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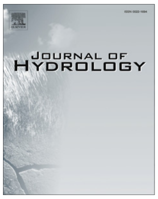

Effects of projected climate change on the glacier and runoff generation in the Naryn River Basin, Central Asia

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SUMMARY

Climate change is a major environmental concern and the melting processes of the glaciers and snowpacks are sensitive to climate change. The ultimate effect of the future changes on the glacier and hydrology is unclear and poorly investigated for Central Asia. Here, we use results from the latest ensemble of climate models in combination with a glacier-enhanced Soil Water Assessment Tool (SWAT) hydrologic model to assess the hydrological impact of climate change in the Naryn River Basin, Central Asia. Results indicate that small glaciers suffer from larger relative area losses than large glaciers. Only 8% of the originally glaciated area for small glaciers will retain glaciers by 2100 for RCP8.5. The rate of area retreat for small glaciers (with an area $<1\ \text{km}^2$) will slow down for the period 2066–2095, while the glacier area shrinkage is projected to accelerate for large glaciers throughout the twenty-first century. In all cases, glaciers will recede but net glacier melt runoff will reach peak in about 2040. Decreases in future runoff are projected in combination with a negative change in precipitation, snowmelt and higher evapotranspiration. Glacier melt is mainly derived by future temperature changes, while the runoff and snowmelt component are determined by future precipitation. The timing of peak runoff is advancing about one month as a result of earlier snowmelt due to the warming temperature. Runoff is projected to increase during the spring and decrease for the summer season for the future periods. Thus water availability on the time will likely undergo significant changes.

1. Introduction

Climate change is emerging as the single most important environmental issue of the 21st century (Campbell et al., 2011; Carter et al., 2015). Global air temperatures have increased by 0.85 °C during the period 1880–2012 (IPCC5, 2013). Precipitation is also changing in volume, intensity, and form (e.g., rain and snow) throughout many regions of the world (Campbell et al., 2011). Most studies agreed on general warming trends in Central Asia with acceleration since the 1970s, but varied with regard to seasonal changes and the magnitude of the warming (Unger-Shayesteh et al., 2013a). The temperature projections for RCP4.5 (representative concentration pathways) reveal a region-wide warming of close to 2 °C (2021–2050 relative to 1961–1990) according to the phase five of the Climate Model Intercomparison Project (CMIP5), and the warming trend is further exacerbated for RCP8.5 (Immerzeel et al., 2013). Based on global climate model projections, climate change is expected to considerably affect the Central Asian region; it has been identified as a "hot spot" of climate change, where warming is expected to increase above the global average and the impact on water resources is predicted to be serious (Unger-Shayesteh et al., 2013b).

Mountain glaciers are recognized as key indicators for climate change and as important water storages on a seasonal, mid-term and long-term time scale (Hagg et al., 2013). Recent research shows that even small-scale natural climate fluctuations have had large impacts on glaciers over the past 100,000 years. Glaciers in the Tien Shan and the Pamir continue to retreat and to shrink (Khromova et al., 2006; Li et al., 2006). Several studies based on remote sensing have shown that glacier recession in Central Asia was accelerated during the past decades, especially those at the outer ranges of the mountain systems (Liu et al., 2006; Aizen et al., 2007; Bolch, 2007; Narama et al., 2009). For the water cycle of the Central Asian mountains, glacier retreat will still be of crucial importance during the next century. There is a decrease in maximum snow depth and a reduction in snow cover duration under climate change (Barnett et al., 2005). It also shows that hydrologi-

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cal regimes of snow- and glacier-melt driven rivers will be impacted by a warming climate (Schaefer et al., 2006; Immerzeel et al., 2010). The shifts in climate ultimately affect the quantity and seasonal distribution of streamflow, having important implications for global water supplies (Campbell et al., 2011).

Snow and glacial melt are important hydrologic processes in Central Asian region, and changes in climate are expected to seriously affect the melt characteristics. A number of studies have addressed the importance of snow and glacial melt and the potential effects of climate change on hydrology, but these are mostly qualitative (Barnett et al., 2005; Singh and Bengtsson, 2005; Immerzeel et al., 2010). Unger-Shayesteh et al. (2013a) had reviewed about 100 studies on past changes in climate, snow cover, glaciers and runoff in Central Asian headwater catchments, which have been published in the past 20 years, and concluded that there is a need for sound attribution studies linking the observed hydrological changes in individual catchments to particular processes triggered by climatic and cryospheric changes. Runoff in the high mountain areas of Central Asia were a complex response of catchments to changes in climate.

