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Glacier changes and their impacts on the discharge in the past half-century in Tekes watershed, Central Asia

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ABSTRACT

The glacier is an important and stable water supply in Central Asia. Monitoring the change of glacier and understanding the impacts of glacier change on river discharge are critical to predict the downstream water availability change in future. Glacier changes were discussed and their impacts on river discharge were evaluated by hydrological modeling with a distributed hydrological model SWAT under two land use and land cover scenarios (1970 and 2007) in Tekes watershed, the most important source of water discharge to the Ili River. Compared to the glacier area of 1511 km^2 in 1970s it decreased by 332 km^2 in 2007, which resulted in the contribution the discharge from precipitation in the glacier area to the average annual discharge of the watershed changing from 9.8% in the period 1966–1975 to 7.8% in the period 2000–2008. In the month scale, with the decrease of glacier area, the distribution of the contribution of monthly discharge from precipitation in the glacier area to the total of the watershed changed from bimodal pattern to unimodal pattern. By linking a hydrological model to remote sensing image analysis and Chinese glacier inventories to determine glacier area change our approach in quantifying the impacts of glacier changes on hydrology at different scales, will provide quantitative information for stakeholders in making decisions for water resource management.

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1. Introduction

Mountains are the water towers of the world (Immerzeel et al., 2010; Viviroli et al., 2007), including for Central Asia, whose rivers all are fed from the TienShan mountains and adjacent mountain ranges. Snow and glacial melt are important hydrologic processes in these areas (Immerzeel et al., 2009; Zhang et al., 2008). For example, glacier retreat will result in decreased summer streamflow (Barnett et al., 2005). Changes in runoff due to glacier retreat is concerning, especially in areas where glacier runoff is a major source of water for agricultural, industrial, and municipal uses (Aizen et al., 2007; Luo et al., 2013). Hydrological investigations of glacier are thus necessary for these watersheds (Luo et al., 2013). Glaciers have been intensively studied through on-site observation and modeling at the glacier scale (Xiao et al., 2008; Ye et al., 2001) and remote sensing at the regional scale (Aizen et al., 2007; Kriegel et al., 2013; Shangguan et al., 2009). At basin scale, melting and runoff generation processes, water yield and its temporal distribution, and glacier contribution to streamflow are the key issues to be addressed (Luo et al., 2013).

Earlier studies have addressed the importance of glacial and snow melt and the potential effects of climate change on downstream hydrology, but these are mostly qualitative (Barnett et al., 2005; Bates et al., 2008; Cyranoski, 2005) or local in nature (Rees and Collins, 2006; Singh and Bengtsson, 2005). This is because hydrological modeling in mountainous catchments is challenged by complex physical conditions and data availability those introduce large uncertainty ranges (Gurtz et al., 2003; Moussa et al., 2007; Wortmann et al., 2013). Most commonly, data have poor coverage and quality at high altitudes requiring extrapolation over large topographically heterogeneous areas and elevation zones.

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Also, complex hydrological processes such as snow and glacier melt paired with data scarcity require catchment models to compromise physical for more empirical representations (Wagener et al., 2004; Wortmann et al., 2013). The relevance of glacial melt for Asian river basin hydrology therefore remains largely unknown (Immerzeel et al., 2010).

Physically-based, distributed hydrological models are currently available and may be used to evaluate distributed snow, ice melting, and runoff formation in glaciered watersheds in a more detailed way (Luo et al., 2013). The Soil Water Assessment Tool (Neitsch et al., 2005), a basin-scale, continuous-time, physically based, distributed model, is capable of continuous simulation over long time periods. Major model components include energy-balance, water-balance, soil temperature and properties, plant growth, mass transport, and land management. SWAT has been used in a wide range of climatic, topographic, soil, and management conditions around the world to investigate a broad range of hydrological and environmental topics (Gassman et al., 2007), including cases of snow hydrology studies (Fontaine et al., 2002; Luo et al., 2013; Wang and Melesse, 2005).

