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Distinguishing the impacts of human activities and climate variability on runoff and sediment load change based on paired periods with similar weather conditions: A case in the Yan River, China

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SUMMARY

Runoff and sediment loads from river basin are largely affected by the interplay of climate variability and human activities within the basin. However, distinguishing the impacts of climate variability and human activities would vastly improve our knowledge of water resources, climate variability and climate adaptation, and watershed management. We propose a new and simple method to determine the impact of human activities within paired datasets under the same or similar weather conditions (SWC). These weather conditions cover one or more meteorological elements such as precipitation, temperature, or evaporation. If there are two or more periods with similar weather conditions but different runoff, the relative runoff and sediment load changes can be considered a consequence of human-induced land surface changes. This study will report on the application of this new method, using the Yan River Basin in China as a case study. We found 10 sets PPs (paired periods) in 1 year intervals and 12 sets of PPs in intervals of 3 years when (1) there was a 2.0% and 1.0% difference of annual precipitation and annual ET0, respectively, (2) the relationship between monthly precipitation and ET0 of PPs was significant ($P < 0.05$) and, (3) there was no overlap of years for the PPs with intervals of 1 and 3 years. We found that the impact of human activities varied greatly between PPs, with the main trend of declining PPs, matched the trends evident from statistical analysis and land use and land cover (LULC) change evaluation. The method is simple and easily applicable to selected periods in most areas and could be extended when more detailed data are available. The result of this method is the impact of all human activities, allowing for further discussion on the contributions of each kind of human activity over time in determining the range which links the research results at different scales, e.g. to define the sediment delivery ratio (SDR) describing soil erosion on catchment slopes and sediment load in the river.

1. Introduction

The response of river hydrology and sediment load to climate variability and human activity is an important issue in hydrological sciences, water resource management and watershed system evolution (Arnell, 1999; Xu, 2011; Marshall and Randhir, 2008). However, it has proven difficult to achieve a thorough understanding of nonlinear mechanisms of any individual hydroclimatic process (Cannon and McKendry, 2002), with current methodological approaches remaining unresolved and requiring further exploration (Xu et al., 2011), even before considering the added complexity provided by the impacts of human activities.

Many climate models have been used to assess the impacts of climate variability and/or human activities on catchment runoff and sediment yields at the basin scale. However, the degree to which the literature takes into account the impacts of human interventions on catchment runoff and sediment yield varies. For instance, in some studies, the human impact was largely ignored, e.g. Jakeman and Hornberger (1993) found that the rainfall-runoff response of all catchments is well represented using

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a linear model; Fu et al. (2007) examined the impacts of climate variability upon the regional hydrological regimes of the Yellow River in China using precipitation and temperature data, while; Taner et al. (2011) used mechanistic models HSPF and UFILS4 for projecting potential impacts of climate variability on lakes. In other studies, the impact of human activity has been suggested but not investigated in detail, e.g., Moraes et al. (1998) found a significant increasing trend in precipitation and evapotranspiration and concluded a significant decreasing trend in runoff for 4 out of 8 gauging stations caused by human activities. In yet other cases, human activities are lumped together with other factors to describe their impacts, e.g., Liu and Cui (2011) investigated runoff change induced by precipitation and potential evapotranspiration (PET) in the Yellow River Basin. The values of PET used took into account changes in land cover and vegetation caused by humans, however these adapted values could not address the full impacts of engineering structures, including check-dam systems, which play a major role in flood control and sediment retention in this region (Xu et al., 2004). Furthermore, process models are powerful tools that could effectively address the impacts of climate variability and human activity (Zhang et al., 2012), but the setting of parameter values are very difficult given the large spatial differences evident in reality but are largely neglected in models.

In some studies, a natural decade (normally like 1991–2000) was used as compared period directly (Ye et al., 2013), but in most cases it was often assumed that there are "no or few impacts of human activities" or "mainly for the intensive human activities that induce abrupt change" to distinguish different periods, with the effects of climate variability and human action were separated as follows:

- Some equations depict the relationship between runoff and precipitation (and potential evaporation) based on "a natural period", "dependent dataset", "base-line period" or "reference period" according to practical experience or the non-parametric (like Mann–Kendall–Sneyers rank test) (Zhang and Lu, 2009; Jiang et al., 2011; Zhang et al., 2011; Ahn and Merwade, 2014; Zhao et al., 2014).
- The difference between observed data and calculated values from referenced equations and weather variables for the target period is treated as the impact caused by of human activities (Hastenrath, 1990; Li et al., 2007).
- Double mass plots of precipitation and runoff are widely used to detect the "base-line period" (Walling, 1996; Xu, 2003; Gao et al., 2011), with the impact of human activities revealed via the difference produced from calculated results and observed data for different periods.

