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Long-term change in the depth of seasonally frozen ground and its ecohydrological impacts in the Qilian Mountains, northeastern Tibetan Plateau

Yue Qin [a], Huimin Lei [a], Dawen Yang [a,*], Bing Gao [b], Yuhan Wang [a], Zhentao Cong [a], Wenjie Fan [c]

[a] State Key Laboratory of Hydroscience and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China
[b] School of Water Resources and Environment, China University of Geosciences, Beijing 100083, China
[c] Institute of Remote Sensing and Geographic Information System, Peking University, Beijing 100871, China

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ABSTRACT

Changes in seasonally frozen ground at high elevations under the effects of global warming and their ecohydrological impacts are important for understanding changes in regional water resources and ecosystems. This study estimates the spatio-temporal variability in the maximum thickness of seasonally frozen ground (MTSFG) in the Qilian Mountains in the northeastern Tibetan Plateau from 1960 to 2014 by using a variant of the Stefan solution. The present study analyzes changes in streamflow and vegetation to reveal the ecohydrological impacts of changes in the MTSFG. Results indicate that the MTSFG shows a mean decreasing trend of 7.4 cm/10a in the past 55 years in correspondence to the significantly increasing air temperature (0.34 °C/10a). The greatest decreasing trend of the MTSFG is at elevations of 3400–3800 m. The annual baseflow has increased significantly in most of the sub-basins for which the increasing precipitation is the main factor. The MTSFG is another major factor for the increase in baseflow during the cold season (from November to April) according to the results of gray relational analysis. The leaf area index (LAI) during the growing season has increased by 0.045/10a since 2000, and the start of growing season has advanced by 1.8–2.1 d/10a at elevations of 3000–3800 m, where the vegetation cover is the densest. Furthermore, results of correlation analysis show that the topsoil moisture increases with the MTSFG decreases. Results of gray relational analysis show that the decrease in MTSFG is the main reason for the advancing green-up dates and increasing LAI in the initial period of the growing season. Our results show that the ecohydrological processes are changing along with frozen soil degradation in the northeastern Tibetan Plateau.

1. Introduction

As climates have warmed in many regions, the effect of changes in frozen soil on ecohydrological processes has become a crucial issue that can intensively affect natural systems and human societies (Huang et al., 2012; Bartos and Chester, 2015; Belmecheri et al., 2016). The hydrological characteristics along seasonally frozen ground are unique considering the low hydraulic conductivity, high soil water content, seasonal freeze/thaw processes, and the redistribution of frozen/thawed water (Jin and Li, 2009; Bense et al., 2012; Zhang et al., 2013b; Zhou et al., 2013). Therefore, analyzing changes in frozen soil has become an increasingly important topic in recent studies to quantitatively assess hydrological processes in cold regions under a changing climate.

Frozen soil has been recognized as a sensitive indicator of changing environments in the context of climate change. The role of seasonally frozen soil in ecosystems and hydrological processes has been widely discussed in the high-latitude cold regions in northern Eurasia and North America (Zhang et al., 2003a; Frauenfeld et al., 2004; Cheng and Wu, 2007; Frauenfeld and Zhang, 2011; Cheng and Jin, 2013). During previous decades, abundant research has focused on the effect of permafrost and frozen soil on surface and groundwater hydrology (Black and Tice, 1989; Koren et al., 1999; Woo et al., 2000; Zhang et al., 2007). Bosson et al. (2012) simulated the terrestrial hydrology associated with different climate and permafrost regime scenarios in a costal catchment of Sweden and indicated that runoff generation was in complex connections with the shifts in climate, landscape and permafrost existence. Bense et al. (2012) evaluated the hydrogeological changes in high-latitude sub-Arctic river basins in North America under permafrost degradation and found that shifts in

* Corresponding author.

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aquifer permeability and the uptake of water into aquifer storage increased the baseflow.

In addition to the Arctic and Antarctic, the Tibetan Plateau (TP) has the largest area of permafrost and seasonally frozen ground in high-elevation regions (Cheng and Jin, 2013). Under a warming climate, the permafrost area on the TP has shrunken from $1.50 \times 10^6\,km^2$ to $1.05 \times 10^6\,km^2$ over the past 30 years (Cheng and Jin, 2013), and the permafrost temperature has increased by approximately 0.43 °C per decade (Wu and Zhang, 2008). The northern and eastern margin of the TP is the headwater area of several major rivers in China and Southeast Asia, such as the Yangtze River, the Yellow River, the Heihe River, the Mekong River and the Salween River (Cuo et al., 2014). Because of the arid climate and high actual evapotranspiration, the surface hydrological cycle on the TP is different from that of the Arctic region (Yang et al., 2010). Zhang et al. (2003b) noted that the soil's freeze/thaw cycle, which affected seasonal water storage, soil moisture and evaporation, was the primary hydrological process during the monsoon season of the eastern TP. Wang et al. (2009) reported that the synergistic effect of the changes in frozen soil and vegetation cover may be the major factor in control of the surface runoff generation in the permafrost watershed of the TP. On the other hand, changes in frozen soil could also affect vegetation activity at the start of the vegetation growing season by changing the soil water content (Cuo et al., 2015) and soil organic carbon content (Mu et al., 2015). Dramatic changes have occurred in the ecohydrological cycle on the seasonally frozen ground of the TP, such as increasing soil temperature and soil moisture (Cuo et al., 2015) and advancing green-up dates (Zhang et al., 2013a), which were associated with the degradation of frozen soil under a warming climate.

