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Trends and variability in streamflow and snowmelt runoff timing in the southern Tianshan Mountains

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ABSTRACT

Streamflow and snowmelt runoff timing of mountain rivers are susceptible to climate change. Trends and variability in streamflow and snowmelt runoff timing in four mountain basins in the southern Tianshan were analyzed in this study. Streamflow trends were detected by Mann-Kendall tests and changes in snowmelt runoff timing were analyzed based on the winter/spring snowmelt runoff center time (WSCT). Pearson's correlation coefficient was further calculated to analyze the relationships between climate variables, streamflow and WSCT. Annual streamflow increased significantly in past decades in the southern Tianshan, especially in spring and winter months. However, the relations between streamflow and temperature/precipitation depend on the different streamflow generation processes. Annual precipitation plays a vital role in controlling recharge in the Toxkon basin, while the Kaidu and Huangshuigou basins are governed by both precipitation and temperature. Seasonally, temperature has a strong effect on streamflow in autumn and winter, while summer streamflow appears more sensitive to changes in precipitation. However, temperature is the dominant factor for streamflow in the glacierized Kunmalik basin at annual and seasonal scales. An uptrend in streamflow begins in the 1990s at both annual and seasonal scales, which is generally consistent with temperature and precipitation fluctuations. Average WSCT dates in the Kaidu and Huangshuigou basins are earlier than in the Toxkon and Kunmalik basins, and shifted towards earlier dates since the mid-1980s in all the basins. It is plausible that WSCT dates are more sensitive to warmer temperature in spring period compared to precipitation, except for the Huangshuigou basin. Taken together, these findings are useful for applications in flood risk regulation, future hydropower projects and integrated water resources management.

1. Introduction

Snowmelt contributes substantially to the springtime runoff and streamflow in mountain regions with colder climates. The timing and volume of snowmelt runoff and streamflow can be particularly sensitive to climate change (Barnett et al., 2005; Stewart et al., 2004; Clow, 2010; Viviroli et al., 2011; Leppi et al., 2012). The rivers flowing from the Tianshan Mountains (known as the "Water tower of Central Asia") are an important freshwater source for Central Asia (Sorg et al., 2012; Chen et al., 2016a,b). Additionally, the snowmelt in the Tianshan Mountains, as in other cold mountain regions, contributes substantially to the springtime runoff and streamflow portions of the regional water balance (Chen et al., 2016b). Average temperature and precipitation have been increasing over recent decades in northwestern China where the Tianshan Mountains are located (Xu et al., 2004; Chen et al., 2006; Kong and Pang, 2012). As precipitation influences streamflow directly, while temperature mainly affects evapotranspiration, snow/glacier melt and the form (rain or snow) of precipitation (Singh and Singh, 2001; Molini et al., 2011); warmer and wetter conditions may result in an accelerated and unstable regional hydrological cycle in this semiarid region (Shen and Chen, 2010; Chen, 2014). Streamflow variability is therefore remarkably important for studying the impacts of climate change.

Streamflow and snowmelt runoff timing in the Tianshan Mountains are expected to change under a changing climate. Streamflow experienced a remarkable increase with climate warming (Chen et al., 2009, 2013; Liu et al., 2011) which-combined with glacier shrinkage-leads to a significant increase in streamflow volume and earlier snowmelt runoff in the Urumqi basin (Sun et al., 2015). According to model simulations, the timing of snowmelt runoff is projected to shift earlier due to temperature increase in spring (Wang et al., 2010; Liu et al., 2011). However, the impacts

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of climate change on streamflow differ in different basins. The Xinjiang province portion of the Tianshan mountains in China runs from west to east (around 1700 km long), and therefore intercepts moist air coming from the westerlies and results in unevenly distributed precipitation and water resources (Chen, 2014). The northern and western slopes of the Tianshan receive more precipitation than the southern and eastern parts (Xu et al., 2010), while temperature on the southern slopes is higher than on the northern slopes (Shen et al., 2016). The climate-related impacts on streamflow are even more complex in glacierized catchments. For instance, streamflow change in the Kaidu basin in summer is mainly attributed to changes in mountain precipitation (Deng et al., 2015), while temperature dominates streamflow changes in the highly glacierized Kunmalik basin (Kundzewicz et al., 2015). Generally, the distribution of streamflow and snowmelt runoff timing are undergoing significant changes due to climate variability, which motivates the need to identify the streamflow variability and snowmelt runoff timing in meltwater-dependent basins.

