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RESEARCH ARTICLE

# Using isotope methods to study alpine headwater regions in the Northern Caucasus and Tien Shan*

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**Abstract** High mountain areas provide water resources for a large share of the world's population. The ongoing deglaciation of these areas is resulting in great instability of mountainous headwater regions, which could significantly affect water supply and intensify dangerous hydrological processes.

The hydrological processes in mountains are still poorly understood due to the complexity of the natural conditions, great spatial variation and a lack of observation. A knowledge of flow-forming processes in alpine areas is essential to predict future possible trends in hydrological conditions and to calculate river runoff characteristics. The goal of this study is to gain detailed field data on various components of natural hydrological processes in the alpine areas of the North Caucasus and Central Tien Shan, and to investigate the possibility that the isotopic method can reveal important regularities of river flow formation in these regions. The study is based on field observations in representative alpine river basins in the North Caucasus (the Dzhankuat river basin) and the Central Tien Shan (the Chon-Kyzyl-Suu river basin) during 2013–2015. A mixing-model approach was used to conduct river hydrograph separation. Isotope methods were used to estimate the contribution of different nourishment sources in total runoff and its regime. $\delta^{18}O$, $\delta D$ and mineralization were used as indicators. Two equation systems for the study sites were derived: in terms of water routing and runoff genesis. The Dzhankuat and Chon-Kyzyl-Suu river hydrographs were separated into 4 components: liquid precipitation/meltwaters, surface routed/subsurface routed waters.

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## 1 Introduction

About 28% of the earth's surface is covered by mountains (Singh et al., 1999). Most of the mountainous regions in the world are very rich in water resources, and high mountain areas provide reliable water supplies for a large share of the world's population (Singh et al., 1999). The amount of water originating from a unit of area rises rapidly as elevation increases in most of the mountain regions in the world. In the North Caucasus and Tien Shan, a unit of area at an elevation of 3–4 km can be 10 times more effective in terms of water resources than the lowlands ( < 0.5–1 km) (Rets and Kireeva, 2010; Bolgov and Trubetskova, 2011). Accordingly, headwaters play a definitive role in the formation of river runoff in mountainous regions, despite their minor share in total watershed area.

The vast majority of glacier mass-balance measurements reveal an active deglaciation process over the last six decades. Heavy ice losses were registered in the first decade after the start of the measurements (in the 1940s), slowing down in the second decade (1956–1965), followed by a moderate mass loss between 1966 and 1985, and a subsequent acceleration of ice loss up to the present (Oerlemans, 2005; Zemp et al., 2008; AMAP, 2011).

The area of glaciers in the North Caucasus dropped by 12.6% during 1970–2000 (Volodicheva and Voitkovskiy, 2004), and by 4.7% between 2000 and 2010/2012 (Shahgedanova et al., 2014), amounting to approximately 17% in total during 1970–2012. A substantial intensification of deglaciation during the last decade in the region is reflected in mass-balance measurements on representative of the central part of the North Caucasus, Dzhankuat glacier. Mean rates of ice mass loss increased from –0.13 m w.e./yr (meters of water equivalent per year) in 1966–2003 (Shahgedanova et al., 2007) to –1.03 m w.e./yr in 2010–2015 (www.wgms.ch).

In the Central Tien Shan region, the overall decrease in total glacier area and mass from 1961 to 2012 is estimated to be 18% and 27%, respectively (Farinotti et al., 2015). Mass loss estimates based on measurements of the Gravity Recovery And Climate Experiment (GRACE) for the Tien Shan range from 0.5 (Jacob et al., 2012) to 0.51 m. w.e./yr (Farinotti et al., 2015). A substantial increase in the glacier shrinkage rate is observed at the end of the 20th century–beginning of the 21st century (Aizen et al., 2007; Kutuzov and Shahgedanova, 2009; Petrakov et al., 2016)

The global glacier retreat is considered to be climate-derived (Oerlemans, 2005). Moreover, as all currently available climate models predict near-surface warming, a further intensification of glacier mass loss is expected (Barnett et al., 2005; AMAP, 2011; IPCC, 2013). The ongoing active deglaciation is resulting in great instability of mountainous headwater regions, which could significantly affect water supply (Barnett et al., 2005) and intensify dangerous hydrological processes (Seynova, 2008).

