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

Citation for published version:
Gao, Z, Zhang, L, Cheng, L, Zhang, X, Cowan, T, Cai, W & Brutsaert, W 2015, 'Groundwater storage trends in the Loess Plateau of China estimated from streamflow records', *Journal of Hydrology*. https://doi.org/doi:10.1016/j.jhydrol.2015.09.063

Digital Object Identifier (DOI):
doi:10.1016/j.jhydrol.2015.09.063

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Journal of Hydrology

Elsevier Editorial System(tm) for Journal of Hydrology
Manuscript Draft

Manuscript Number: HYDROL19571R1

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

Article Type: Research Paper

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

Corresponding Author: Dr. Lu Zhang, Ph.D.

Corresponding Author's Institution:

First Author: Zhaoliang Gao, PhD

Order of Authors: Zhaoliang Gao, PhD; Lu Zhang, Ph.D.; Lei Cheng, PhD; Xiaoping Zhang, PhD; Tim Cowan, PhD; Wenju Cai, PhD; Wilfried Brutsaert, PhD

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.

CSIRO LAND AND WATER FLAGSHIP
www.csiro.au

Clunies Ross Street, Black Mountain, Canberra ACT
GPO Box 1666, Canberra ACT 2601 Australia
Telephone: +61 2 6246 5700 Facsimile: +61 2 6246 5800

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,

Dr. Lu Zhang
Senior Principal Research Scientist
CSIRO Land and Water Flagship, Black Mountain
P.O. Box 1666, Canberra, ACT 2601, Australia
Lu.Zhang@csiro.au | +61 2 62465802

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

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

Zhaoliang Gao[a], Lu Zhang[b,*], Lei Cheng[b], Xiaoping Zhang[a], Tim Cowan[c], Wenju Cai[c], Wilfried Brutsaert[d]

[a] State key laboratory of soil erosion and dryland farming on Loess Plateau, Northwest Agriculture and Forest University, Chinese Academy of Sciences, Yangling, Shaanxi, China.

[b] CSIRO Land and Water Flagship, Christian Laboratory, Canberra, ACT, Australia.

[c] CSIRO Oceans and Atmosphere Flagship, Aspendale, Victoria, Australia.

[d] School of Civil and Environmental Engineering, Cornell University, Ithaca, NY 14850, USA

[*]Corresponding author: Lu.Zhang@CSIRO.au

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.

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

1 Introduction

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

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

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

2 Catchment description and data

The study area is located in the middle of the Loess Plateau and covers an area about 1.4×10^5 km^2 (Figure 1). Seventeen catchments within the study area were selected and some features of these catchments are provided in Table 1. The average mean annual precipitation

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

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

Insert Figure 1 here.

3 Methods

3.1 Estimation of groundwater storage

The baseflow from a catchment can be expressed as:

$$Q = Q(t) \tag{1}$$

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

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

where K is the characteristic time scale of the catchment drainage process $[\mathrm{T}]$, and y_0 is the value of y at the selected time origin $t = 0$. Brutsaert (2005) showed that the "long-time" solution of the linearized Boussinesq equation yields the following expression for the characteristic drainage time scale

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

where k_0 $[\mathrm{LT}^{-1}]$ is the hydraulic conductivity, n_e the drainable porosity, η_0 is the average vertical thickness $[\mathrm{L}]$ of the layer in the soil profile occupied by flowing water, $D_d = L / A$ is the drainage density, where L is the total length of upstream channels in the catchment.

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

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

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

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

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

3.2 The characteristic drainage timescale

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

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

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

$$\frac{dy}{dt} = -\frac{y}{K} \tag{7}$$

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

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

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

3.3 Trend analysis of annual groundwater storage

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

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

and

$$\begin{array}{lll} if & \theta > 0, & \mathrm{sgn}(\theta) = 1 \\ if & \theta = 0, & \mathrm{sgn}(\theta) = 0 \\ if & \theta < 0, & \mathrm{sgn}(\theta) = -1 \end{array}$$

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

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

$$\mathrm{var}(T) = \frac{n(n-1)(2n+5)}{18} \tag{9}$$

The normal Z-test statistic is calculated as

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

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, β, 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):

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

where 1 < k < j < n. In other words, the slope estimator β 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

(Office of Land and Resources of Shaanxi Province, 2008) with much higher baseflow index (i.e. the ratio of average annual baseflow to the total average annual streamflow) compared to the rest of the catchments (Zhu et al., 2010). As a result, these catchments sustain higher baseflow rates and show slower flow recession during dry periods. The south-eastern part of the study area is characterized by a heavily dissected landscape with high gully density and deep loess soil, exceeding 200 m in many locations. The groundwater recharge is limited in this region and the surface water is weakly coupled with the groundwater system, resulting in quick flow recession. In a different approach, Zhu et al., (2010) estimated the catchment drainage time scale in the Loess Plateau and showed that it varied from 5 to 16 days across the catchments. In their estimation of the drainage time scale, the master recession curve approach was used. Xu et al., (2010) analysed isotopic characteristics of rainfall, soil moisture, and groundwater samples taken from the Yangou catchment located in the south of the Loess Plateau and showed that the time lags between rainfall and groundwater discharge are about 35 days. Although obtained by a different method, in general, the K values obtained in the present study are similar with the results of Xu et al. (2010), but larger than the estimates of Zhu et al. (2010). However, the average K value for the catchments in the Loess Plateau is smaller than those reported by Brutsaert (2008, 2010) for US catchments and Zhang et al. (2014) for Australian catchments, where it was found that K is on average 46 days, with an uncertainty of less than 15 days. Studies show that the loess soils in the Loess Plateau are highly permeable with saturated hydraulic conductivity values ranging from 1.1 m/day to 7.2 m/day (Jiang and Huang, 1986). Moreover, as noted earlier, the region is highly dissected with drainage densities varying from roughly 2 to 8 km/km^2 (Tang and Chen, 1990; Ran et al., 2000). These rather large hydraulic conductivity values and large drainage density values indicate that water drains faster from the catchments implying smaller K values. Actually, this can also readily be seen in the theoretical expression **Error! Reference source not found.**, where larger values of k_0 and D_d result in smaller values of K.

Insert Figure 2 here.

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 reductions in groundwater storage in these catchments 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 (Table 1). 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 as baseflow is a result of groundwater discharge and the good agreement between the two estimates suggests that the method used in our study is appropriate for estimating groundwater storage trends. It should also be noted that the magnitudes of the upward trends in groundwater storage are similar to those of the Souris-Red-Rainy and the Missouri regions reported by Brutsaert (2010).

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

Insert Figure 3 and Figure 4 here.

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

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

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

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

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

Insert Figure 5 here.

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

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

Insert Figure 6 here.

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

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

Insert Figure 7 here.

5 Conclusions

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

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

Acknowledgements

The work was supported by the National Natural Science Foundation of China (Grant No. 41440012, 41230852; 41101265), the Knowledge Innovation Program of the Chinese Academy of Sciences (KZCX2-XB3-13; KZZD-EW-04-03-03), the National Key Technology Support Program (2011BAD31B01), and the International Science & Technology Cooperation Program of China (2013DFG70990). We would like to thank Jing Zhao and Hongxing Zheng for discussion on groundwater conditions in the Loess Plateau.

References

Bartley, R, Roth CH, Ludwig, J et al., 2006. Runoff and erosion from Australia's tropical semi-arid rangelands: influence of ground cover for differing space and time scales. Hydrol Processes, 20, 3317–3333

Bertrand, G., Goldscheider, N., Gobat, J.M., and Hunkeler, D., 2012. Review: From multi-scale conceptualization to a classification system for inland groundwater-dependent ecosystems. Hydrogeol J, 20: 5-25.

