the strongest downward trend (i.e.  $-0.2612$  mm/year) (Figure 3a), while the Yanhe River catchment showed an upward trend in groundwater storage of  $0.0010$  mm/year. The Wuding River catchment at Qingyangcha station shows stable groundwater storage (i.e. no statistically significant trend) over the period of 1959 to 2005 (Figure 3c). Over the period of record, which varies from 39 to 57 years, 30 catchments show statistically significant trends at least at the 0.1 significance level (Table 1). Among them, 20 catchments, i.e. the majority, showed statistically significant downward trends ranging from  $-0.0002$  to  $-0.2612$  mm per year with an average value of  $-0.0299$  mm per year (Table 1). The downward trends in groundwater storage are similar to those of the South Atlantic-Gulf region in the US (Brutsaert, 2010), of the Kherlen River basin in Mongolia (Brutsaert and Sugita, 2009), and of the Australian catchments studied by Zhang et al. (2014) over a similar period. The reduction in groundwater storage in these catchments are consistent with the annual streamflow

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280 and baseflow trends reported by Gao et al. (2015). There are 10 catchments where groundwater  
281 storage exhibited upward trends ranging from 0.0011 to 0.0119 mm per year with an average  
282 value of 0.0047 mm per year (Table 1). These groundwater trends are opposite to the annual  
283 streamflow trends obtained by Gao et al. (2015), but consistent with their annual baseflow  
284 trends. The baseflow trends of Gao et al. (2015) provide an independent measure of the  
285 groundwater storage trends as baseflow is a result of groundwater discharge and the good  
286 agreement between the two estimates suggests that the method used in our study is appropriate  
287 for estimating groundwater storage trends. It should also be noted that the magnitudes of the  
288 upward trends in groundwater storage are similar to those of the Souris-Red-Rainy and the  
289 Missouri regions reported by Brutsaert (2010).

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290 Spatial patterns of the groundwater storage trends in the Loess Plateau are shown in Figure  
291 4. The catchments with significant downward trends in groundwater storage are mostly those  
292 located in the northern part of the study area, where the landscape tends to be flatter with more  
293 sandy soils and shallower groundwater tables. The baseflow index in this region is also higher  
294 than that of the catchments in the southern part of the study area (Zhu et al., 2010). Upward  
295 groundwater storage trends occurred mostly in the Beluo River basin located in the southern  
296 part of the Plateau (Figure 4).

297 ***Insert Figure 3 and Figure 4 here.***

298 The observed groundwater storage trends in the Loess Plateau are probably caused mostly  
299 by land use changes and climate variability. Indeed, over the period of 1959 to 2006, the  
300 catchments reported in this study experienced major land use changes including the  
301 establishment of sediment check dams and revegetation (Zhang et al. 2008). A number of  
302 studies have shown that the soil conservation measures implemented in this region since the  
303 1950s contributed to marked reductions in annual streamflow (Huang and Zhang, 2004; Mu et  
304 al., 2007, Zhang et al., 2008). The observed downward groundwater storage trends may be at

308 least partly explained by the soil conservation measures as they can reduce runoff and increase  
309 evapotranspiration. Huang and Pang (2010) examined the effects of land use changes in the  
310 Loess Plateau using a chloride mass balance approach and their results indicate that  
311 conservation measures such as afforestation have considerably reduced groundwater recharge  
312 through increased transpiration. Also, large scale open coal mining activities commenced  
313 recently in parts of the study area (Lei et al., 2013; Jiang et al., 2010) appear to have affected  
314 water balance components and reduced groundwater storage. Other studies have demonstrated  
315 that revegetation can enhance evapotranspiration and reduced streamflow (Zhang et al., 2001;  
316 Brown et al., 2005) and that revegetation can also improve soil conditions and result in higher  
317 infiltration capacity (Wilcox et al., 1988; Bartley et al., 2006).