Changes in streamflow and snowmelt runoff timing have become evident in other regions in recent decades. Global streamflow has tended to increase in the warming climate (Labat et al., 2004). In addition, streamflow increases have been projected due to increased temperature and precipitation in a glacierized river basin in Nepal (Immerzeel et al., 2012). Quantified by means of center of volume date (CT) and spring pulse onset, streamflow and snowmelt runoff timing were shifted earlier due to temperature increase in New England (Hodgkins et al., 2003) and Colorado (Clow, 2010). These changes are also observed in western North America and Eurasian Arctic rivers (Stewart et al., 2004, 2005; Cayan et al., 2001; Tan et al., 2011). Based on GCM models, the projected streamflow in Quebec, Canada, is expected to increase in winter and decrease in spring (Boyer et al., 2010). Taken together, changes in streamflow and snowmelt runoff timing are important indicators of climate-related changes (Hodgkins et al., 2003). However, climate change and its impacts on streamflow are still poorly described, especially with respect to snowmelt runoff changes in glacierized catchments in the Tianshan Mountains (Chen et al., 2016b). Currently, not much research in the Tianshan Mountains focuses on the streamflow variability at the basin scale, while much of the recent work has focused on large regional areas (Shi et al., 2007; Chen et al., 2009; Tao et al., 2011; Xu et al., 2010; Wang et al., 2013). Therefore, it is not well known how changes in climate might impact streamflow and snowmelt runoff timing in different basins of the Tianshan Mountains. To improve our general understanding of the impacts of climate change, the knowledge of seasonal relationships between hydro-meteorological variables at the basin scale must be improved.

This study therefore seeks to estimate the trends and variability of streamflow and snowmelt runoff timing in four mountain basins in the southern Tianshan (from west to east) and their possible sensitivity to climate change. The objectives are: (1) to estimate annual, seasonal and monthly historical streamflow characteristics in four glacierized basins in the Tianshan Mountains; (2) to characterize possible changes in snowmelt runoff timing; (3) to obtain insights into hydrological processes and to identify the relationships between hydrological changes associated with climate variables.

2. Study area, data and methods

2.1. Study area

Four glacierized basins (Toxkon, Kunmalik, Kaidu and Huangshuigou, respectively) in the southern Tianshan were chosen based on the location and data availability (Fig. 1 and Table 1). Mean elevations of the Toxkon, Kunmalik, Kaidu and Huangshuigou basins are 3634, 3707, 3008 and 2840 m above sea level (a.s.l), respectively. The Toxkon and Kunmalik basins drain approximately 19,166 and 12,816 km^2 upstream from the Shaliguilanke and Xiehela stations (Table 1). They are the main headwater subcatchments of the Aksu River, which is the main tributary of the Tarim basin, accounting for about 80% of its annual streamflow. In addition, approximately 4% and 20% of the Toxkon and Kunmalik basins, respectively, are glacierized (Doris et al., 2016). The Kaidu and Huangshuigou basins are located in the central southern part of the Tianshan Mountains and cover 18,649 and 4298 km^2 upstream from the Dashankou and Huangshuigou gauge stations. Streamflow from the Kaidu and Huangshuigou basins finally arrive at Bosten Lake which is another important water source for the Tarim basin.

The basins are characterized by a continental semiarid climate. Mean annual streamflow in the Toxkon, Kunmalik, Kaidu and Huangshuigou basins are 148, 381, 189 and 69 mm/year, respectively (Table 1). Temperature and precipitation (from APHRODITE, see the Data section) are highly heterogeneous due to large elevational gradients and complex topography. The Kaidu basin has the coldest winters (mean winter temperature −20.4 °C), followed by the Kunmalik (−17.2 °C), Huangshuigou (−15.8 °C) and Toxkon (−15.2 °C) basins (Fig. 2). The highest mean summer temperature is found in the Huangshuigou basin (10.4 °C). Average summer temperatures in the Toxkon, Kunmalik and Kaidu basins are 9.3, 6.9 and 9.2 °C, respectively. Generally, temperature in winter is more variable than in summer, while the opposite holds true for precipitation (Fig. 2). Winter is the driest season for all the basins (15, 23, 11 and 6 mm for the Toxkon, Kunmalik, Kaidu and Huangshuigou basins, respectively). Precipitation mainly occurs in summer (115, 152, 138 and 127 mm for the Toxkon, Kunmalik, Kaidu and Huangshuigou basins). Moreover, average precipitation in spring is higher in the Toxkon and Kunmalik (65 and 79 mm) than the Kaidu and Huangshuigou (37 and 30 mm, respectively) basins.

2.2. Data

Streamflow gauge data were obtained from the Hydrology and - Water Resources Bureau of Xinjiang. Four stations with daily streamflow data are available in the Tianshan Mountains. The gauge locations are shown in Fig. 1 and the corresponding summary information is listed in Table 1. The streamflow data cover a period of more than 30 years and all the data were strictly checked for homogeneity. There are a few days of missing data (<1% of the daily values) for the daily streamflow in the Shaliguilanke, Xiehela and Huangshuigou stations. However, monthly data are available. We interpolated the missing data using linear regression with neighboring data. Although uncertainties remain, we assume that they won't have much influence on the trend detection.

There is only one observation station in each basin, which cannot represent the spatial climate for the whole basin. Therefore, time series of mean temperature and precipitation data within these basins were extracted form APHRODITE (Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources) gridded data (Yatagai et al., 2012). APHRODITE covers time span more than 45 years (1951–2007 for precipitation and 1961–2007 for temperature) and it features a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$. APHRODITE is an interpolated dataset that can provides a basic description for the local climate and has been widely applied in central Asia (Immerzeel et al., 2015; Shea et al., 2015; Krysanova et al., 2015). Climate stations are sparse in the Tianshan Mountains and most of the stations are located in the valley; APHRODITE may therefore underestimate the mountain precipitation due to the