However, these methods suffer from several potential problems, which limit their usefulness to distinguish between climate induced and human induced change. For instance:

1. Human activities change continuously at different rates of change, thus it is difficult to define a point in time that can be used to divide the total record into two or more distinct periods.
2. If given sufficient time, even small and slow cumulative changes can appreciably alter the runoff.
3. Runoff is the result of complex interactions of each factor. The periods divided by change point of runoff alone is not the result induced by the single factor of climate, but the integrated result of climate and human impact.
4. The difference in precipitation between "base-line period" and target period might be too great to describe the change induced by human activity.
5. Long-term natural variability is neglected, and is therefore attributed to human induced change if it does occur in reality.

A new method is proposed to determine the impact of human activities within paired datasets under the same or similar climatic conditions. These conditions cover one or more meteorological elements such as precipitation, temperature, evaporation. If there are two or more periods with similar weather conditions but different runoff, the relative runoff and sediment load changes can be considered the impact of changes of the land surface condition caused by humans. The aim of this paper is to report on the application of this new method, using the Yan River Basin in China as a case study.

2. Study area, data sources and methodology

2.1. Study area

The Yan River is a first-order branch of the Yellow River, China, draining the 7687 km^2 basin within Shaanxi Province, with its catchment (36°21′–37°19′N, 108°38′–110°29′E) situated in the middle of the Loess Plateau (Fig. 1). The basin is located within the north temperate continental monsoonal climatic region with an average annual precipitation varying from 500 to 550 mm and an average annual air temperature ranging from 8.5 to 11.4 °C (Wang et al., 2010). The study area is covered by thick, erosion-prone loess: a fine silt soil (Fu and Gulinck, 1994). Soil loss is severe and results in enormous sedimentation problems and high flood risks in areas downstream on the Yellow River (Hessel et al., 2003). Therefore the landform is very degraded due to long-term soil erosion with gully density (the length of channel in one km^2) at 2.1–4.6 km km^{-2} (Wang et al., 2005).

The Ganguyi Hydrologic Station (GHS, 109°′48′E, 36°42′N) located in Ganguyi Town, Baota County, records hydrological data draining the 5891 km^2 area, or 76.7% of the Yan River Basin (Fig. 1). The average annual runoff and sediment load in 1952–2010 was 203.5 Mm^3 (million m^3) and 41.5 Mt (million tons) respectively, with sediment concentration at 204 kg m^{-3} and sediment load of 7040 t km^{-2} yr^{-1} (Ministry of Water Resources of China, 2011).

2.2. Data sources

A 56-year dataset of climate, runoff and sediment load from 1955 to 2010 was analyzed. Annual and monthly runoff (R, Mm^3) and sediment load (S, Mt) data were obtained from daily monitoring records from the GHS. Sediment concentration (SC, kg m^{-3}) was derived from monthly runoff and sediment load. Weather data, including precipitation, temperature, wind speed, humidity, were spatially averaged based on 5 weather stations (Fig. 1) within and around the basin using the Thiessen polygon method.

Land Use and Land Cover (LULC) data from 1980 and 2005 at a scale of 1:250,000, (Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China: http://westdc.westgis.ac.cn), were used to test the method reported in this manuscript. The classification procedure was based on image interpretation combined with field investigation. LULC was classified into 6 categories, namely forest, arable land, grassland, built-up land, wetland/water body and barren land (Liu, 1996).

2.3. Method

2.3.1. Statistical analysis and trend detection

The entire Yan Basin area upstream of GHS was considered in its entirety for this analysis. The areal precipitation (P) and reference evapotranspiration (ET0) (FAO 56) (Allen et al., 1998)) were induced from observed data of weather stations within the basin. The mean, range, minimum, maximum and coefficient of variation