Knowledge of flow-forming processes in alpine areas is essential to predict future possible trends in hydrological conditions and to calculate river runoff characteristics. Nevertheless, there are still many blind-spots in the understanding of flow-forming processes in mountainous headwaters (Klemes, 1988; Gietl, 1990; Bales et al., 2006; Chaponnière et al., 2008). For example, processes in the control of distribution of energy and water fluxes, scaling from a one-point measurement of hydrological and meteorological characteristics, factors controlling the partitioning of snowmelt into runoff versus infiltration and into evapotranspiration versus recharge, principal geologic factors controlling groundwater storage, discharge to streams, and chemical composition (Bales et al., 2006), what minimum measurement strategy of some key variables can ensure proper assessment of the water balance components (Chaponnière et al., 2008), drainage of meltwater and rainfall through the glacier to the glacier snout (Klok et al., 2001; Rets et al., 2014). The possibility of adapting the methods and experience acquired in the lowlands in order to solve mountainous regions is highly questionable because of the specific climatic, morphological and energy conditions that control and influence the water cycle in the mountains (Gietl, 1990).

The main reasons for the poor understanding of hydrological processes in mountains are the complex conditions, great spatial variation and lack of observation (Gietl, 1990; Singh et al., 1999; Schaefli et al., 2005; Bales et al., 2006).

The density of hydrological stations in the world's mountainous regions is 3 to 5 times lower than those recommended by the World Meteorological Organization (WMO) (Bobrovitskaya and Kokorev, 2014). The minimum density of hydrological stations in mountains recommended by WMO is 1000 km$^2$ per station (WMO, 2008). This translates into a recommended total number of approximately 150 stations for Kyrgyzstan's part of the Tien Shan's mountainous region. Presently, the vast majority of the 70 gauging stations working in this region are below 2000 m (Mamatkanov et al., 2006). The density of hydrological stations in the North Caucasus is 2350 km$^2$ per station (Bobrovitskaya and Kokorev, 2014).

Besides gaining standard network hydrological and meteorological observations, a detailed study of the hydraulic conditions in representative basins provides an opportunity to better understand the regionally specific regularities of the hydrological cycle (Gietl, 1990).

An extremely complex structure of river flow nourishment is characteristic of high-altitude territories. As the melting of snow and ice lasts throughout the summer period in alpine regions, the energy balance becomes the major factor for water regime formation in a highly glaciarized river basin (Golubev, 1976; Bales et al., 2006). The typical hydrograph of an alpine river has a sawtooth shape during the warm season, defined by the intensification and deceleration of ice and snow melting due to changes in weather conditions, which is overlapped with rain floods.

In an attempt to draw a dependency between weather characteristics and river discharge, a significant scatter of the points is always discovered (Rets et al., 2014). The reason for this is that the time lags of the different components forming river flow can vary greatly and change during the season (Golubev, 1976; Jansson et al, 2003; Rets et al., 2014). Modeling the englacial drainage system explicitly is difficult (Baker et al, 1982; Hooke, 2005). Ice meltwater that originated on a snow-free glacier tongue can reach the gauging station in several hours depending on its location (Golubev, 1976; Hooke, 2005). This is reflected in a well-pronounced diurnal minimum and maximum water level of an alpine river. Meanwhile, the time required for percolation through 4–6 meters of snow in a firn zone cover can be, depending on the physical properties and characteristics of the process of melting, from 5–7 to 15–18 days (DeWalle and Rango, 2008). Further time lag of meltwater from the glacier firn zone can also take several days. For Dzhankuat glacier, according to estimates of Golubev (1976), the lag is about 5 days in late July–early August. Furthermore, some water formed during the ablation season is stored in natural regulating reservoirs of the watershed that supply alpine rivers during the winter period (Golubev, 1976). The time lag of seasonal snow melt and rain water on the glacier-free part of the watershed depends greatly on its geological structure (Golubev, 1976; Rets et al., 2014).

This results in a sufficient complexity of any schema-