318 Groundwater storage is affected by a number of factors, including soil hydraulic properties,  
319 riparian aquifer characteristics, stream network, land scape topography, and evapotranspiration  
320 (Brutsaert 2005). Land use changes can affect these factors and result in changes in groundwater  
321 storage. The selected catchments in this study have experienced considerable land use change  
322 such as revegetation and it is expected that these changes will affect evapotranspiration and  
323 infiltration. In the case of the catchments located in the northern part of the study area, increases  
324 in vegetation cover led to greater infiltration of rainfall into the soil, but the additional water  
325 stored in the soil was used by vegetation, resulting decreases in groundwater storage. The effect  
326 of the soil conservation measures on groundwater storage was exacerbated by large scale open  
327 coal mining commenced more recently in the northern parts of the study area (Lei et al., 2013;  
328 Jiang et al., 2010). For the catchments in the south-western part of the study area, increases in  
329 groundwater storage may be partly attributed to enhanced infiltration following land use change  
330 as the region is highly dissected with a high gully density and drainage density, and focused  
331 recharge is potentially an important process. This means that infiltrated water can quickly  
332 escape the root zone and recharge groundwater storage before being used by vegetation.

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334 The Loess Plateau has experienced slight downward trends in annual precipitation over the  
335 period of 1957 to 2010, albeit mostly in its southern half (Wang et al., 2012, Figure 5). This is  
336 also illustrated for several catchments in Figure 5, where it can be seen that the number of years  
337 with below average annual precipitation has increased over time; this may at least partly explain  
338 the downward trends in groundwater storage. However, the upward groundwater storage trends  
339 in the south of the study area cannot be explained by the downward precipitation trends, where  
340 the precipitation decreases are most pronounced. This should perhaps not be surprising because,  
341 according to the water budget equation, beside evaporation and runoff, precipitation is related  
342 to the change in storage, rather than to storage itself; as a result, groundwater storage is a more  
343 slowly changing hydrologic variable, and its correlation with concurrent precipitation cannot  
344 be expected to be very strong over short time scales. It should be acknowledged that  
345 groundwater storage is a complex process and many factors can influence the ability of water  
346 to flow in or out of the storage. Price (2011) argued that little is known about baseflow or  
347 groundwater storage responses to land use change in large and complex systems and called for  
348 more studies investigating the relative influences of these factors. Our study provided useful  
349 information on changes in groundwater storage following large scale land use change. However,  
350 it is difficult to attribute the groundwater storage change to individual factors due to limited  
351 data available on land use change, especially their spatial distribution. Further studies are  
352 needed to explore how specific land use change affects groundwater storage by combining data  
353 analysis with modelling.

354 Hanson et al. (2004) analysed time series of streamflow, base flow, and groundwater levels  
355 and showed that these hydrological variables were strongly correlated over longer time scales,  
356 namely with temporal variability in the Pacific Ocean, as manifested by the Pacific Decadal  
357 Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO) indices. The PDO represents  
358 a pattern of Pacific climate variability involving interdecadal fluctuations in sea surface

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360 temperatures (SSTs). Its regional climate signatures are similar to those associated with ENSO,  
361 which is one of strongest ocean-atmosphere coupled modes of variability. Typically, PDO  
362 phases last for 2–3 decades, much longer than ENSO phases of 6 to 18 months. Brabets and  
363 Walvoord (2009) investigated streamflow trends in the Yukon River basin of Alaska and  
364 Canada and found changes in streamflow patterns correlated with a PDO regime shift. More  
365 recently, Brutsaert (2012) found that the PDO and ENSO affected groundwater storage in four  
366 desert regions of North America. It is of interest to put these findings in context for the Loess  
367 Plateau.

368 The evolution of the PDO can be represented as an index, defined as the leading principal  
369 component of monthly sea surface temperature (SST) anomalies over the North Pacific region  
370 (Mantua et al. 1997). For this study, we utilised the PDO index calculated in Mantua et al.  
371 (1997), based on Version 1 and 2 of Reynolds's Optimally Interpolated SST product (Reynolds  
372 and Smith 1994). A 13-year running average was applied to the PDO index as a low-pass filter,  
373 similar to how the closely related inter-decadal Pacific Oscillation is calculated (Parker et al.  
374 2007). Positive PDO index values reflect the warm phase associated with anomalously cool  
375 central-North Pacific SSTs and warm SST anomalies in the eastern tropical Pacific. When the  
376 PDO index is negative (i.e. cold phase), the anomalous SST patterns are reversed, with warming  
377 in the central-North Pacific and cooling along the equatorial Pacific. The changes in distribution  
378 of cold and warm ocean water masses alter the path of the jet stream responsible for storm  
379 delivery.

