Cold Regions Science and Technology 126 (2016) 36–43

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Reduced winter runoff in a mountainous permafrost region in the northern Tibetan Plateau

Tanguang Gao [a,*], Tingjun Zhang [a], Lin Cao [a], Shichang Kang [b,c], Mika Sillanpää [d]

[a] Key Laboratory of Western China's Environmental System (Ministry of Education), College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China
[b] State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China
[c] Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing 100101, China
[d] Laboratory of Green Chemistry, Lappeenranta University of Technology, Sammonkatu 12, FI-Mikkeli 50130, Finland

A R T I C L E I N F O

Article history:
Received 16 June 2015
Received in revised form 6 March 2016
Accepted 18 March 2016
Available online 22 March 2016

Keywords:
Hydrological regime
Permafrost degradation
Runoff
Climate change
Tibetan Plateau

A B S T R A C T

The degradation of mountain permafrost under climate warming may alter the runoff regime of high mountainous catchments. In this study, we evaluated the influence of permafrost on the hydrological regime using hydrological signals in the Yeniugou Basin located in a mountainous permafrost region in the Qilian Mountains of the northern Tibetan Plateau (TP). The effect of permafrost degradation on the hydrological response was assessed based on 28 years of runoff and meteorological data. The results indicated that the investigated region exhibited a large increase in annual surface ground temperature from 1979 to 2006, with almost unchanged precipitation and evaporation potential. The winter runoff levels exhibited a significant decreasing linear trend, whereas the annual runoff and runoff in other seasons did not show any distinct linear trends. According to a comprehensive analysis of the relationships between winter runoff and meteorological factors, the ratio of maximum (Q_{max}) and minimum (Q_{min}) discharge, the recession coefficient and baseflow separation, and the reduced winter runoff were significantly correlated with thawing of permafrost. However, due to a time-lag response of climate forcing to permafrost thawing, some of these changes are undetectable over a short period. This study provides preliminary data on cold region hydrology and its response to climate change.

1. Introduction

Frozen ground is the largest component of the cryosphere, occupying an area of approximately 22.79×10^6 km^2 and accounting for 23.9% (excluding glaciers and ice sheets) of the land surface in the northern hemisphere (Zhang et al. 2003). Given that the cryosphere plays a significant role in the Earth's climate system through its impact on the surface energy budget and water cycle, cryospheric changes and their impacts are triggering wide attentions from international scientists and communities (Vaughan et al. 2013).

Because permafrost and seasonally frozen ground contain significant fractions of ice, changes in hydrological processes occur during their formation or degradation (Jorgenson et al. 2006; Gruber and Haeberli 2007). In cold regions in particular, the hydrological regime is closely related to permafrost conditions, such as the permafrost extent and thermal characteristics (Ye et al. 2009). An existing permafrost layer acts as a barrier to vertical soil water percolation and lateral subsurface flow in an overlying organic, highly porous active soil layer (Carey and Woo 2001). There is abundant and significant evidence that modification of river regimes results from regional climate change and permafrost degradation (Ye et al. 2003; Yang et al. 2004; Zhang et al. 2005).

In permafrost regions, watersheds with higher permafrost extents had lower subsurface storage capacity and, thus, lower winter runoff and higher summer runoff (Yang et al., 2004; Woo et al. 2008). The degradation of permafrost and increase in active-layer thickness should result in increased amounts of surface water (McNamara et al. 1998). Walvoord and Striegl (2007) suggested that permafrost thawing enhanced infiltration and supported deep flowpaths, which increase the contribution of groundwater to baseflow. Bense et al. (2009, 2012) developed a conceptual model for cold region groundwater flow and heat transport. Consequently, permafrost degradation gives rise to shifts in regional connectivity between basins in combination with increasing aquifer storage, which modifies space–time trends in groundwater recharge and discharge. Therefore, although there is growing evidence of marked changes in the annual and seasonal flow of rivers across Arctic and sub-Arctic regions (Walvoord and Striegl 2007; Janowicz 2008), the effect of permafrost degradation on streamflow is a long-term process, as is the response of permafrost degradation to climate warming.

China accounts for approximately 74.5% of the mountain permafrost area in the northern hemisphere (Cheng 1990). The degradation of mountainous permafrost under warmer climates may change the runoff regime in high mountain catchments (Woo et al. 2008). Widespread

* Corresponding author at: 222 Tianshui South Road, Chengguan District, Lanzhou 730000, Gansu Province, PR China.
E-mail address: gaotanguang@163.com (T. Gao).

http://dx.doi.org/10.1016/j.coldregions.2016.03.007
0165-232X/

permafrost degradation has been extensively reported on the Tibetan Plateau (TP) (Cheng and Wu 2007; Wu and Zhang 2010; Zhao et al. 2010; Li et al. 2012). Previous studies have indicated that winter warming at high latitudes and elevation in the permafrost zone of northwest China led to increases in winter runoff and seasonal infiltration on the TP (Gong et al. 2006; Liu et al. 2007, 2011; Niu et al. 2011). Although previous studies have provided interesting insights into permafrost environments and their runoff characteristics, data about mountain permafrost are often sparse and biased toward areas with existing infrastructure because access to and measurements of most mountain slopes are difficult and expensive (Gruber and Haeberli 2009). There is still very little known about the hydrological regime in the permafrost zone.