The Tekes River, originates at the northern slope of the Hantengri Peak, is the primary headstream of the Ili River, a border river between China and Kazakhstan. The Tekes watershed is a typical data-scarce area, in which there is not observational station above 2000 m (Lu et al., 2012; Ye et al., 1996). A few of research has been done on the hydrological modeling with model and experimental flood forecasting method (Lu et al., 2012; Wang et al., 2005; Ye et al., 1996; Zeng and Wang, 2004). Lu et al. (2012) applied SWAT to Ili River basin for modeling the hydrological process and developed a new suitable method for calibration in data-scarce basin; Zeng and Wang (2004) and Wang et al. (2005) analyzed the characteristics of the runoff and flood based on the observational data including precipitation, temperature and runoff. Meanwhile, scientists have estimated the glacier area variation according to the selected glaciers. Li et al. (2010) researched 1800 glaciers in Xinjiang (1543 glacier in the Chinese Tianshan Mountains), and the total area was reduced by 11.7% starting from the 1960s/1970s to the 2000s. Wang et al. (2011) weighted the data according to the glacier area of ten drainage basins and got that the total area of glaciers in the Chinese Tianshan Mountains was reduced by 11.5% in the past five decades. In Ili River basin, the research on the contribution of glaciers to the discharge and the impacts of glaciers change on the discharge was inadequate except for three studies (Li et al., 2010; Liu et al., 1999; Yang, 1987). They reached a consensus on the number, area and reserves of the glaciers in our country part of Ili River basin, but there were difference in the discharge of glaciers. It is difficult to judge which is right, because there is not a glacier in monitoring in this basin (Li et al., 2010). Thus, greater understanding of the contribution of glaciers to the discharge and the impacts of glaciers change on the discharge is needed to guide comprehensive water resources management in this region.

The overarching goal of this study is to reveal the contribution of the discharge from precipitation in glacier area to the total and its temporal variation with the change of glacier area over the past half century in the Tekes watershed, which is under the assumption that the glaciers is viewed as a special underlaying surface with very low infiltration rate and without change in a given period. The specific objectives are: (1) to investigate the changes of the glacier based on two periods images which are respectively acquired in about 1970 and 2007 and two Chinese glacier inventories; (2) to evaluate the contribution of the discharge from precipitation in glacier area to the total discharge based on SWAT, and (3) to analyze the temporal change of the discharge from precipitation in glacier area.

2. Study area

The Tekes River flows into the Kunes River in Xinjiang, China, and converges with the Kash River to form the Ili River, which flows into the Lake Balkhash in Kazakhstan. As a part of the Ili River basin, the Tekes watershed is located in the hinterlands of Eurasia, being hidden deeply inland, surrounded with mountains on three sides, and distant from oceans. However, a humid and temperate climate is formed in the Ili River Valley, which becomes the precipitation center of the Tianshan Mountains and central Asia (Xu et al., 2011). This is a comprehensive result of the unique topography, physiognomy, and mountain strikes (Xu et al., 2011).

The Tekes watershed is located in the geographical range of 80°9′–83°43′E, 42°15′–43°36′N, including the main rives such as Tekes, Shata, Akeyaz, and K-sou (Fig. 1). It covers an area of 27,671 km^2, which in our country totals 231,68 km^2. There is a complex topography and landform. The terrain increases from northeast toward southwest, with the elevation between 785 m and 6038 m. The climate type is temperate continental climate. The mean annual temperature is about 4.2 °C, mean annual precipitation is more than 400 mm, with most of the rainfall occurring between April and September, accounting for 80% of the total annual rainfall, and the average annual evaporation is 1358 mm (Zhang et al., 2011). Because of abundant precipitation and low temperature in the high mountain, there are a large number of glaciers and snow, whose melting water together with atmosphere precipitation and groundwater become the supply of discharge in Tekes watershed. For much of the year, the glacier and snow-melt in mountain chains provide main freshwater flows to downstream cities and agricultural land.

There are widespread forests and vast grasslands in Tekes watershed, which is known as "small Jiangnan of Xinjiang". In addition, the cultivated land is present for a certain percentage. Hence, it is the prominent base of cereals and oils, forestry and fruit industry and animal husbandry of Xinjiang (Zhang et al., 2011). The main soil types in the watershed include felty soil (29%), chernozem (15%), dark felty soil (15%), alpine frost soil (10%) and chestnut soil (10%).

3. Method and data processing

3.1. Conceptual framework for analyzing the impacts of glacier changes on the hydrology in Tekes watershed

A conceptual framework was developed to reveal the impacts of glacier changes on the hydrology in Tekes watershed over the past half century (Fig. 2). In this framework, the glacier changes was considered to be a main cause of hydrological process changes, including the changes of the contribution of the discharge from precipitation in glacier area to the total and its distribution in a year. This framework included three major tasks: investigating the hydrological responses to glacier changes, constructing a distributed hydrological model-SWAT, and preparing a set of systematic and impeccable data to drive the model, including soil, land use and land cover (LULC) and climate data, e.g. the soil data in foreign part needed to replace by the data from Harmonized World Soil Database. These three tasks were introduced in the following sections of 3.2, 3.3 and 3.4, respectively.

3.2. Investigating the hydrological responses to glacier changes

In order to investigate the hydrological responses to the glacier changes, the LULC data for two times (1970 and 2007) combined with two Chinese glacier inventories were used to represent the underlying surface conditions in two periods, including the periods

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