Brabets, T. P. and Walvoord, M. A.. 2009. Trends in streamflow in the Yukon River Basin from 1944 to 2005 and the influence of the Pacific Decadal Oscillation. J of Hydrol 371:108-119.

Brown, A., Zhang, L., McMahon, T., Western, A., and Vertessy, R., 2005. A review of paired catchment studies with reference to the seasonal flows. J of Hydrol, 310: 28-61

Brutsaert W., and Nieber J. L., 1977 Regionalized drought flow hydrographs from a Mature Glaciated plateau. Water Resour Res. http://dx.doi.org/10.1029/WR013i003p00637.

Brutsaert, W., 2005. Hydrology: An Introduction. Cambridge University Press, 6180.

Brutsaert, W., 2008. Long-term groundwater storage trends estimated from streamflow records: Climatic perspective. Water Resource Res. 44:W02409.

Brutsaert W., and Sugita M., 2008. Is Mongolia's groundwater increasing or decreasing? The case of the Kherlen River basin. Hydrol Sci J, 53(6), 1221–1229.

Brutsaert, W., 2010. Annual drought flow and groundwater storage trends in the eastern half of the United States during the past two-third century. Theor Appl. Climatol, 100(1), 93–103.

Brutsaert, W., 2012. Are the North American deserts expanding? Some climate signals from groundwater storage conditions, *Ecohydrology, 5*, 541-549.

Cai, W., and van Rensch, P., 2012, The 2011 southeast Queensland extreme summer rainfall: A confirmation of a negative Pacific Decadal Oscillation phase? Geophysical Research Letters, 39, L08702.

Chan, J. C. L., and Zhou W., 2005: PDO, ENSO and the early summer monsoon rainfall over south China. Geophys. Res. Lett., 32, L08810.

Chiew FHS, Teng J, Vaze J, Post DA, Perraud JM, Kirono DGC, Viney NR., 2009. Estimating climate change impact on runoff across southeast Australia: method, results, and implications of the modeling method. Water Resour Res ;45:W10414.

Christensen, N.S. and Lettenmaier, D.P., 2007. Amultimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. Hydrol. Earth Syst. Sci., 11, 1417-1434.

Feng, J., L. Wang, and Chen W., 2014: How Does the East Asian Summer Monsoon Behave in the Decaying Phase of El Niño during Different PDO Phases? J. Climate 27:7, 2682-2698.

Gao, P. Mu, X.M., Wang, F., and Li, R. 2011. Changes in streamflow and sediment discharge and the response to human activities in the middle reaches of the Yellow River. Hydrol. Earth Syst., Sci., 15, 1-10.

Gao, Z.L., Zhang, L., Cheng, L., Zhang, X.P., Potter, N., Cowan, T., Cai, W., 2015. Long-term streamflow trends in the middle reaches of the Yellow River Basin: detecting drivers of change (submitted to Hydrological Processes)

Goderniaux, P., Brouyère, S., Fowler, H.J., Blenkinsop, S., Therrien, R., Orban, P., Dassargues, A., 2009. Large scale surface–subsurface hydrological model to assess climate change impacts on groundwater reserves. J. Hydrol. 373 (1–2), 122–138.

Hanson, R. T., M. W. Newhouse, and Dettinger M. D., 2004. A methodology to assess relations between climatic variability and variations in hydrologic time series in the southwestern United States, J. Hydrol., 287 (1–4), 252–269.

Hirsch, R. M., J. R. Slack, and Smith R. A., 1982, Techniques of trend analysis for monthly water quality data, Water Resour. Res., 18, 107–121.

Huang M, and Zhang L., 2004. Hydrological responses to conservation practices in a catchment of the Loess Plateau, China. Hydrol Processes 18: 1885–1898.

Jiang, D.S., and Huang, G.J., 1986. Study on the filtration rate of soils on the Loess Plateau of China, ACTA Pedologica Sinica, 23(4), 299-305 (in Chinese).

Jiang X.H., Gu X.W., and He H.M., 2010. The influence of coal mining on water resources in the Kuye River basin. Journal of Natural Resources, 25(2):300-307 (in Chinese).

Jiménez Cisneros, B.E., Oki T., Arnell N.W., Benito G., Cogley J.G., Döll P., Jiang T., and S.S. Mwakalila, 2014: Freshwater resources. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229-269.

Kalnay, E., Kanamitsu M., Kistler R., Collins W., Deaven D., Gandin L., Iredell M., Saha S., White G., Woollen J., Zhu Y., Chelliah M., Ebisuzaki W., Higgins W., Janowiak J., Mo K. C., Ropelewski C., Wang J., Leetmaa A., Reynolds R., Jenne R., and Joseph, D., 1996, The NCEP/NCAR 40-Year Reanalysis Project. Bull. Amer. Meteor. Soc., 77, 437–471.

Kendall, M. G., 1975, Rank Correlation Measures, 202 pp., Charles Griffin, London.

Kim, J-W, S-W Yeh, and Chang E-C, 2014: Combined effect of El Niño-Southern Oscillation and Pacific Decadal Oscillation on the East Asian winter monsoon. Climate Dynamics 42:3-4, 957-971.

Lei Y.N., Zhang X.P., Zhang J.J., Liu E.J., 2013. Change trends and driving factors of base flow in Kuye River Catchment. Acta Ecologica Sinica, 2013, 33(5):1559-1568 (in Chinese).

Liu, G.B., 1999. Soil conservation and sustainable agriculture on the Loess Plateau: Challenges and prospects. Ambio, Vol. 28, No.8, 663-668.

Lyne, V., and Hollick, M., 1979. Stochastic time variable rainfall-runoff modelling, Proceedings of the Hydrology and Water Resources Symposium, Perth, 10-12 September, Institution of Engineers National Conference Publication, No. 79/10, pp. 89-92.

Mann, H. B., 1945, Non-parametric tests against trend, Econometrica, 13, 245– 259.

Mantua, N. J., Hare S., Zhang Y., Wallace J., and Francis R., 1997, A Pacific interdecadal climate oscillation with impacts on salmon production, B AM Meteorol S, 78, 1069–1079.

Milly, P.C.D., Dunne, K.A., and Vecchia, A.V., 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature, 438(17).

Mu, X. M., Zhang L., McVicar T. R., Chille B. S., and Gao P., 2007. Analysis of the impact of conservation measures on stream flow regime in catchments of the Loess Plateau, China, Hydrol. Process., 21, 2124–2134.

Office of Land and Resources of Shaanxi Province, Xi'an Geological Survey Research Center of China Geological Survey (eds.). Groundwater Investigation Report of Energy and Chemical Industrial Bases in Northern Shanxi Province (First draft), 2008.

Parker, D., Folland C., Scaife A., Knight J., Colman A., Baines P., and Dong B., 2007, Decadal to multidecadal variability and the climate change background. J.Geophys. Res., 112, D18115.

Petrone, K.C., Hughes, J.D., Van Niel, T.G., and Silberstein, R., 2010. Streamflow declined southwestern Australia, 1950-2008. Geophys Res Lett, 37: L11401.

Price, K., 2011. Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review. Progress in Physical Geography, 35(4) 365-492.

Ran, D. C., L. W. Liu, L. Y. Zhao, Z. G. Bai, B. Liu, and H. Wang (Eds.), 2000. The Change of Soil and Water Conservation, Streamflow and Sediment in Hekou-Longmen Region in Middle Reaches of Yellow River, 204 pp., Yellow River Water Resour. Press, Zhengzhou, China.

