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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, Christian Laboratory, Canberra, ACT, Australia*
[c] *CSIRO Oceans and Atmosphere, Aspendale, Victoria, Australia*
[d] *School of Civil and Environmental Engineering, Cornell University, Ithaca, NY 14850, USA*

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SUMMARY

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 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. 1955–2010), 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.

1. Introduction

Changes in the 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, 2011; Petrone et al., 2010; Zhao et al., 2010). 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

* Corresponding author.
E-mail address: Lu.Zhang@CSIRO.au (L. Zhang).

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(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 (Fig. 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).

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 ($L^3\,T^{-1}$) 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

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

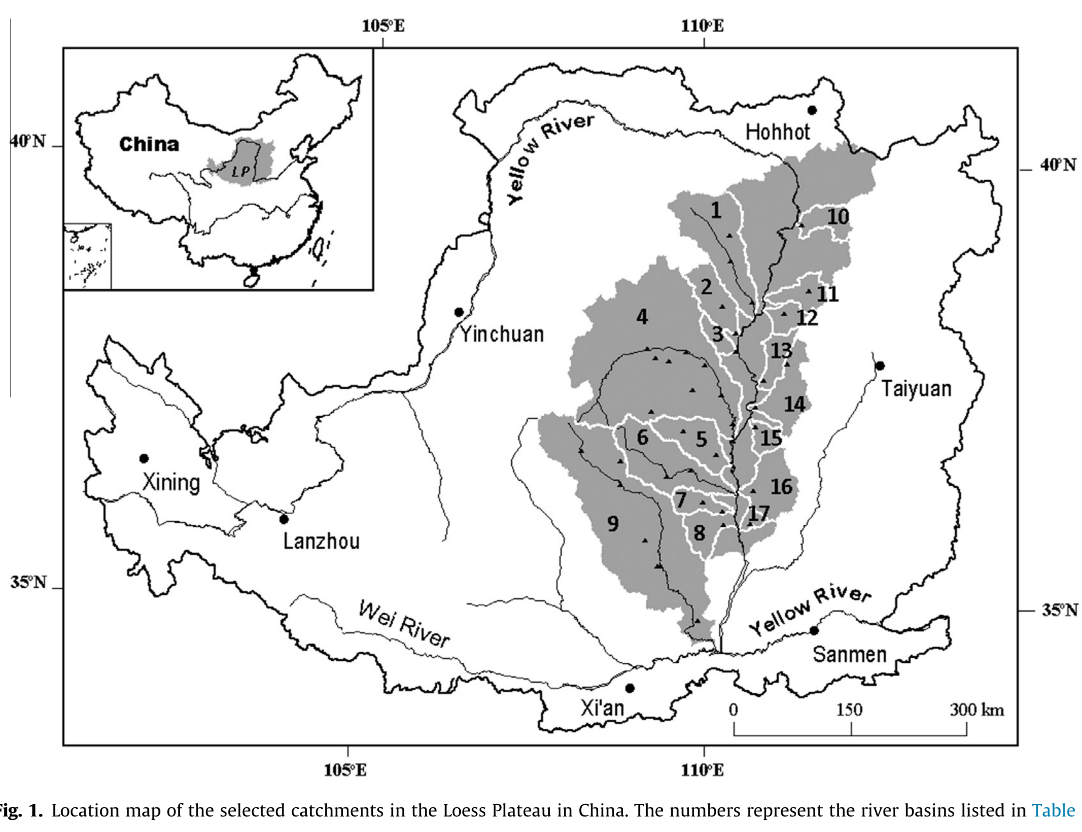

Fig. 1. Location map of the selected catchments in the Loess Plateau in China. The numbers represent the river basins listed in Table 1.