Most studies investigated the glacier area changes in Central Asia consistently showing regionally heterogenous, with stronger glacier area losses at the northern and eastern margins of the mountain system (Li et al., 2006; Narama et al., 2006; Bolch, 2007; Kutuzov and Shahgedanova, 2009). Aizen et al. (2007) thoroughly studied the changes in glacier area and volume between 1943 and 2003 in the Akshiirak massif, which partly drains to the Naryn basin based on topographic maps, SRTM and ASTER data sources. Niederer et al. (2008) reported a glacier retreat of about 28% between 1963 and 2000 for the rather small Sokoluk catchment located in the Northern Tien Shan. Narama et al. (2006), who documented a rather small glacier area loss of about 8% for the Western Terskey Alatoo and the period 1971–2002, found that small glaciers with a size of less than 1 km^2 are mostly affected by the retreat. Based on the glacier area inventory and ground penetrating radar measurements, Hagg et al. (2013) found that a volume of about 20% had been lost and the total glacier area decreased by 23.4% due to increasing summer temperatures over the second half of the 20th century in the Big Naryn catchment, Upper Syrdarya. The assessment of glacier area changes was extended to the entire Naryn basin and clearly indicated strong variation in glacier loss rates across the basin within the 30-years investigation period. Positive trends in spring and autumn discharge were detected and are likely to be associated with the enhanced snow and glacier melt driven by temperatures in those seasons. However no discharge trends in August – the month with the largest expected glacier melt – were detected from Naryn headwaters (Kriegel et al., 2013).

The ultimate effect of the projected changes on the glacier and regional water cycle is uncertain and poorly investigated for Central Asia. Projections of future hydrological changes are of vital importance for water management in Central Asia. The objective of this research is to investigate how changes in future precipitation and temperature will affect the glacier and snow melt, change the magnitude and timing of the annual hydrograph and cause shifts in the runoff components using the latest climate model ensemble.

2. Materials and methods

2.1. Study area

The Naryn River is one of the main tributaries of Syrdarya River, which originates in Tien Shan Mountains in Kyrgyzstan and flows towards northern Aral Sea through Tajikistan, Uzbekistan and Kazakhstan (Fig. 1). The Naryn River is formed at the confluence of the Big and the Small Naryn rivers. It flows into Ferghana Valley, where it merges with Karadarya to form the Syrdarya River (Hagg et al., 2013). The area of the basin covers 58,205 km^2, and about 2% of the basin area is glacierized. The majority of glaciers is concentrated in the eastern part of the basin. Most part of the catchment area is located mainly in Kyrgyzstan, but small parts of it belong to Uzbekistan.

The Naryn River Basin has a continental climate with dry and hot summer and cold winter. The average temperature is 10 °C in July, −18 °C in January. Annual precipitation ranges between 280 mm and 450 mm depending on altitude. The highest share of precipitation falls in spring and early summer (Kriegel et al., 2013). There is the smallest precipitation in summer. Snowfall occurs in winter and takes account of significant parts of precipitation in the mountainous area due to abundant precipitation and low temperature. The maximum runoff occurs in June when the snow in the mountains melts and contributes to river flow. Snow melt contributes a remarkable portion of streamflow. Glacier melt particularly supplies the river in summer.

2.2. The glacier-enhanced SWAT model

Soil Water Assessment Tool (SWAT, Arnold and Fohrer, 2005) is a continuous time, distributed watershed model using physically based algorithms designed to simulate most of the hydrological processes. It has been widely used around the world and successfully applied in climatic, land cover and land use, and management practices conditions (Spruill et al., 2000; Chu et al., 2004; Gassman et al., 2007; Liu et al., 2010; Ficklin et al., 2013).

The SWAT model delineates a basin into a number of subbasins. Heterogeneities exist within a subbasin with respect to soil and land use and land cover. To resolve these heterogeneities, a practical alternative is to represent the effects of these heterogeneities statistically by use of the hydrologic response unit (HRU) (Leavesley et al., 1983). The HRUs are lumped land areas within the subbasin that are comprised of unique land cover, soil, and slope. Hydrologic simulation is first performed with regard to each HRU, and then routed through the tributary of each subbasin and the main channel of the basin to the outlet.

SWAT simulates the entire hydrologic processes within a HRU included plant growth, energy balance, soil evaporation and plant transpiration, water body evaporation, snow pack and snow melt, runoff generation and infiltration. Snow pack depletion is accounted for by using the depletion curves. Snow melt is estimated using the conventional temperature-index or degree-day approach (Neitsch et al., 2005). Baseflow was simulated by a linear two-reservoir approach (Luo et al., 2012; Gan and Luo, 2013). However, glacier processes are not presently available. Luo et al. (2013) developed a glacier hydrology module and incorporated it into the code of SWAT 2005 to simulate glacier hydrology in alpine catchments.

The glacier module takes a single glacier as a HRU. Each glacier HRU is divided into elevation bands. Mass balance of glacier HRU is simulated by calculating mass accumulation, melt and evaporation within each band. A degree day approach is used to calculate the glacier melt. The glacier mass balance is calculated on basis of that of the bands. A volume–area scaling relation is used to derive the area change of the glacier. The runoff generated from glacier melt is routed through the tributaries and channel to the catchment outlet. Detailed description to the glacier-enhanced model can be found in Luo et al. (2013). However, there is a lack that an increase in number of glaciers due to disintegration of large compound valley glaciers into a number of simple valley and cirque glaciers is not considered in this simulation.