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Research papers

Quantifying the streamflow response to frozen ground degradation in the source region of the Yellow River within the Budyko framework

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A B S T R A C T

The source region of the Yellow River (SRYR) is greatly important for water resources throughout the entire Yellow River Basin. Streamflow in the SRYR has experienced great changes over the past few decades, which is closely related to the frozen ground degradation; however, the extent of this influence is still unclear. In this study, the air freezing index (DDF_a) is selected as an indicator for the degree of frozen ground degradation. A water-energy balance equation within the Budyko framework is employed to quantify the streamflow response to the direct impact of climate change, which manifests as changes in the precipitation and potential evapotranspiration, as well as the impact of frozen ground degradation, which can be regarded as part of the indirect impact of climate change. The results show that the direct impact of climate change and the impact of frozen ground degradation can explain 55% and 33%, respectively, of the streamflow decrease for the entire SRYR from Period 1 (1965–1989) to Period 2 (1990–2003). In the permafrost-dominated region upstream of the Jimai hydrological station, the impact of frozen ground degradation can explain 71% of the streamflow decrease. From Period 2 (1990–2003) to Period 3 (2004–2015), the observed streamflow did not increase as much as the precipitation; this could be attributed to the combined effects of increasing potential evapotranspiration and more importantly, frozen ground degradation. Frozen ground degradation could influence streamflow by increasing the groundwater storage when the active layer thickness increases in permafrost-dominated regions. These findings will help develop a better understanding of the impact of frozen ground degradation on water resources in the Tibetan Plateau.

1. Introduction

The Tibetan Plateau (TP), also known as the third pole of the globe, has the largest area of alpine permafrost in the world (Qiu, 2008; Immerzeel et al., 2010; Cuo et al., 2015). Almost all of the TP is underlain by permafrost and seasonally frozen ground because of its high elevation (Guo and Wang, 2013). The TP contains the headwaters of several major Asian rivers, including the Yellow River, Yangtze River, and Brahmaputra River, and these rivers provide water for more than 1.4 billion people (Immerzeel et al., 2010). However, due to limited observations and the complicated interactions between hydrological and cryospheric processes, the responses of streamflow and other eco-hydrological variables to climate change and the consequent cryospheric changes in the TP are not well understood, which has aroused wide concern recently (Cao et al., 2006; Immerzeel et al., 2010; Kang et al., 2010; Yang et al., 2011; Qiu, 2012; Yi et al., 2014; Cuo et al., 2015; Qin et al., 2016; Zhang et al., 2016b; Qin et al., 2017).

The source region of the Yellow River (SRYR) upstream of the Tangnaihai hydrological station is located in the northeastern TP and provides 34.8% of the total water resources of the Yellow River (Hu et al., 2011; Yuan et al., 2015; Qin et al., 2017). Several studies have reported the degradation of frozen ground in the SRYR, including an upward shift in the permafrost lower limit, shifts in the permafrost boundary and a decrease in the maximum frozen depth (Jin et al., 2009; Fang et al., 2011). Frozen ground degradation can influence soil infiltration and drainage, enhance groundwater-surface water interaction and increase the baseflow in many cold regions (Walvoord and Kurylyk, 2016). Bense et al. (2012) suggested a large increase in groundwater discharge to streams in response to permafrost degradation based on numerical simulations for several Arctic rivers. Applying gray relational analysis to the upper Heihe River Basin, northeastern TP, Qin et al. (2016) found that the annual maximum frozen depth was one of the major factors on increases in the baseflow during the cold season. Cuo et al. (2015) discovered that precipitation changes and

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frozen ground degradation enhanced the surface hydrological processes in the northern TP based on Variable Infiltration Capacity (VIC) model simulations. Frozen ground degradation was also found to be associated with a slowdown in winter recession and the flattening of intra-annual streamflow in the SRYR (Niu et al., 2016; Qin et al., 2017; Wang et al., 2017), in northeastern China (Duan et al., 2017a), and in Arctic rivers (Lyon and Destouni, 2010; Walvoord and Kurylyk, 2016).

The influence of frozen ground degradation on annual streamflow, however, is not consistent among different regions. To the best of our knowledge, few quantitative analyses have been employed to investigate the impacts of frozen ground degradation on streamflow in the TP, and the mechanism of the streamflow response to frozen ground degradation is still unclear. Recently, Duan et al. (2017b) quantified the streamflow response to permafrost degradation based on the assumption that an increase in the active layer thickness would increase the annual streamflow in northeastern China. However, many researchers hypothesized that permafrost degradation would decrease the streamflow in the TP by lowering the groundwater table (Cheng and Wu, 2007; Jin et al., 2009; Yang et al., 2010) and enlarging the water storage capacity via an increased thawing depth (Niu et al., 2016). This is different from the hypothesis provided by Duan et al. (2017b) and different from the situation observed for Arctic rivers (Qiu, 2012).