Reynolds, R. W. and Smith T. M., 1994. Improved global sea surface temperature analyses using optimum interpolation. J. Climate, 7, 929-948.

Sen, P. K., 1968. Estimates of the regression coefficient based on Kendall’s tau, J. Am. Stat. Assoc., 63, 1379–1389.

Smakhtin, V.U., 2001. Low flow hydrology: a review. J of Hydrol, 240, 147-186.

Tang, K.L. and Chen, Y.Z., 1990. Regional characteristics of soil erosion on the Loess Plateau and its control. Chinese Science and Technology Press, pp.300.

Todd, D.K., and Mays, L. W., 2005. Groundwater hydrology. 3rd edition, John Wiley& Sons, NJ, pp. 636.

Troch P.A., De Troch F.P., and Brutsaert W., 1993. Effective water table depth to describe initial conditions prior to storm rainfall in humid regions. Water Resour Res 29:427–434

Wang, Q.X., Fan X.H., Qin Z.D., and Wang M.B., 2012. Change trends of temperature and precipitation in the Loess Plateau Region of China, 1961-2010. Global and Planet. Change 92-93: 138-147.

Wang Z.X., Liu Z.Z., and Wang G.Z., 1990. Study of rational development and utilization of groundwater resources in Loessial Plateau area. Beijing: Xueyuan Press (in Chinese).

Wilcox B.P., Wood M.K., and Tromble J.M., 1988. Factors influencing infiltrability of semiarid mountain slopes. Journal of Range Management, 41, 197–206.

Xu X.X., Zhang B.Y., and Tian J.L., 2010. Experimental study on the precipitation-soil water -groundwater transformation in loss hilly region. Advance in water science, 21(1):16-22 (in Chinese)

Yoon, J. and Yeh S.-W., 2010. Influence of the Pacific Decadal Oscillation on the Relationship between El Niño and the Northeast Asian Summer Monsoon. J. Climate, 23, 4525–4537.

Yu, L., Furevik T., Otterå O. H., and Gao Y., 2015. Modulation of the Pacific Decadal Oscillation on the summer precipitation over East China: a comparison of observations to 600-years control run of Bergen Climate Model. Clim Dynam, 44(1-2), 475-494.

Zektser I. S. and Everett L. G. (ed), 2004. Groundwater Resources of the World and Their Use http://unesdoc.unesco.org/images/0013/001344/134433e.pdf UNESCO IHP-VI Series on Groundwater No 6.

Zhang, L., Dawes, W.R., and Walker, G.R., 2001. The response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour Res, 37: 701-708.

Zhang, L., Brutsaert, W., Crosbie, R., and Potter, N., 2014. Long-term groundwater storage trends In Australian catchments. Adv Water Res. 74: 156-165.

Zhang, L., Zhao, F. F., Chen, Y., and Dixon, R. N. M., 2011. Estimating effects of plantation expansion and climate variability on streamflow for catchments in Australia, Water Resour. Res., 47, W12539.

Zhang, X. P., 2007. Responses of streamflow to land use/cover change in He-Long region, the middle reaches of the Yellow River basin, Ph.D. Thesis, 123 pp., Res. Cent. of Soil and Water Conserv. and Ecol. Environ., Chin. Acad. of Sci., Yangling, China.

Zhang, X.P., Zhang, L., Zhao, J., Rustomji, P., and Hairsine, P., 2008. Responses of streamflow to changes in climate and land use/cover in the Loess Plateau, China. Water Resour Res. 44, W00A07.

Zhao, F.F., Zhang, L. Xu, Z.X, and Scott, D.F., 2010. Evaluation of methods for estimating the effects of vegetation change and climate variability on streamflow. Water Resour Res, 46, W03505.

Zhu, R.R., Zheng, H.X., and Liu, C.M., 2010. Estimation of groundwater residence time and recession rate in watershed of the Loess Plateau, J. Geogr. Sci, 273-282

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^2)	Slope (‰)	Rainfall (mm yr^{-1})	Runoff (mm yr^{-1})	Period of streamflow record	Drainage time scale *K* (days)	Average groundwater storage (mm)	Groundwater storage trend (mm yr^{-1}) [a]
1 Kuye	Xinmiao	1527	4.89	385	60.9	1966 – 2005	31	0.1886	–0.0050**
	Wangdaohengta	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+
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**
	Liujiahe	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+

Notes: [a] the symbols indicate different significance levels: *** when $p < 0.001$, ** when $p < 0.01$, * when $p < 0.05$ or + when $p < 0.1$.

Figure

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.

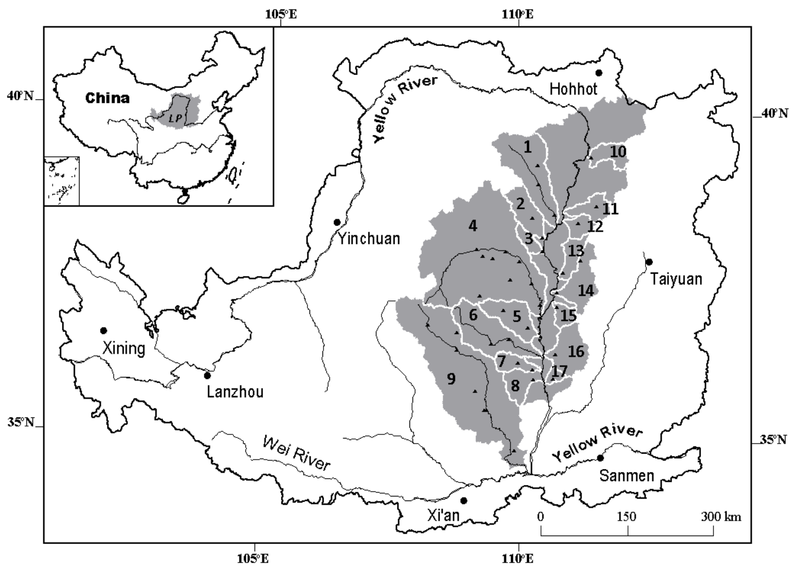

Figure 1. Location map of the selected catchments in the Loess Plateau in China. The numbers represent the river basins listed in Table 1.