Table 1 presents a summary of previous studies on the changes in frozen soil and their ecohydrological effects. Most studies that were based on station observations or small-scale experiments focused on changes in the permafrost regions. For the changes in frozen soil, the soil temperature, soil moisture, frozen soil depth and area of frozen soil were described in the permafrost region (Cheng and Wu, 2007; Cheng and Jin, 2013; Cable et al., 2014; Iijima et al., 2014; Cuo et al., 2015), but the frozen soil changes on seasonally frozen ground were not fully understood (Frauenfeld and Zhang, 2011; Wang et al., 2015a). For the effects of frozen soil on streamflow, some studies used numerical models to simulate the hydrological effect of frozen soil (Wang et al., 2010; Bense et al., 2012; Cuo et al., 2015) but lacked analysis of the relationship between long-term observations of the streamflow and frozen soil. For the influence of frozen soil on vegetation growth, the sap flow and transpiration rate of the plant at a point scale and the ecological regime shifts at a continental scale were analyzed (Karlsson et al., 2011; Cable et al., 2014; Iijima et al., 2014), but the impact of frozen soil changes on the vegetation growth at a basin scale or regional scale was unclear.

The Qilian Mountains along the northeastern margin of the TP is the headwater area of the Heihe basin, and this is a typical study area of the TP with relatively abundant climatic and hydrological observations. The hydrological and thermal properties, heat transport and spatio-temporal variations of the frozen soil in this area have been intensively discussed (Wang et al., 2010, 2015a; Zhang et al., 2013b; Zhou et al., 2014; Gao et al., 2016). Recently, the integrated observation experiment "Heihe Watershed Allied Telemetry Experimental Research" (HiWATER) presents new opportunities to reveal the ecohydrological processes of the frozen region in this area (Li et al., 2013; Cheng et al., 2014). Previous studies have mostly focused on the role of frozen soil in thermal and hydrological regimes by using distributed models at a small watershed scale (Wang et al., 2010; Zhang et al., 2013b) or by meteorological observations at a point scale (Wang et al., 2015a). However, the spatio-temporal changes in seasonally frozen soil and the relationship between changes in frozen soil and ecohydrology still remain unclear at a large regional scale.

The main objectives of this study are: (i) to understand the long-term changes and spatial characteristics of the seasonally frozen ground in the Qilian Mountains of the northeastern Tibetan Plateau; (ii) to analyze the effect of frozen soil degradation on runoff; and (iii) on the vegetation growth. The characteristics of the study area are presented in the following section. Then, methods to estimate the maximum thickness of seasonally frozen ground (MTSFG), separate the baseflow, retrieve the vegetation green-up dates and calculate the gray relational grade are introduced. The estimated MTSFG is validated in the results section, followed by the spatio-temporal variability of the seasonally frozen soil depth over the past 55 years. Finally, the effects of changes in frozen soil on runoff and vegetation growth are analyzed, and the uncertainty and limitations in estimating the MTSFG are discussed.

2. Study area and data

2.1. Heihe basin

Heihe basin is the second largest inland basin in Northwest China and originates from the Qilian Mountains in the northeastern Tibetan Plateau. The upper reach of the Heihe basin has a drainage area of 34,200 km^2 and contributes to approximately 70% of the total runoff in the entire basin, which is the major water source area that supports the socio-economic development in the middle and lower reaches (Chen et al., 2005; Lu et al., 2015). The elevation (defined per McVicar and Körner, 2013) of the upper Heihe basin ranges from 1600 m to 5400 m above sea level (a.s.l.), and the annual precipitation ranges from 200 mm/a to 700 mm/a, which is concentrated mostly in the summer. The major vegetation types in this area include alpine meadows, alpine sparse vegetation, shrubs and steppes (Gao et al., 2016).

According to the literature, the climatic and environmental changes in the study area during the past few decades include the following: (i) the annual precipitation, air temperature and river discharge have significantly increased from 1960 to 2013 (Wang et al., 2015b); (ii) the maximum thickness of seasonally frozen ground has decreased by approximately 20 cm from 1960 to 2007 according to site observations (Wang et al., 2015a); and (iii) long-term changes in upstream river discharge have affected human water consumption in the middle reach and downstream since the 1950s (Lu et al., 2015).

2.2. Data

The data that are used in this study include calculation-related data (e.g., historical climatic data and geographic information) and data for result validation.

The meteorological data in this study include the daily air temperature, ground surface temperature, precipitation, and frozen soil depth during 1960–2014. These data are available at the national meteorological stations that are managed by the China Meteorological Administration (CMA). Eleven stations are present in the study area and its surrounding area (see Fig. 1) and the data were downloaded from the National Meteorological Information Center of the CMA (http://data.cma.cn). In addition, eight automatic weather stations were in operation during the HiWATER experiment period (Liu et al., 2011; Li et al., 2013), and these meteorological data were downloaded from the HiWATER Data Center (http://www.heihedata.org). The gridded precipitation data were spatially interpolated from the site observations by using the method developed by Shen and Xiong (2016). Digital elevation data with a resolution of 90 m were downloaded from the shuttle