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Different land management measures and climate change impacts on the runoff – A simple empirical method derived in a mesoscale catchment on the Loess Plateau

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A B S T R A C T

Large-scale vegetation restoration and climate change triggered a significant decline in runoff in the middle reaches of the Yellow River and its tributaries. This runoff decline intensifies inherent water shortage and results in more severe water use conflicts that are threatening sustainable development in the Loess Plateau. Innovative strategies for more water-efficient land management are essential. To this end, the factors controlling runoff were investigated using the upstream area of the Jing River as an example. Runoff was found to be mainly controlled by evaporative demand, precipitation, and land cover type. Budyko's frameworks were applied to predict the annual and long-term runoff; however, the effect of changes in land management (*e.g.*, afforestation) on runoff cannot be assessed due to lack of vegetation factors. Therefore, an empirical analysis tool was derived based on an existing relationship for runoff estimation. This method was found to be more effective in reproducing the annual and long-term runoff than others. The incorporation of temporal changes in land cover and form in approach enables the estimation of the possible impact of soil conservation measures (*e.g.*, afforestation or terracing). Our study highlights the importance of adaptive land management strategies for mitigating water shortage on the Loess Plateau.

1. Introduction

The Loess Plateau of NW China experiences very high rates of soil erosion due to short and intense summer showers, sparse vegetation, and highly erodible soil at steep and thus vulnerable landforms. To control soil erosion, various conservation measures (wood and grass plantation, terrace and check-dam construction) have been applied since the 1950s. Recent researches have shown that these actions have resulted in a notable decline in water yield from streams in NW China (McVicar et al., 2007). In addition, projected climate change may put further strain on existing water shortages (Li et al., 2012). Developing adaptive strategies to balance water and land management and control soil erosion in the Loess Plateau region requires improved knowledge of the hydrological impacts of changes in land cover and land form (*i.e.*, farming on slope *vs.* terraces) and climate.

The vast majority of previous studies about the effects of soil and land management measures and climate change on the water resources of the Loess Plateau have focused on trends analysis of annual streamflow and attribution of the changes in streamflow to climate and land use change (Ma et al., 2008; Qiang et al., 2009; Yang and Liu, 2011; Zhang et al., 2008a; Zheng et al., 2009). This is mainly owing to the availability of analysis tools. Among various applied approaches the Budyko's frameworks are the most frequently used ones. Budyko (1974) derived a statistical framework that describes the dependency of annual evapotranspiration on annual water availability (*i.e.*, precipitation) and energy supply (*i.e.*, potential evapotranspiration (PET)). Since then, a considerable amount of additional research has been conducted on this framework by analysing the influences of climate, soil and vegetation on water balance (Choudhury, 1999; Milly, 1994; Yang et al., 2007; Zhang et al., 2001). Independent from Budyko's framework, Fu (1981) developed an approach that depicts the relationship

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between long-term evapotranspiration (ET) and precipitation (P). This approach has been widely applied (Yang et al., 2007; Zhang et al., 2004) after the main concepts were brought to the attention of the international research community by Zhang et al. (2004). The frameworks of Budyko (1974) and Fu (1981) enable the investigation of the inter-linkage of ET and water-energy availability. In addition, modifications of Budyko's framework allow consideration of how catchment characteristics affect streamflow (Choudhury, 1999), or to relate ET to a dryness index (PET/P) and water storage capacity under woody and non-woody land cover (Zhang et al., 2001). Despite those improvements, one of the shortcomings of Budyko's frameworks is that it is not particularly suitable for simulating the effects of different conversion in land cover (*e.g.*, afforestation) and form (*e.g.*, terracing of slopes as a measure to minimize soil erosion) on evapotranspiration. Even if applied, it is only possible to simulate the impact of afforestation on the evapotranspiration (McVicar et al., 2007; Wang et al., 2011; Zhang et al., 2008b) due to the modification of Zhang et al. (2001). In addition to afforestation, there are other major methods to modify landscapes, such as planting grass and land terracing, which probably also have made their contributions to the alteration in water yield. But the impacts of these soil conservation practices on water yield have been rarely addressed due to the limitation of the methods applied. In a previous study (Zhang et al., 2014), we demonstrated that specific land cover types (*e.g.*, forest, grass) and land forms (*e.g.*, farmland on slope or terrace) do play a significant role in controlling seepage and runoff on the Loess Plateau. It is therefore reasonable to expect that some interlink might exist between land-use characteristics, climate variability, and streamflow.