380 ***Insert Figure 5 here.***

381 The inter-decadal relationship between PDO, ENSO and China rainfall has been addressed  
382 in a number of studies (e.g., Chan and Zhou, 2005; Yoon and Yeh 2010) with focus on both  
383 boreal winter and summer monsoon rainfall over East Asia (Kim et al. 2014; Feng et al. 2014).  
384 The consensus is that the influence of ENSO on East Asian rainfall is either enhanced or damped

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386 by the decadal phases of the PDO. For example, during the peak ENSO season (December-  
387 February), there is a tendency for SSTs along the subtropical and tropical eastern Pacific to  
388 warm during positive PDO, which causes an anomalous zonal circulation response that  
389 strengthens the west Pacific subtropical high (Yu et al. 2014). This restricts moisture transport  
390 into northern China, but increases the moisture transport into the Yangtze River Valley region  
391 (southeastern China). Many studies have documented the fact that when the state of ENSO is  
392 in phase with the PDO this can strongly influence rainfall totals over South China (Chan and  
393 Zhou 2005), and northeast China during the summer monsoon (Yoon and Yeh 2010).

394 For the purpose of this study, we define ENSO using the NINO3.4 index, defined as areal  
395 averaged SST anomalies over 5°N-5°S and 170°-120°W. The association between ENSO and  
396 groundwater storage averaged across all study catchments in the Loess Plateau is statistically  
397 significant at the 95% confidence level (negative correlation exceeds -0.53 based on 12 degrees  
398 of freedom) for most of the positive warm PDO phase (1977-2002), as shown in Figure 6. As  
399 the PDO trends towards the negative cool phase (i.e. mid 1990s), the ENSO-ground water  
400 storage association becomes weak and insignificant on interannual time-scales. What this  
401 suggests is that during the warm PDO phase, annual precipitation across catchments decreases  
402 (*increases*) during an El Niño (*La Niña*) event, with flow-on effects for runoff generation and  
403 groundwater storage.

404 ***Insert Figure 6 here.***

405 To help better understand how the variability in the Pacific might explain changes in  
406 groundwater storage over the Loess Plateau, we focus on the atmospheric circulation  
407 differences over the northern Pacific between the positive [1977-2002] and negative [1950-  
408 1976] PDO phases (i.e. circulation averaged over positive PDO index years [1977-2002] minus  
409 circulation averaged over negative PDO index years [1950-1976]; see Figure 7). The change in  
410 the circulation is represented by mean sea level pressure (colour), 500-mb vertical velocity

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412 (contour) and near-surface (850-mb) winds (vectors) based on output from the National Centers  
413 for Environmental Prediction (NCEP) and the National Center for Atmospheric  
414 Research (NCAR) Reanalysis dataset (Kalnay et al. 1996). The circulation difference between  
415 PDO phases merely reflects the long-term trends in circulation over the Asia and the North  
416 Pacific (not shown).