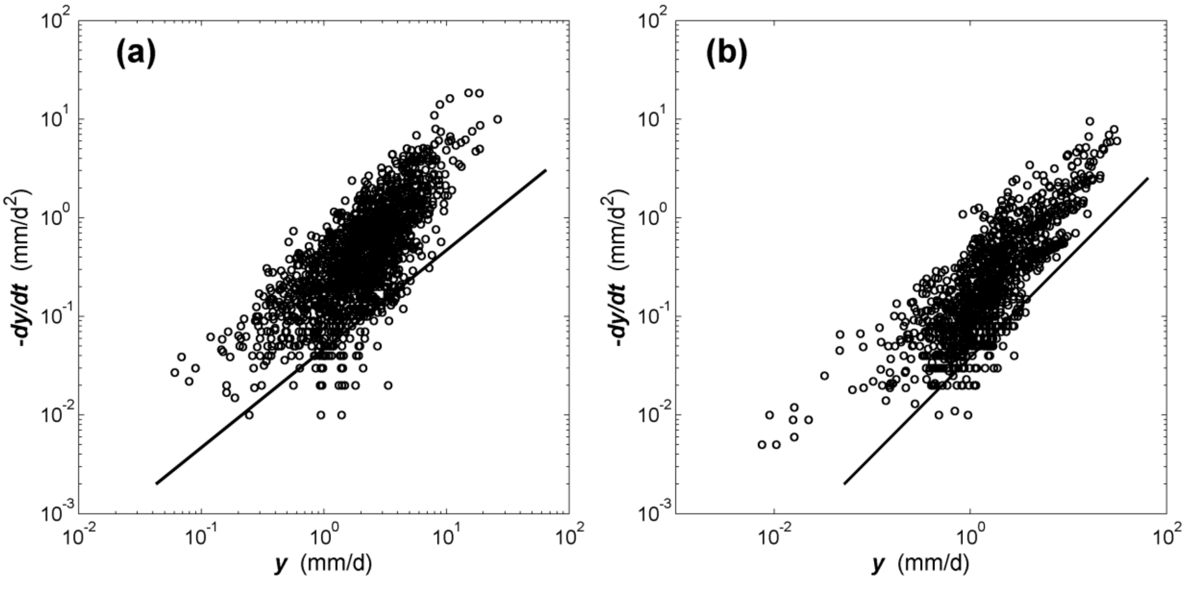

Figure 2. Relationships between log(−*dy* / *dt*) and log(*y*) for (a) the Qingjian River and (b) the Shiwang River. The lower envelope line has a unit slope and the estimate of the characteristic drainage timescale (*K*) is 25 and 30 days, respectively.

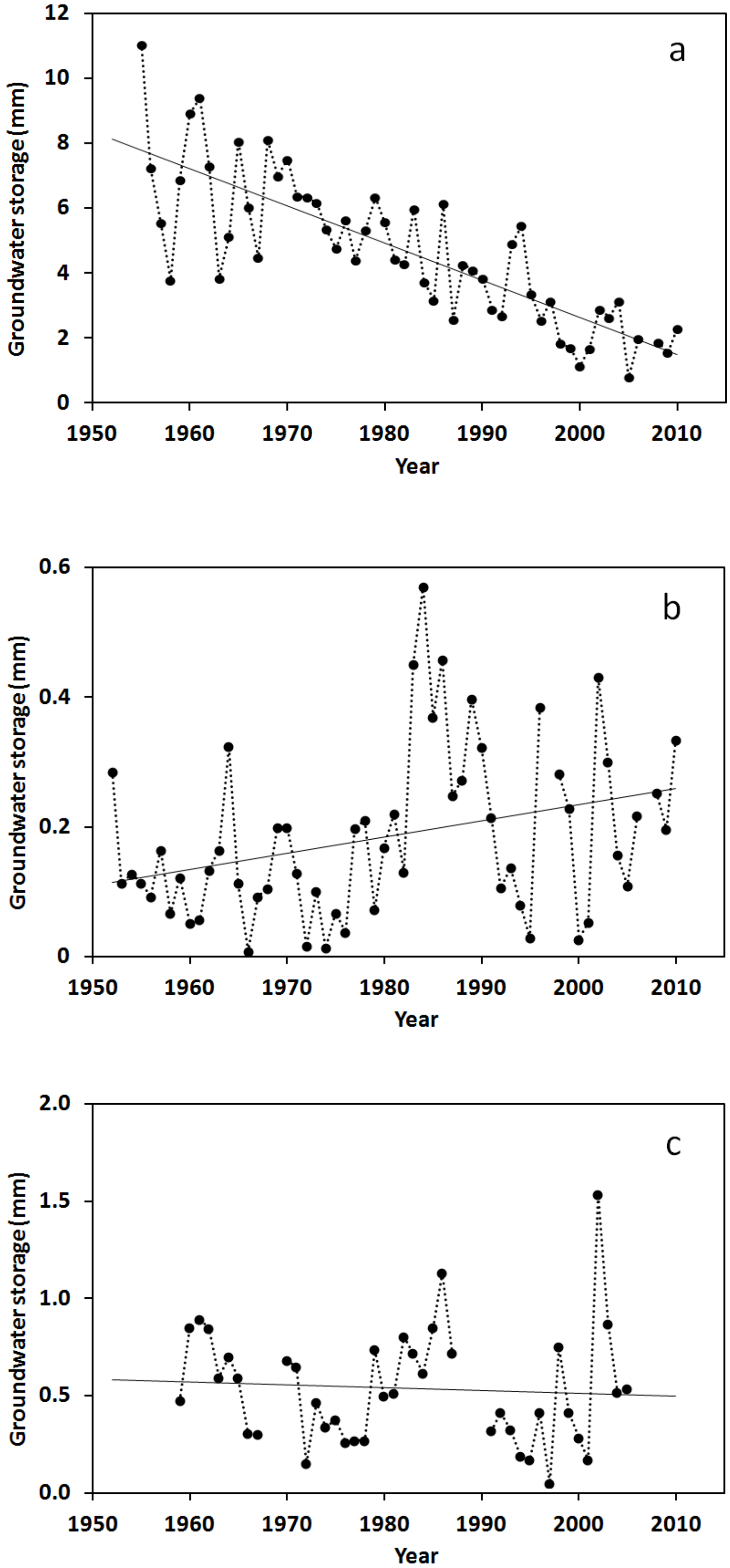

Figure 3. Evolution of the annual lowest groundwater storage for (a) Tuwei River catchment, (b) Yanhe River catchment, and (c) Qingyangcha River catchment. The groundwater storage is expressed in millimetre above the zero-flow level over the period of records.

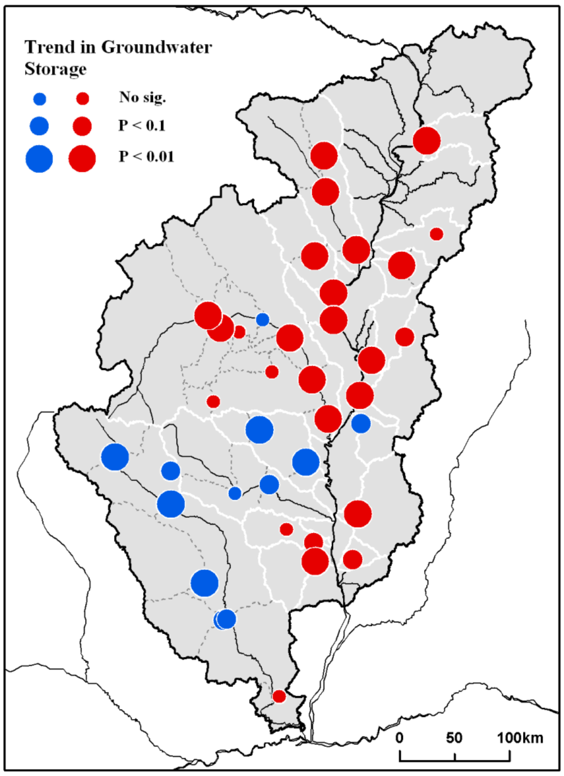

Figure 4. Spatial patterns of the annual lowest groundwater storage trends in the Loess Plateau. Red circles represent downward trends and blue circles indicate upward trends.

