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Hydrologic response of a high altitude glacierized basin in the central Tibetan Plateau

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ABSTRACT

Hydrologic cycles of most high altitude glacierized watersheds in the Tibetan Plateau are not closely monitored due to their inaccessibility. Understanding the hydrologic cycle in such a basin may provide insight into the role climate plays on changes in glacier mass. Thus, hydrologic simulations with a physical perspective in the Tibetan glacierized watershed are of great significance. A high altitude glacierized basin in the central Tibetan Plateau, Qugaqie basin, was investigated with an energy-balance based glacier-melt model and the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model. With these two models, glacier mass balance was estimated and basin runoff from glaciers was simulated at a daily time step. Results from the simulation period (October 1, 2006–September 30, 2011) demonstrated that the glaciers experienced a large negative surface mass balance with the cumulative value of −300 cm w.e.. In other words, up to 13.93×10^6 m^3 water volume was melting out from the glaciers during these five years. In the 2007/08 year, however, the glaciers experienced a surplus mass balance because of the low air temperature and increased precipitation in the summer season. Infiltration, evapotranspiration (ET), and overland flow were also calculated using the GSSHA model. Results showed that precipitation, the main water source, contributed roughly 95% to the total mass gain of the annual water balance in the Qugaqie basin during the study period, while the glacial runoff (snow/ice melting) contributed 5% water balance. In the water loss, 17% of annual water volume was consumed by the ET process. As a result, the remaining water volume (83%) converted to the basin river flow to the Lake Nam Co. In the summertime, the glacial runoff accounted for 15% of the total basin runoff volume, while this contribution increased in the upstream portion to 46% due to a large percentage of glacierized area. The analysis showed that the glacial runoff contributions to the total river flow decrease significantly due to the decreased air temperature in the summer of 2008. In general, the integrated model produced acceptable estimations of hydrologic response in this high altitude glacierized basin, which is jointly fed by precipitation and glacial runoff. This study suggests that, a process-based model for glacierized basins can provide a reasonable simulation of hydrologic response and further enhance our understanding of this high altitude region in the Tibetan Plateau.

1. Introduction

The Tibetan Plateau (TP) has abundant glacier resources, which feed many major rivers and lakes (e.g. the Brahmaputra, Ganges, Indus, Yangtze, and Yellow Rivers, and Lake Nam Co). Quantifying melt contributions from these glaciers is a difficult task due to the lack of field data (e.g. hydrometeorological). There are few mathematical models which can provide reasonably good descriptions of hydrologic processes of glacier melt in this region. Glacier melt modeling typically falls into two categories: temperature index and energy-balance techniques (Hock, 2005). The degree-day factor, in temperature index models, has a large range of variation: from two to 20 mm day^{-1} $°C^{-1}$, and no clear regional pattern has been found to date (Hock, 2003, 2005). For energy-balance models, mass balance monitoring and more detailed climate data are needed for calibration. However, most glaciers in the TP lack long-term continuous data.

Recently, researchers have started collecting field data on glacier mass balance and hydrometeorology in the western Nyainqêntanglha Range in the central TP. A recent glacier inventory based on remote sensing indicates that the glaciers in the region are retreating (Bolch et al., 2010). Based on the observed glacier mass balance data, some studies have been conducted for better understanding the regional glacier surface energy and mass balance (Mölg et al., 2012; Yu et al., 2013; Zhang et al., 2013; Mölg et al., 2014). Obviously, glacier melt-runoff plays significant roles in sustaining seasonal river flows in this region.

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Thus, a hydrologic model combined with a glacier melt component would provide valuable information at the watershed level and with regard to streamflow contributions. There have been some attempts on the glacierized basins of the TP in this direction, e.g., Krause et al. (2010), Gao et al. (2011) and Immerzeel et al. (2012). For the understanding of the major hydrologic processes such as evapotranspiration (ET), surface and subsurface flows, there are many hydrologic models that are currently in use, e.g. Xinanjiang (Zhao, 1992), Arno (Todini, 1996), TOPographic Kinematic APproximation and Integration (TOPKAPI) (Liu and Todini, 2002) and Gridded Surface Subsurface Hydrologic Analysis (GSSHA) (Downer and Ogden, 2004). Among these, process-based distributed hydrologic models have recently received much attention (Khakbaz et al., 2012). Most of the currently implemented distributed models do not consider the glacier-melt process, or even if they do, they greatly simplify the actual melting process. However, in higher elevation areas, snowfall accumulation and glacier retreat effects can dominate the timing of runoff and streamflow. Some hydrologic models have incorporated the temperature index approach for snow and ice melting (Krause et al., 2010; Ragettli and Pellicciotti, 2012). One of the few detailed hydrologic studies that have been conducted in glacierized basins of the TP is that of Krause et al. (2010). They modeled the basin of the Lake Nam Co using a spatially distributed model which was forced by a down-scaled ECHAM5 data set, and the glacier-melt was projected by using the degree–day method. In addition, Gao et al. (2011) applied a hydrologic model J2000 coupling a temperature index glacier-melt method in a glacierized subbasin of Lake Nam Co. However, no previous studies have made use of spatially distributed hydrologic model coupled with energy-balance based glacier-melt model to investigate the basin-wide hydrologic response and no study has explicitly considered glacier contribution to total streamflow from this physical perspective.