417 The composite difference captures anomalous easterlies along the equatorial Pacific and  
418 an anti-cyclonic flow flanking the anomalous low pressure cell over the extratropical Pacific –  
419 this reflects the conditions during the warm PDO phase with El-Niño-like conditions. Over the  
420 Loess Plateau region lies an anomalously high mean sea level pressure center, directing  
421 anomalous northerlies to the region, along with downward motion as represented by the positive  
422 vertical velocity at 500-mb. The circulation over the Loess Plateau suggests that local  
423 convection/divergence is much stronger during the PDO warm phase and plays an important  
424 role in precipitation variability. The strong tendency for large El Niño episodes to predominate  
425 during the positive PDO phase (e.g., 1982/83, 1997/98) would result in a dynamical set-up that  
426 involves anomalous northerlies and subsidence conducive to a reduction in precipitation and  
427 thus groundwater storage over the Loess Plateau. This may partially explain the decline in  
428 precipitation and storage in many of the catchments to the north of the Loess Plateau over the  
429 late 20<sup>th</sup> century, however it fails to explain increases in groundwater storage in several  
430 catchments located in the south. As the ENSO-Loess Plateau precipitation teleconnection  
431 breaks down during the negative PDO phase (i.e. post-2002), variations in ENSO show no  
432 control on precipitation and ground water storage over the catchments. Variations in  
433 precipitation, runoff and groundwater storage during the cool PDO phase would more likely be  
434 associated with changes in local atmospheric conditions, related to the strength of summer and  
435 winter monsoons.

436 *Insert Figure 7 here.*

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## 442 5 Conclusions

443 Annual values of groundwater storage from 38 catchments in the Loess Plateau of China  
444 were derived from daily streamflow data using the method proposed by Brutsaert (2008). The  
445 method can be considered reliable for estimating catchment scale groundwater storage as shown  
446 in several studies (e.g. Brutsaert, 2008; Zhang et al., 2014). The selected catchments in this  
447 study have at least 39 years of continuous daily streamflow data with catchment area ranging  
448 from 327 to 29662 km<sup>2</sup>. These catchments are representative of the hydro-climatic, and hydro-  
449 geologic conditions of the Loess Plateau and have been under the influence of both climate  
450 variability and human activities.

451 The analysis showed that the drainage time scale  $K$  varied between 12 and 83 days with an  
452 average value of 30 days. The  $K$  values obtained in this study are similar with results of Xu et  
453 al. (2010), but smaller than those reported by Brutsaert (2008, 2010) for US catchments and  
454 Zhang et al. (2014) for Australian catchments. Over the period of record, 20 catchments showed  
455 statistically significant ( $p < 0.1$ ) downward trends ranging from -0.0002 to -0.2612 mm per year  
456 with an average value of -0.0299 mm per. In 10 catchments groundwater storage exhibited  
457 upward trends ranging from 0.0011 to 0.0119 mm per year with an average value of 0.00467  
458 mm per year. Groundwater storage showed no statistically significant trends in 8 out of the 38  
459 selected catchments. The groundwater storage trends are consistent with changes in annual  
460 streamflow and baseflow reported in other studies. Soil conservation measures implemented in  
461 the Loess Plateau such as large-scale revegetation may have contributed to the observed  
462 groundwater storage trends. Changes in sea surface temperature in the Pacific Ocean, as  
463 indicated by variations in ENSO and phase shifts of the PDO, appear to have also affected  
464 longer term rainfall patterns and hence contributed to decreasing trends in groundwater storage,  
465 predominantly through the 1990s.

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**Table 1. Characteristics of selected catchments in the Loess Plateau. Also shown are estimates of drainage time scale ( $K$ ), average groundwater storage (S), and groundwater storage trends over the period of records estimated from daily streamflow.**