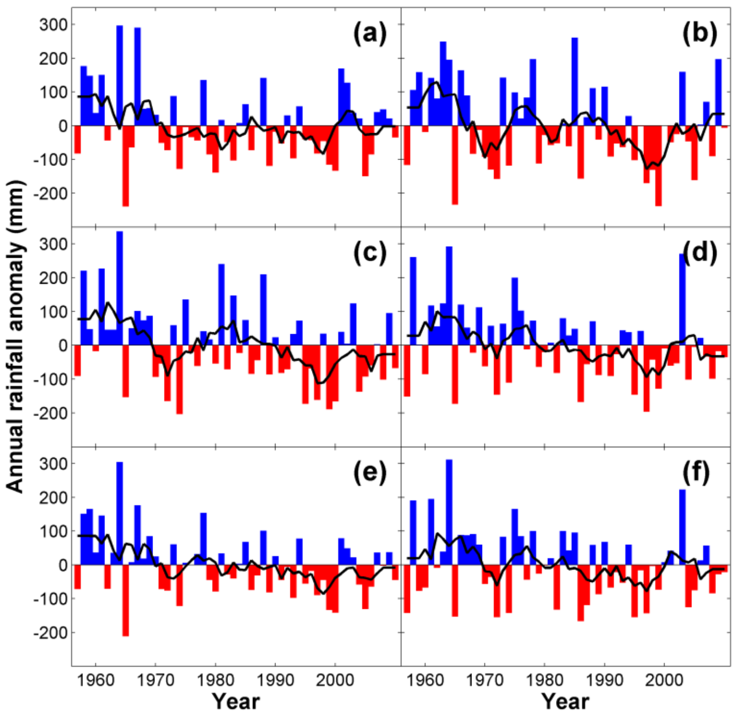

Figure 5. Evolution of the annual rainfall anomalies over the period of 1957-2010 for (a) Tuwei River, (b) Sanchuan River, (c) Yanhe River, (d) Kuye River, (e)Wuding River, and (f) Beiluo River.

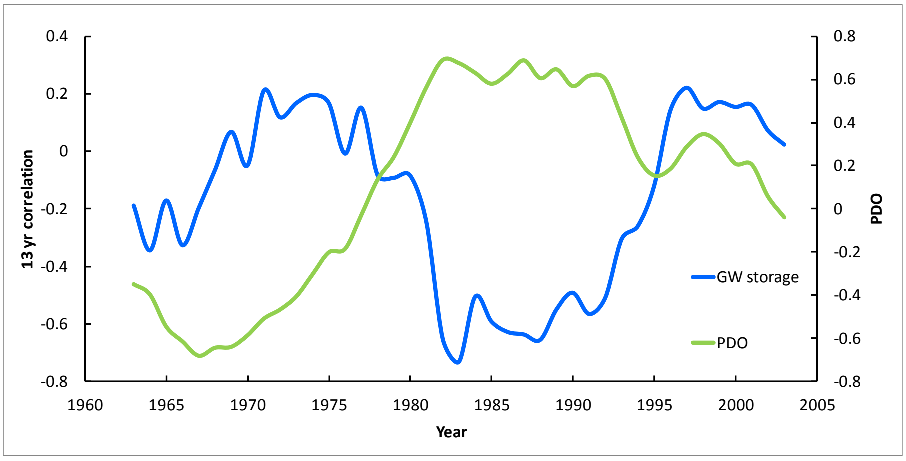

Figure 6. Time series showing 13-year sliding window correlation between annual groundwater storage and ENSO over the period 1957-2009 (blue), for the catchments in the Loess Plateau. Also shown in a time-series of the PDO (green) smoothed using a 13-year running mean.

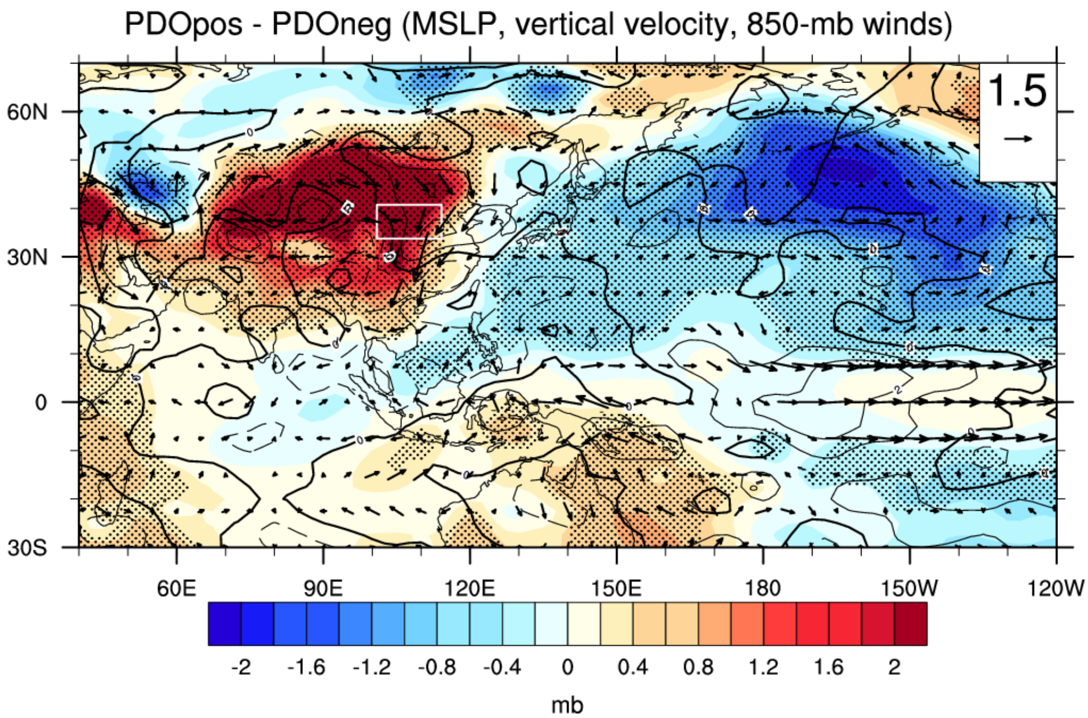

Figure 7. Map showing the difference in circulation anomalies between the positive and negative phases of the PDO for mean sea level pressure (mb; colour), 500-mb vertical velocity (Pa/s; contour) and 850-mb winds (m/s; vectors). The positive phase of the PDO covers 1977-2002, while the negative phase 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.

***Revision Notes**

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

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.

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.

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 requirment.

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 Sl was calculated from annual 7-day low flow yl by multiplication with K, thus Sl = K * yl, 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).

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.

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

Zhaoliang Gao[a], Lu Zhang[b,*], Lei Cheng[b], Xiaoping Zhang[a], Tim Cowan[c], Wenju Cai[c], Wilfried Brutsaert[d]

[a] State key laboratory of soil erosion and dryland farming on Loess Plateau, Northwest Agriculture and Forest University, Chinese Academy of Sciences, Yangling, Shaanxi, China.

[b] CSIRO Land and Water Flagship, Christian Laboratory, Canberra, ACT, Australia.

[c] CSIRO Oceans and Atmosphere Flagship, Aspendale, Victoria, Australia.

[d] School of Civil and Environmental Engineering, Cornell University, Ithaca, NY 14850, USA

[*]Corresponding author: Lu.Zhang@CSIRO.au

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.

Deleted: affected the

Deleted: trends

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

1 Introduction

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

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

Deleted: earlier

Deleted: (

Deleted: ,

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

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

2 Catchment description and data

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

Deleted: , while requiring

Deleted: more recently

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

Deleted: (see Table 1)

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

Insert Figure 1 here.

3 Methods

3.1 Estimation of groundwater storage

Deleted: trends

The baseflow from a catchment can be expressed as:

$$Q = Q(t) \tag{1}$$

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

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

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

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

where k_0 [LT^{-1}] is the hydraulic conductivity, n_e the drainable porosity, η_0 is the average vertical thickness [L] of the layer in the soil profile occupied by flowing water, $D_d = L / A$ is the drainage density, where L is the total length of upstream channels in the catchment.