Because of the inconsistency in the streamflow response to frozen ground degradation among different regions, this study does not initially assume whether frozen ground degradation will increase or decrease streamflow. Instead, this study employs the Budyko framework to quantify the streamflow response to frozen ground degradation. The Budyko hypothesis (Budyko, 1974) states that the annual water balance can be expressed as a function of the available water and energy. The Budyko framework has been applied to reflect the impacts of changes in dynamic landscape factors, including vegetation cover (Potter and Zhang, 2009; Donohue et al., 2010; Zhang et al., 2016a), human activities (Xu et al., 2014; Yang et al., 2014; Ning et al., 2017), and snowfall fraction (Berghuijs et al., 2014; Zhang et al., 2015; Barnhart et al., 2016), on annual streamflow. However, the Budyko framework has not yet been extended to quantify the impacts of frozen ground degradation.

A number of previous studies identified a decrease in streamflow in the SRYR during the 1990s (Cao et al., 2006; Zheng et al., 2007). Consequently, numerous attempts have been made to understand the causes of such streamflow variations. Hu et al. (2011) found that the correlation coefficients between the annual precipitation and annual streamflow increase from upstream to downstream and that a decrease in streamflow can be associated with decreasing wet season precipitation and rising temperatures. Utilizing sensitivity-based methods, Zheng et al. (2009) and Zhao et al. (2009) estimated that climate change manifesting as variations in precipitation and potential evapotranspiration contributed to <30% of the streamflow reduction at the Tangnaihai station in the 1990s; they further attributed the other 70% of the streamflow reduction to land use changes and human activities. By employing the VIC model in the SRYR, Cuo et al. (2015) discovered a deviation between observed streamflow and VIC-simulated streamflow values using a static land use map, and they found that the land use-induced deviation expanded during 1960–2000. Streamflow changes that cannot be directly explained by climate factors may also arise from cryospheric changes, such as frozen ground degradation (Cheng and Wu, 2007; Cuo et al., 2015) and variations in the snowfall fraction of the total precipitation (Berghuijs et al., 2014; Zhang et al., 2015), where further investigations are needed.

Recent studies have found that the streamflow trend reversed from decreasing to increasing since the 2000s due to the increasing precipitation. However, the streamflow did not recover as much as precipitation (Meng et al., 2016). Meng et al. (2016) attributed all of the streamflow changes in the 2000s to evapotranspiration changes based on the VIC model. Meanwhile, Xu et al. (2013) highlighted the importance of the increase in the water storage detected by Gravity Recovery and Climate Experiment (GRACE) satellite since 2003. Cuo et al. (2015) claimed that the "Three Rivers Source Region Reserve" project, which was launched in 2003, also played a role in the observed streamflow changes. Such ecological projects have already produced positive effects on grassland restoration on the TP (Xu et al., 2016) and reduced the growing season water yield due to increased evapotranspiration and soil water retention in the source region of the Yangtze River (Li et al., 2017). The impacts of ecological projects on annual streamflow in the SRYR, however, have rarely been analyzed.

In summary, previous studies used sensitivity-based methods or process-based models to analyze the possible reasons for streamflow changes in the SRYR (Zhao et al., 2009; Zheng et al., 2009; Cuo et al., 2015). However, most of these studies included only one change point close to the year 1990, and they did not explain the observed increase in streamflow since the 2000s. While the impacts of frozen ground degradation on streamflow changes were conceptualized in previous investigations, few quantitative analyses have been performed, and thus, the underlying mechanisms are still unclear. Therefore, the objectives of this study are to (1) understand the long-term streamflow changes over the past 50 years in the SRYR, (2) develop a decomposition approach within the Budyko framework to analyze the streamflow response to frozen ground degradation, and (3) use the extended Budyko framework to quantify the direct impact of climate change, manifesting as changes in the precipitation and potential evapotranspiration, as well as the impact of frozen ground degradation on streamflow.

2. Study area and data

2.1. Study area

The SRYR is located in the transitional zone of seasonally frozen ground and permafrost in the northeastern TP (Jin et al., 2009). In this study, the SRYR refers to the upstream catchment above the Tangnaihai hydrological station. The SRYR covers an area of 122,000 km^2 that accounts for 16% of the total area of the Yellow River Basin, and it yields 35% of the total runoff of the Yellow River (Hu et al., 2011). The elevation of the SRYR ranges from 2656 m to 6350 m (Fig. 1) and decreases from the southwest to the northeast. The Zoige wetland, which is located in the southeastern SRYR, is one of the largest alpine wetlands in the TP, and it is dominated by helophyte species (Zhang et al., 2016b).

2.2. Data

Digital elevation data with a resolution of 90 m were obtained from the Shuttle Radar Topography Mission (SRTM) (Jarvis et al., 2008). Daily mean air temperature, wind speed, daily average relative humidity and sunshine hour data from the 22 meteorological stations (Fig. 1) located within and around the SRYR were downloaded from the China Meteorological Administration (CMA) (http://data.cma.cn). An angular distance weighting method with elevation corrections (Yang et al., 2004) was utilized to produce 1-km gridded datasets on a daily basis.

The gridded precipitation data were spatially interpolated from gauge observations using the climatology-based optimal method proposed by Shen and Xiong (2016). The fraction of precipitation falling as snow (f_s) was estimated using a single temperature