Catchment	Gauging station	Area (km <sup>2</sup> )	Slope (%)	Rainfall (mm yr <sup>-1</sup> )	Runoff (mm yr <sup>-1</sup> )	Period of streamflow record	Drainage time scale $K$ (days)	<u>Average groundwater storage (mm)</u>	Groundwater storage trend (mm yr <sup>-1</sup> ) <sup>a</sup>
1 Kuye	Xinmiao	1527	4.89	385	60.9	1966 – 2005	31	0.1886	-0.0050**
	Wangdaohengt a	3839	4.88	437	49.0	1959 – 2005	34	0.3174	-0.0099***
	Wenjiachuan	8645	4.28	425	67.4	1953 – 2010	36	0.3888	-0.0100***
2 Tuwei	Gaojiabao	2095	4.93	444	130.4	1966 – 2005	83	16.1245	-0.2612***
	Gaojiachuan	3253	3.87	444	106.1	1955 – 2010	41	4.6855	-0.1214***
3 Jialu	Shenjiawan	1121	6.28	401	55.0	1957 – 2010	19	0.5113	-0.0165***
4 Wuding	Dianshi	327	10.62	370	41.2	1958 – 2005	24	0.5531	-0.0049
	Mahuyu	371	7.10	457	42.9	1962 – 2005	18	0.2276	-0.0040***
	Qingyangcha	662	7.94	457	38.8	1959 – 2005	29	0.5375	-0.0027
	Lijiahe	807	5.03	457	41.6	1959 – 2005	16	0.1232	-0.0012
	Hengshan	2415	4.01	370	28.5	1957 – 2005	42	0.9013	-0.0282***
	Hanjiamao	2452	3.7	401	35.1	1957 – 2005	189	2.5959	-0.0353***
	Zhaoshiyao	15325	2.72	407	35.8	1954 – 1990	61	2.3234	0.0027
	Dingjiagou	23422	2.04	407	38.0	1959 – 2005	33	0.7654	-0.0243***
Baijiachuan	29662	1.80	458	38.7	1956 – 2010	24	0.4355	-0.0160***	
5 Qingjian	Zichang	913	6.22	494	45.0	1958 – 2005	21	0.1918	0.0058***
	Yanchuan	3468	8.37	494	41.1	1954 – 2010	25	0.3325	0.0052**
6 Yanhe	Yan'an	3208	3.53	484	39.7	1965 – 2005	16	0.0916	0.0010

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	Ganguyi	5891	3.26	484	35.8	1952 – 2010	20	0.1846	0.0022*
7 Yunyan	Linzhen	1121	5.7	544	17.8	1959 – 2005	16	0.1144	-0.0013
	Xinshihe	1662	5.2	544	19.7	1966 – 2010	17	0.1500	-0.0013 <sup>+</sup>
8 Shiwang	Dacun	2141	11.41	544	34.1	1959 – 2010	30	0.3974	-0.0083**
9 Beiluo	Zhidan	774	5.86	502	38.5	1964 – 2009	18	0.1253	0.0015*
	Huangling	2266	4.96	543	46.8	1967 – 2009	25	0.7664	0.0119*
	Wuqi	3408	3.27	377	27.6	1963 – 2009	30	0.2123	0.0057***
	Zhangcunyi	4715	3.88	523	22.7	1958 – 2009	28	0.2400	0.0054**
	Liujiuhe	7325	2.17	432	32.3	1958 – 2009	33	0.4778	0.0062***
	Jiaokouhe	17180	2.06	512	25.9	1952 – 2009	28	0.3930	0.0017*
	Zhuangtou	25154	1.98	524	25.4	1957 – 2009	27	0.2353	-0.0041
10 Pianguan	Pianguan	1915	6.52	411	17.9	1957 – 2010	24	0.2505	-0.0126***
11 Lanyi	Kelan	476	9.6	467	49.4	1959 – 2010	42	1.0183	-0.0086
12 Weifen	Xingxian	650	9.73	488	42.3	1956 – 2010	14	0.0188	-0.0003***
13 Qiushui	Linjiaping	1873	6.51	487	39.4	1953 – 2010	21	0.0747	-0.0002**
14 Sanchuan	Gedong	749	9.69	487	65.0	1960 – 2004	46	1.8402	-0.0256***
	Houdacheng	4102	4.70	468	53.8	1953 – 2010	23	1.2281	-0.0135*
15 Quchan	Peigou	1023	8.12	503	31.8	1962 – 2010	15	0.1008	0.0011*
16 Xinshui	Daning	3992	9.35	518	33.4	1955 – 2010	20	0.1829	-0.0034***
17 Zhouchuan	Jixian	436	15.2	500	34.8	1959 – 2010	12	0.2435	-0.0012 <sup>+</sup>

Notes: <sup>a</sup> the symbols indicate different significance levels: \*\*\* when  $p < 0.001$ , \*\* when  $p < 0.01$ , \* when  $p < 0.05$  or + when  $p < 0.1$ .