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

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

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

$$S = Ky \qquad (5)$$

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

3.2 The characteristic drainage timescale

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

Formatted: Font: Italic

Deleted: [L^3]

Deleted: (2)

Deleted: basin

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

Deleted: trends

Deleted: 6

Deleted: (1)

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

Deleted: (7)

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

Deleted: (2)

Deleted: (7)

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

Deleted: (8)

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

Deleted: (8)

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

Deleted: (8)

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

3.3 Trend analysis of annual groundwater storage

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

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

Deleted: 9

and

$$\begin{array}{lll} if & \theta > 0, & \operatorname{sgn}(\theta) = 1 \\ if & \theta = 0, & \operatorname{sgn}(\theta) = 0 \\ if & \theta < 0, & \operatorname{sgn}(\theta) = -1 \end{array}$$

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

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

$$\operatorname{var}(T) = \frac{n(n-1)(2n+5)}{18} \qquad (9)$$

Deleted: 10

The normal Z-test statistic is calculated as

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

Deleted: 11

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, β, 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):

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

Deleted: 12

where 1 < k < j < n. In other words, the slope estimator β 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 (Office of Land and Resources of Shaanxi Province, 2008) with much higher baseflow index (i.e. the ratio of average annual baseflow to the total average annual streamflow) compared to the rest of the catchments (Zhu et al., 2010). As a result, these catchments sustain higher baseflow rates and show slower flow recession during dry periods. The south-eastern part of the study area is characterized by a heavily dissected landscape with high gully density and deep loess soil, exceeding 200 m in many locations. The groundwater recharge is limited in this region and the surface water is weakly coupled with the groundwater system, resulting in quick flow recession. In a different approach, Zhu et al., (2010) estimated the catchment drainage time scale in the Loess Plateau and showed that it varied from 5 to 16 days across the catchments. In their estimation of the drainage time scale, the master recession curve approach was used. Xu et al., (2010) analysed isotopic characteristics of rainfall, soil moisture, and groundwater samples taken from the Yangou catchment located in the south of the Loess Plateau and showed that the time lags between rainfall and groundwater discharge are about 35 days. Although obtained by a different method, in general, the K values obtained in the present study are similar with the results of Xu et al. (2010), but larger than the estimates of Zhu et al. (2010). However, the average K value for the catchments in the Loess Plateau is smaller than those reported by Brutsaert (2008, 2010) for US catchments and Zhang et al. (2014) for Australian catchments, where it was found that K is on average 46 days, with an uncertainty of less than 15 days. Studies show that the loess soils in the Loess Plateau are highly permeable with saturated hydraulic conductivity values ranging from 1.1 m/day to 7.2 m/day (Jiang and Huang, 1986). Moreover, as noted earlier, the region is highly dissected with drainage densities varying from roughly 2 to 8 km/km^2 (Tang and Chen, 1990; Ran et al., 2000). These rather large hydraulic conductivity values and large drainage density values indicate that water drains faster from the catchments implying smaller K values. Actually, this can also readily be seen in the theoretical expression **Error! Reference source not found.**, where larger values of k_0 and D_d result in smaller values of K.

Insert Figure 2 here.

Deleted: (3)

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 reductions in groundwater storage in these catchments are consistent with the annual streamflow

Deleted: (6)

Deleted: trends dS / dt

Deleted: (6)

Deleted: is

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 (Table 1). 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 as baseflow is a result of groundwater discharge and the good agreement between the two estimates suggests that the method used in our study is appropriate for estimating groundwater storage trends. It should also be noted that the magnitudes of the upward trends in groundwater storage are similar to those of the Souris-Red-Rainy and the Missouri regions reported by Brutsaert (2010).

Deleted: ,

Deleted: (Gao et al., 2014)

Deleted: T

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

Insert Figure 3 and Figure 4 here.

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

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

Deleted: and has

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

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

Deleted: In contrast,

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

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

Deleted: is

Insert Figure 5 here.

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

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

Deleted: -

Insert Figure 6 here.

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

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

Deleted: -

Deleted: catchments

Deleted: in the more southward

Deleted: catchments

Insert Figure 7 here.

5 Conclusions

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

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

Deleted: previous

Deleted: the

Deleted: trends

Acknowledgements

The work was supported by the National Natural Science Foundation of China (Grant No. 41440012, 41230852; 41101265), the Knowledge Innovation Program of the Chinese Academy of Sciences (KZCX2-XB3-13; KZZD-EW-04-03-03), the National Key Technology Support Program (2011BAD31B01), and the International Science & Technology Cooperation Program of China (2013DFG70990). We would like to thank Jing Zhao and Hongxing Zheng for discussion on groundwater conditions in the Loess Plateau.

References

Bartley, R, Roth CH, Ludwig, J et al., 2006. Runoff and erosion from Australia's tropical semi-arid rangelands: influence of ground cover for differing space and time scales. Hydrol Processes, 20, 3317–3333

Bertrand, G., Goldscheider, N., Gobat, J.M., and Hunkeler, D., 2012. Review: From multi-scale conceptualization to a classification system for inland groundwater-dependent ecosystems. Hydrogeol J. 20: 5-25.

Brabets, T. P. and Walvoord, M. A.. 2009. Trends in streamflow in the Yukon River Basin from 1944 to 2005 and the influence of the Pacific Decadal Oscillation. J of Hydrol 371:108-119.

Brown, A., Zhang, L., McMahon, T., Western, A., and Vertessy, R., 2005. A review of paired catchment studies with reference to the seasonal flows. J of Hydrol, 310: 28-61

Brutsaert W., and Nieber J. L., 1977. Regionalized drought flow hydrographs from a Mature Glaciated plateau. Water Resour Res. http://dx.doi.org/10.1029/WR013i003p00637.

Brutsaert, W., 2005. Hydrology: An Introduction. Cambridge University Press, 6180.

Brutsaert, W., 2008. Long-term groundwater storage trends estimated from streamflow records: Climatic perspective. Water Resource Res. 44:W02409.

Deleted: (
Deleted:)
Deleted: ogical
Deleted: (
Deleted:)
Deleted: ogy
Deleted: ournal
Moved down [1]: M. A.
Moved (insertion) [1]
Deleted: (
Deleted:)
Deleted: ournal
Deleted: ogy
Deleted: (
Deleted:)
Deleted: ournal
Deleted: ogy
Deleted: (
Deleted:)
Deleted: (
Deleted:)
Deleted: (
Deleted:)
Deleted: doi:10.1029/2007WR006518.

Brutsaert W., and Sugita M., 2008. Is Mongolia's groundwater increasing or decreasing? The case of the Kherlen River basin. Hydrol Sci J, 53(6), 1221–1229.

Brutsaert, W., 2010. Annual drought flow and groundwater storage trends in the eastern half of the United States during the past two-third century. Theor Appl. Climatol, 100(1), 93–103.

Brutsaert, W., 2012. Are the North American deserts expanding? Some climate signals from groundwater storage conditions, *Ecohydrology, 5*, 541-549.

Cai, W., and van Rensch, P., 2012. The 2011 southeast Queensland extreme summer rainfall: A confirmation of a negative Pacific Decadal Oscillation phase? Geophysical Research Letters, 39, L08702.

Chan, J. C. L., and Zhou W., 2005: PDO, ENSO and the early summer monsoon rainfall over south China. Geophys. Res. Lett., 32, L08810.