Thus far, most attempts to incorporate vegetation characteristics into water-energy balance models were made based on Budyko's framework (Oudin et al., 2008; Yang et al., 2009, 2007). Exploration of relating climate and vegetation dynamics to runoff and the quantification of their impact on runoff has rarely been conducted. Given the need to develop adaptive water and soil conservation strategies for the Loess Plateau region, simple empirical methods that can adequately depict the relationship between land-use pattern, climate variability, and runoff are required. Such methods may be useful in developing adaptive, water-saving land management strategies in the Loess Plateau region. To this end, this research aims to explore the relationship between land-use characteristics, climate variability, and runoff and develop a quantitative empirical formula for assessing the impacts of various land management practices and climate change on runoff by integrating important factors. This empirical tool should directly link the effects of climate, catchment characteristics, and different land use/management forms to variations in runoff, while keeping simplicity and predictive efficiency at the forefront.

2. Study region and data

2.1. Study site description

The upper stream of the Jing River (Jinghe), located in the Loess Plateau (NW China), was chosen as an appropriate watershed for this study. As the largest feeder river of the Wei River (the largest tributary of the Yellow River), Jinghe supplies streamflow for a vast area in the Loess Plateau. The upstream of the Jinghe is located to the west of the main stream (106°11'~107°21′ E, 35°15'~35°45′ N) and covers a drainage area of 3082 km^2 (Fig. 1). Of the total upper catchment, 39% is mountainous, rocky terrain covered by grey cinnamon soil, while 61% is loess area and covered by loess deposit that is more than 50 m deep. The altitude drops from west (mountainous) to east (loess) with a range of 2898 to 1022 m asl. The distribution of precipitation in the upper Jinghe watershed is characterized by a distinct spatial and temporal variability. The average annual precipitation and temperature equals 614 mm and 6.5 °C in the (upstream) mountainous area, and 475 mm and 8.8 °C in the (downstream) loess area, respectively. About 70% of rainfall occurs during the summer season (June to September). As a result of soil conservation measures implemented in the last several decades, the proportion of woodland and grassland in 2010 increased to 24% and 18% respectively, while croplands cover has been reduced to 58% (Fig. 1).

2.2. Data description and processing

The data in this study includes information on daily hydrometeorological events and annual land use from 1979 to 2010. The daily meteorological data (precipitation, temperature) was obtained from the National Centres for Environmental Prediction (NCEP). The data from NCEP is provided in grid format (0.25°, approx. 27 km resolution). The reanalysis of the NECP climate data is well documented in Saha et al. (2010). For this study, the reanalysis showed that the NCEP data can adequately predict the station variables (*i.e.*, precipitation and temperature in Pingliang and Jingchuan) and represent their spatial variability within the watershed. To calculate area-averaged hydro-meteorological variables, the watershed boundary was extracted by using a Digital Elevation Model (DEM) of 30 m and then resampled to 100 m resolution for analysis. The grid NECP precipitation and temperature (maximum, minimum, and average) were interpolated in ArcGIS. Simple linear interpolation was applied for precipitation while modification with elevation for temperature. Due to the lack of other variables (*e.g.*, relative humidity, wind speed), use of Penman equation (Penman, 1948) for PET estimation was limited. Following FAO recommendations, PET was estimated following the approach by Hargreaves and Allen (2003) using maximum, minimum, average temperature and solar radiation at monthly intervals and then aggregated to annual values. Long-term daily discharge for the upper stream of the Jinghe watershed (at Jingchuan gauge) was acquired from the Geo-data Service Centre of the Loess Plateau (http://loess.geodata.cn). Within the study period of 1979–2010, there is a gap of measured data of runoff for 1991 and 1992. Hence, these two years were excluded from our analysis. Three land-use maps of 1986, 2000 and 2010 were obtained from the Institute of Geographic Sciences and National Resources Research (IGSNRR) and Landsat to identify changes in land cover. The annual land-use information for the remainder of the study period was obtained from the regional statistical and management year book.

3. Methods

3.1. Trends analyses of meteorological variables and runoff

For assessing the temporal trends of hydrological and metrological variables over the study period, we applied the Mann–Kendall (M–K) test on annual precipitation, PET, climatic water balance (CWB, which is equivalent to P minus PET), and runoff (Q). The M–K test is a commonly used method for detecting hydrological and climatological time-series trends (Liu and McVicar, 2012). Two parameters are used to test if a time series contains statistically significant trends: the significance level and the slope (Hamed, 2008). In our work, the M–K test was employed at a level of 5% significance, which indicates a corresponding slope $|Z| = 1.96$. Any trend of the $|Z|$ value exceeding 1.96 will be considered as significant.