To assess the effect of permafrost degradation on the hydrological regime, runoff and meteorological data from 1979 to 2006 in the Yeniugou Basin, in the upper Heihe River basin in the northern TP, were analyzed in this study. The objective is to discuss the influence of permafrost degradation on the hydrological regime via five hydrological signals (Trend analysis, Correlation analysis, Ratio of Q_{max}/Q_{min}, Recession coefficient, and Hydrograph separation) over the Yeniugou Basin on Qilian Mountain, on the northeastern TP, where there is little human activity and where discontinuous mountain permafrost is widespread. We explore the hydrological and meteorological trends with a Modified Mann–Kendall (MK) test, focusing on the ratio of the maximum to minimum discharge (Q_{max}/Q_{min}) and its relationship to runoff; we also examine seasonal changes in the recession coefficient and hydrograph separation. This study provides new insights into cold region hydrology and its response to the impact of climate change.

2. Materials and methodology

2.1. Study area

The Yeniugou Basin is located in the western portion of the upper reaches of the Heihe Basin in the middle of Qilian Mountain, in the northern TP (Fig. 1), and it covers an area of approximately 4589 km^2 with an elevation stretching from 2847 to 4876 m a.s.l. The basin is covered by a distinct cold-weather landscape: glaciers, permafrost and seasonal frozen soil, alpine desert, and alpine meadow. The glacier area in the Heihe upstream is only 11.34 km^2 in 2010, which has decreased by 46% over the past 50 years (Huai et al. 2014); however, the contribution from glacier meltwater has accounted for 3.6% of the total river runoff (Cheng et al. 2014). Altitudinal zonality of permafrost distribution has been studied in different high mountain regions (Jin et al. 2000; Zhou et al. 2000). A total of 18 boreholes, located between 3609 and 4132 m a.s.l. in the Yeniugou Basin, were drilled to a depth of 20–100 m during 2011–2014. Based on observations from drilling samples and subsequent temperature measurements, it is estimated that active layer thickness varies from 1.6 m at elevation of 4132 m a.s.l. to more than 4.0 m at 3700 m a.s.l. (Wang et al. 2013). However, the average active layer thickness is approximately 1 m with a range from 0.7 to 1.20 m at the Ebo ridge site (Eastern of upstream of Heihe, 3600 m a.s.l.). The thinner active layer over the Ebo ridge is perhaps due to the north-facing slope and thick peat layer (ranging from 0.3–0.5 m). Using data and information from borehole drilling, temperature measurements, and mechanical probing of active layer depth, it is found that the lower boundary of permafrost over the upper reaches of the Heihe River basin is at approximately 3650 m a.s.l. Certainly, the lower boundary is affected by many local

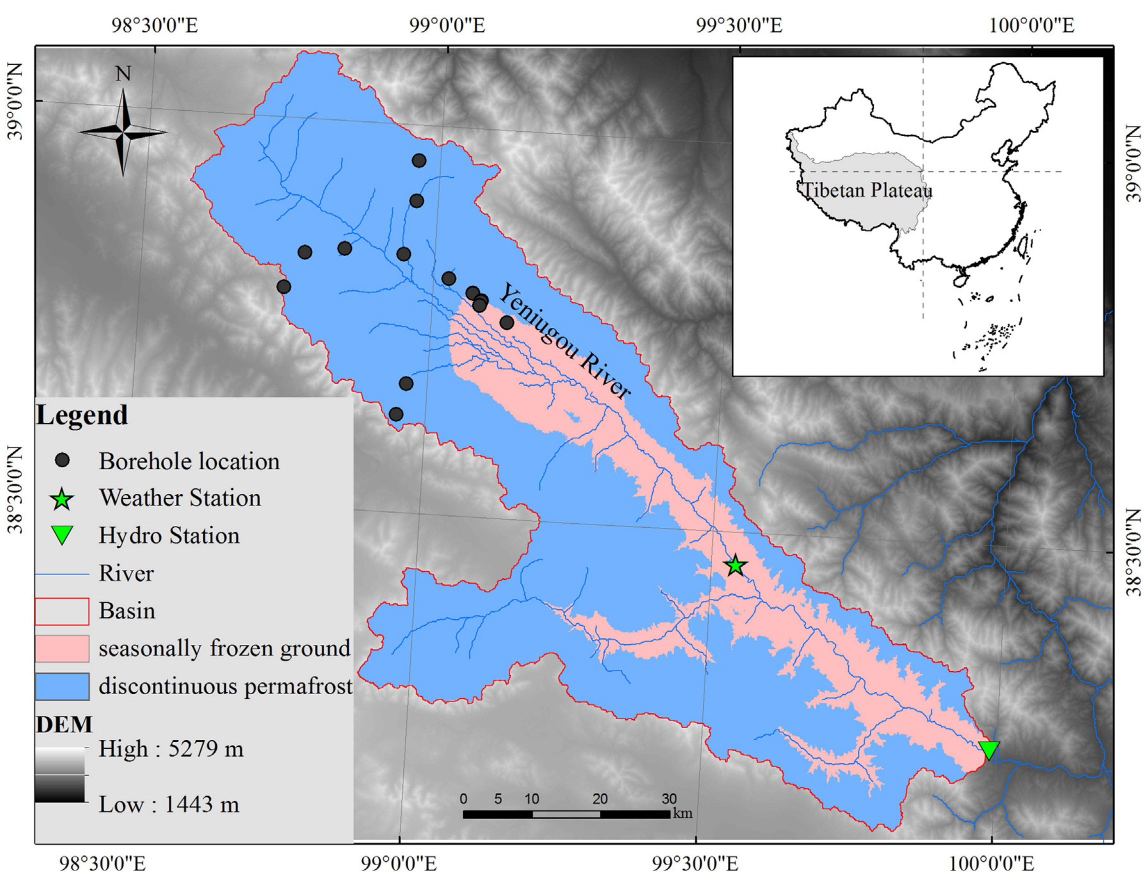

Fig. 1. Hydrological and meteorological stations with elevations and reaches in the Yeniugou basin, and the permafrost distributions in the same basin.