Chiew FHS, Teng J, Vaze J, Post DA, Perraud JM, Kirono DGC, Viney NR., 2009. Estimating climate change impact on runoff across southeast Australia: method, results, and implications of the modeling method. Water Resour Res ;45:W10414.

Christensen, N.S. and Lettenmaier, D.P., 2007. Amultimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. Hydrol. Earth Syst. Sci., 11, 1417-1434.

Feng, J., L. Wang, and Chen W., 2014: How Does the East Asian Summer Monsoon Behave in the Decaying Phase of El Niño during Different PDO Phases? J. Climate 27:7, 2682-2698.

Gao, P. Mu, X.M., Wang, F., and Li, R. 2011. Changes in streamflow and sediment discharge and the response to human activities in the middle reaches of the Yellow River. Hydrol. Earth Syst., Sci., 15, 1-10.

Gao, Z.L., Zhang, L., Cheng, L., Zhang, X.P., Potter, N., Cowan, T., Cai, W., 2015. Long-term streamflow trends in the middle reaches of the Yellow River Basin: detecting drivers of change (submitted to Hydrological Processes)

Goderniaux, P., Brouyère, S., Fowler, H.J., Blenkinsop, S., Therrien, R., Orban, P., Dassargues, A., 2009. Large scale surface–subsurface hydrological model to assess climate change impacts on groundwater reserves. J. Hydrol. 373 (1–2), 122–138.

Deleted: (
Deleted:)
Deleted: (
Deleted:)
Deleted: (
Deleted:)
Deleted:
Deleted: , DOI: 10.1002/eco.263
Deleted: P.
Deleted: (
Deleted:)
Deleted: , doi:10.1029/2011GL050820
Deleted: W.
Deleted: , doi:10.1029/2004GL022015
Deleted: w10414
Deleted: http://dx.doi.org/10.1029/2008WR007338.
Deleted: W.
Deleted: (
Deleted:)
Deleted: , doi:10.5194/hess-15-1-2011
Deleted: Wenju
Deleted: , and Brutsaert
Deleted: W.
Deleted: (
Deleted:)
Deleted: draft paper

Hanson, R. T., M. W. Newhouse, and Dettinger M. D., 2004. A methodology to assess relations between climatic variability and variations in hydrologic time series in the southwestern United States, J. Hydrol., 287 (1–4), 252–269.

Hirsch, R. M., J. R. Slack, and Smith R. A., 1982. Techniques of trend analysis for monthly water quality data, Water Resour. Res., 18, 107–121.

Huang M, and Zhang L., 2004. Hydrological responses to conservation practices in a catchment of the Loess Plateau, China. Hydrol Processes 18: 1885–1898.

Jiang, D.S., and Huang, G.J., 1986. Study on the filtration rate of soils on the Loess Plateau of China. ACTA Pedologica Sinica, 23(4), 299-305 (in Chinese).

Jiang X.H., Gu X.W., and He H.M., 2010. The influence of coal mining on water resources in the Kuye River basin. Journal of Natural Resources, 25(2):300-307 (in Chinese).

Jiménez Cisneros, B.E., Oki T., Arnell N.W., Benito G., Cogley J.G., Döll P., Jiang T., and S.S. Mwakalila, 2014: Freshwater resources. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229-269.

Kalnay, E., Kanamitsu M., Kistler R., Collins W., Deaven D., Gandin L., Iredell M., Saha S., White G., Woollen J., Zhu Y., Chelliah M., Ebisuzaki W., Higgins W., Janowiak J., Mo K. C., Ropelewski C., Wang J., Leetmaa A., Reynolds R., Jenne R., and Joseph, D., 1996. The NCEP/NCAR 40-Year Reanalysis Project. Bull. Amer. Meteor. Soc., 77, 437–471.

Kendall, M. G., 1975. Rank Correlation Measures, 202 pp., Charles Griffin, London.

Kim, J-W, S-W Yeh, and Chang E-C, 2014: Combined effect of El Niño-Southern Oscillation and Pacific Decadal Oscillation on the East Asian winter monsoon. Climate Dynamics 42:3-4, 957-971.

Lei Y.N., Zhang X.P., Zhang J.J., Liu E.J., 2013. Change trends and driving factors of base flow in Kuye River Catchment. Acta Ecologica Sinica, 2013, 33(5):1559-1568 (in Chinese).

Liu, G.B., 1999. Soil conservation and sustainable agriculture on the Loess Plateau: Challenges and prospects. Ambio, Vol. 28, No.8, 663-668.

Moved down [2]: M. D.

Moved (insertion) [2]

Deleted: (…004)

Deleted: R. A.…Smith R. A., (…982)… Techniques of trend analysis for monthly water quality data, Water Resour. Res., 18, 107–121, doi:10.1029/WR018i001p00107

Deleted: (…004)… Hydrological responses to conservation practices in a catchment of the Loess Plateau, China. Hydrologi

Deleted: (…986)… Study on the filtration rate of soils on the Loess Plateau of China, …ACTA Pedologica Sinica, Vol, …3(, No.

Deleted: (…010)

Deleted: T. …ki T., N.W. …rnell N.W., G. …enito G., J.G. …ogley J.G., P. …öll P., T.

Deleted: M. …anamitsu M., R. …istler R., W. …ollins W., D. …eaven D., L. …andin L., M. …redell M., S. …aha S., G. …hite G., J. …oollen J., Y. …hu Y., M. …helliah M., W. …bisuzaki W., W. …iggins W., J.

Moved down [7]: K. C.

Moved (insertion) [7]

Deleted: C. …opelewski C., J. …ang J., A. …eetmaa A., R. …eynolds R., R. …enne R., and D. …oseph, D., (…996)… The NCEP/NCAR 40-Year Reanalysis Project.

Deleted: (…975)

Deleted: E-C

Deleted: .. …, 2013. Change trends and driving factors of base flow in Kuye River Catchment.

Deleted: (…999)

Lyne, V., and Hollick, M., 1979. Stochastic time variable rainfall-runoff modelling, Proceedings of the Hydrology and Water Resources Symposium, Perth, 10-12 September, Institution of Engineers National Conference Publication, No. 79/10, pp. 89-92.

Mann, H. B., 1945. Non-parametric tests against trend, Econometrica, 13, 245– 259.

Mantua, N. J., Hare S., Zhang Y., Wallace J., and Francis R., 1997. A Pacific interdecadal climate oscillation with impacts on salmon production, B AM Meteorol S, 78, 1069–1079.

Milly, P.C.D., Dunne, K.A., and Vecchia, A.V., 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature, 438(17).

Mu, X. M., Zhang L., McVicar T. R., Chille B. S., and Gao P., 2007. Analysis of the impact of conservation measures on stream flow regime in catchments of the Loess Plateau, China, Hydrol. Process., 21, 2124–2134.

Office of Land and Resources of Shaanxi Province, Xi'an Geological Survey Research Center of China Geological Survey (eds.). Groundwater Investigation Report of Energy and Chemical Industrial Bases in Northern Shanxi Province (First draft), 2008.

Parker, D., Folland C., Scaife A., Knight J., Colman A., Baines P., and Dong B., 2007. Decadal to multidecadal variability and the climate change background. J.Geophys. Res., 112, D18115.

Petrone, K.C., Hughes, J.D., Van Niel, T.G., and Silberstein, R., 2010. Streamflow declined southwestern Australia, 1950-2008. Geophys Res Lett, 37: L11401.

Price, K., 2011. Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review. Progress in Physical Geography, 35(4) 365-492.