In this study, we attempt to develop such an integrated energy-balance based glacier-melt and surface distributed hydrologic model for a glacier-covered basin in the TP. The GSSHA model (Downer and Ogden, 2004) was revised by adding an energy-balance based glacier-melt module, and applied to a high altitude glacierized basin in the western edge of the Nyainqêntanglha Range. The Qugaqie basin is partially glacier-covered, with a median altitude of 5429 meters (m) above sea level (a.s.l.). Specifically, the hydrologic response and glacier contribution to total streamflow were examined in the Qugaqie basin in the central TP. Application of the modified GSSHA at this study area allows the integration of the glacier-melt model and GSSHA to be examined in the high altitude cold regions of the TP. The integrated model can explore the complex hydrologic response from the physical perspective that is different from those lumped models with simple representatives of glacier-melt and hydrologic processes.

2. Study area and data

2.1. Qugaqie basin

The study basin, named after the Qugaqie River, covers an area of 59.6 km^2 with 8.4% glacierized coverage at the western edge of the Nyainqêntanglha Range in the central TP (Fig. 1). The Qugaqie River (length 15.4 km, average channel bed slope > 0.04) drains into Lake Nam Co, which is the second largest saline lake in the TP. In the upstream drainage area, Zhadang Glacier, to the southeast, covers an area of 1.9 km^2 and spans an elevation ranging from 5518 to 6042 m a.s.l. Two other glaciers are the Genpu Glacier to the south (2.6 km^2, 5542–6081 m a.s.l.) and the Chuxiguo Glacier to the west (0.5 km^2, 5517–5887 m a.s.l.). Three automatic weather stations (AWSs) are located near the upstream section of the Qugaqie River (ZD1, 5400 m a.s.l., ZD2, 5800 m a.s.l. and ZD3, 5665 m a.s.l.) (Kang et al., 2009; Maussion et al., 2011). A rain gauge at the glacier terminus (5580 m a.s.l.) has been operational since May 21, 2010 (Zhang et al., 2013). Stream stage is measured in the upstream and downstream sections of the river (S1, 5364 m a.s.l. and S2, 4780 m a.s.l.) with controlled drainage areas of 7.4 and 57.6 km^2, respectively. Measured water stages can be used for calculating streamflow. S3 represents the basin outlet. This area has a semi-arid subarctic climate with an average annual precipitation of 415 mm measured at station NAMOR (Nam Co station for Multisphere Observation and Research, 30°46.44′N, 90°59.31′E, 4730 m a.s.l., 50 km north-east of the basin) from 2006 to 2008 (Gao, 2011). The average annual air temperature and relative humidity at NAMOR are 0 °C and 52%, respectively. The region is under a complex influence of both the continental climate of Central Asia and the Indian Monsoon system, which leads to a climate characterized by a strong seasonality in both temperature and precipitation. Little precipitation occurs during winter, while about 90% of the mean annual precipitation is measured from June to September; the ablation season is short (June to mid-August) but intense (Mölg et al., 2012; Zhang et al., 2013). The three continental type glaciers, located in this continental summer precipitation climate, are called summer accumulation type glaciers as the maximum of annual accumulation and ablation occurs simultaneously.

The study area mainly consists of periglacial, morainic, and aeolian landforms (Kang, 2011). The periglacial landform, which is developed due to the effects of frost weather and gravity, covers about 60% land surface of the Qugaqie basin. The morainic landform dominates the glacial peripheral area where freezing and thawing influences are very strong in the downriver area. The aeolian landform mainly developed with the increase of the newly exposed surface after glacier retreat, consisting of fine and medium sands, are found at the lake coast (close to the basin outlet). In general, soils in this area are alpine meadow soil up to 20 cm depth and silty soil below 20 cm depth (Tian et al., 2009). The lower altitude limit of high plateau permafrost is 5300 m a.s.l., while the remaining area in the study basin is seasonal frozen soil (Tian et al., 2009). According to the 1-km Harmonized World Soil Database (Nachtergaele et al., 2008), soil types in this basin are sandy loam and loam (Fig. 2). Land cover is composed of bare ground, grassland, wetland, water body and glacier (Ran et al., 2009; Gao et al., 2011). Wetlands exist along the mainstem of the river, where the proportion of vegetation coverage is >70%, consisting of plants such as hassock, meadow and shrub (Tian et al., 2009). As for the geology of this region, much of it is known only at a cursory or exploratory level due to insufficient data. The Qugaqie basin mainly consists of Quaternary sediments, limestone, arenite and orthogneiss (Kidd et al., 1988).

2.2. Forcing data

The study period in this paper is from October 1, 2005 to September 30, 2011. Daily precipitation at ZD1; air temperature, global radiation, and wind speed at both ZD1 and ZD2 (May 18–October 17, 2007 and May 18–October 16, 2008); and the streamflow data at S1 and S2 (for the summer periods of 2007–2008) were collected in this study (Kang et al., 2009; Zhou et al., 2010). In addition, the ZD3 station which locates in the ablation zone has been operational since 2009. At this site, daily air temperature, wind speed, relative humidity, global radiation, surface temperature, and surface albedo data (from October 4, 2009 to September 15, 2011) were also available (Zhang et al., 2013). From the rain gauge at the glacier terminus, more than one year precipitation observation (May 21, 2010–September 15, 2011) was collected. In addition, climate data (air temperature, relative humidity and wind speed) at the NAMOR station were also collected for the whole study period from the Third Pole Environmental (TPE) Database (http://www.tpedatabase.cn). In the Zhadang Glacier, annual mass balance of five balance years (from 2005/06 to 2009/10) and seasonal/monthly mass balance of the 2006/07 and 2007/08 balance years were also available. In this study basin, mass balance values were calculated from observations of ablation stake records, accumulated snow depth, and snow/ice density by the local group. The mass balance data used in this study were from the TPE Database and Kang et al. (2009).