Ran, D. C., L. W. Liu, L. Y. Zhao, Z. G. Bai, B. Liu, and H. Wang (Eds.), 2000. The Change of Soil and Water Conservation, Streamflow and Sediment in Hekou-Longmen Region in Middle Reaches of Yellow River, 204 pp., Yellow River Water Resour. Press, Zhengzhou, China.

Reynolds, R. W. and Smith T. M., 1994. Improved global sea surface temperature analyses using optimum interpolation. J. Climate, 7, 929-948.

Sen, P. K., 1968. Estimates of the regression coefficient based on Kendall's tau, J. Am. Stat. Assoc., 63, 1379–1389.

Smakhtin, V.U., 2001. Low flow hydrology: a review. J of Hydrol, 240, 147-186.

Deleted: (…979)

Deleted: (…945)… Non-parametric tests against trend, Econometrica, 13, 245– 259, doi:10.2307/1907187

Deleted: S. …are S., Y. …hang Y., J. …allace J., and R. …rancis R., (…997)… A Pacific interdecadal climate oscillation with impacts on salmon production, Bulletin…of the American…M Meteorological…Society

Deleted: (…005)… Global pattern of trends in streamflow and water availability in a changing climate. Nature, Vol …38|…17) November 2005|doi:10.1038/nature04312

Moved down [4]: B. S.

Moved (insertion) [4]

Deleted: L.

Moved down [3]: T. R.

Moved (insertion) [3]

Deleted: P. …ao P., (…007)… Analysis of the impact of conservation measures on stream flow regime in catchments of the Loess Plateau, China, Hydrol. Process., 21, 2124–2134, doi:10.1002/hyp.6391

Deleted: C. …olland C., A. …caife A., J. …night J., A. …olman A., P. …aines P., and B. …ong B., (…007)

Deleted: . (… 2010)… Streamflow declined southwestern Australia, 1950-2008. Geophysical…Research…Letters… 37: L11401, doi:10.1029/2010GL043102

Deleted: (… 2011)

Deleted: (…000),

Moved down [5]: T. M.

Moved (insertion) [5]

Deleted: (…994),… Improved global sea surface temperature analyses using optimum interpolation.

Deleted: (…968), … Estimates of the regression coefficient based on Kendall's tau, J. Am. Stat. Assoc., 63, 1379– …389, doi:10.2307/2285891

Deleted: (…001)… Low flow hydrology: a review. Journal…of Hydrology

Tang, K.L. and Chen, Y.Z., 1990. Regional characteristics of soil erosion on the Loess Plateau and its control. Chinese Science and Technology Press, pp.300.

Todd, D.K., and Mays, L. W., 2005. Groundwater hydrology. 3rd edition, John Wiley& Sons, NJ, pp. 636.

Troch P.A., De Troch F.P., and Brutsaert W., 1993. Effective water table depth to describe initial conditions prior to storm rainfall in humid regions. Water Resour Res 29:427–434

Wang, Q.X., Fan X.H., Qin Z.D., and Wang M.B., 2012. Change trends of temperature and precipitation in the Loess Plateau Region of China, 1961-2010. Global and Planet. Change 92-93: 138-147.

Wang Z.X., Liu Z.Z., and Wang G.Z., 1990. Study of rational development and utilization of groundwater resources in Loessial Plateau area. Beijing: Xueyuan Press (in Chinese).

Wilcox B.P., Wood M.K., and Tromble J.M., 1988. Factors influencing infiltrability of semiarid mountain slopes. Journal of Range Management, 41, 197–206.

Xu X.X., Zhang B.Y., and Tian J.L., 2010. Experimental study on the precipitation-soil water - groundwater transformation in loss hilly region. Advance in water science, 21(1):16-22 (in Chinese)

Yoon, J. and Yeh S.-W., 2010. Influence of the Pacific Decadal Oscillation on the Relationship between El Niño and the Northeast Asian Summer Monsoon. J. Climate, 23, 4525–4537.

Yu, L., Furevik T., Otterå O. H., and Gao Y., 2015. Modulation of the Pacific Decadal Oscillation on the summer precipitation over East China: a comparison of observations to 600-years control run of Bergen Climate Model. Clim Dynam, 44(1-2), 475-494.

Zektser I. S. and Everett L. G. (ed), 2004. Groundwater Resources of the World and Their Use http://unesdoc.unesco.org/images/0013/001344/134433e.pdf UNESCO IHP-VI Series on Groundwater No 6.

Zhang, L., Dawes, W.R., and Walker, G.R., 2001. The response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour Res, 37: 701-708.

Zhang, L., Brutsaert, W., Crosbie, R., and Potter, N., 2014. Long-term groundwater storage trends In Australian catchments. Adv Water Res, 74: 156-165.

Deleted: (
Deleted:)
Deleted: (
Deleted:)
Deleted: (
Deleted:)
Deleted: (
Deleted:)
Deleted: Planetary
Deleted: (
Deleted:)
Deleted: (
Deleted:)
Deleted: S-W
Deleted: (
Deleted:)
Deleted: T.
Moved down [6]: O. H.
Moved (insertion) [6]
Deleted: Y.
Deleted: (
Deleted: 4
Deleted:)
Deleted: ate
Deleted: ics
Deleted: doi:10.1007/s00382-014-2141-5
Deleted: (
Deleted:)
Deleted: ces
Deleted: earch
Deleted: (
Deleted:)
Deleted: ances in
Deleted: ources

Zhang, L., Zhao, F. F., Chen, Y., and Dixon, R. N. M., 2011. Estimating effects of plantation expansion and climate variability on streamflow for catchments in Australia, Water Resour. Res., 47, W12539.

Zhang, X. P., 2007. Responses of streamflow to land use/cover change in He-Long region, the middle reaches of the Yellow River basin, Ph.D. Thesis, 123 pp., Res. Cent. of Soil and Water Conserv. and Ecol. Environ., Chin. Acad. of Sci., Yangling, China.

Zhang, X.P., Zhang, L., Zhao, J., Rustomji, P., and Hairsine, P., 2008. Responses of streamflow to changes in climate and land use/cover in the Loess Plateau, China. Water Resour Res, 44, W00A07.

Zhao, F.F., Zhang, L. Xu, Z.X, and Scott, D.F., 2010. Evaluation of methods for estimating the effects of vegetation change and climate variability on streamflow. Water Resour Res, 46, W03505.

Zhu, R.R., Zheng, H.X., and Liu, C.M., 2010. Estimation of groundwater residence time and recession rate in watershed of the Loess Plateau, J. Geogr. Sci, 273-282

Deleted: (
Deleted:):
Deleted: , doi:10.1029/2011WR010711
Deleted: (
Deleted:),
Deleted: (
Deleted:)
Deleted: ces
Deleted: earch
Deleted: , doi:10.1029/2007WR006711
Deleted: (
Deleted:)
Deleted: ces
Deleted: earch
Formatted: English (Australia)
Formatted: English (Australia)
Deleted: doi:10.1029/2009WR007702
Deleted: (
Deleted:)

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^2)	Slope (‰)	Rainfall (mm yr^{-1})	Runoff (mm yr^{-1})	Period of streamflow record	Drainage time scale *K* (days)	Average groundwater storage (mm)	Groundwater storage trend (mm yr^{-1}) [a]
1 Kuye	Xinmiao	1527	4.89	385	60.9	1966 – 2005	31	0.1886	–0.0050**
	Wangdaohengta	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

Deleted: and

Formatted Table

	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+
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**
	Liujiahe	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+

Notes: [a] the symbols indicate different significance levels: *** when $p < 0.001$, ** when $p < 0.01$, * when $p < 0.05$ or + when $p < 0.1$.