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Inclusion of glacier processes for distributed hydrological modeling at basin scale with application to a watershed in Tianshan Mountains, northwest China

Yi Luo [a,b,*], Jeff Arnold [c], Shiyin Liu [d], Xiuying Wang [e], Xi Chen [a]

[a] State Key Laboratory of Oasis and Desert Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences (CAS), 80031 Urumqi, China
[b] Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, CAS, 100101 Beijing, China
[c] Grassland Soil and Water Research Laboratory, 808 E. Blackland Rd., Temple, TX 76502, USA
[d] Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, 730000 Lanzhou, China
[e] Blackland Research and Extension Center, 720 E. Blackland Rd., Temple, TX 76502, USA

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SUMMARY

In this paper we proposed: (1) an algorithm of glacier melt, sublimation/evaporation, accumulation, mass balance and retreat; (2) a dynamic Hydrological Response Unit approach for incorporating the algorithm into the Soil and Water Assessment Tool (SWAT) model; and (3) simulated the transient glacier retreat and its impacts on streamflow at basin scale. Application of the enhanced SWAT model in the Manas River Basin (MRB) in the Tianshan Mountains in northwest China, shows that the approach is viable as evidenced by a Nash–Sutcliff efficiency of 0.65 and a percent bias of −3.7% for daily streamflow and water balance, respectively. The results indicate that the glacier area decreased by 11% during the simulation period from 1961 to 1999, which is within the range of records from other glaciers. On average, glacier melt contributed 25% to streamflow, although glacier area accounts for only 14% of the catchment drainage area in the MRB. Glacier melt was positively correlated to temperature change ($R^2 = 0.70$, statistical significance $P < 0.001$) and negatively correlated to precipitation ($R^2 = 0.20$, statistical significance $P < 0.005$). The results indicate that glacier melt was more sensitive to temperature change than to precipitation change, implying that modeling the effects of climate change with increasing temperatures and decreasing precipitation should be further studied.

1. Introduction

Many of the large river systems worldwide originate from mountains where a significant quantity of fresh water is stored in the form of snow and glaciers. Glaciers are sensitive to global climatic changes and are the most visible indicators of global change (Fischer, 2010). The worldwide general retreat of glaciers during recent decades (Dyurgerov, 2002) has many implications on all spatial scales, ranging from global effects on sea level and ocean systems (Dyurgerov and Carter, 2004) to regional and local effects on catchment hydrology (Hock et al., 2005). Climate warming will cause accelerated glacier retreat, which 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. Hydrological investigations of glaciers are thus necessary for these watersheds.

Glaciers have been intensively studied through on-site observation and modeling at the glacier scale (Xiao et al., 2008) and remote sensing at the regional scale (Aizen et al., 2007a,b; 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. Hydrological models have been increasingly used to investigate glacier effects to streamflow and the impacts imposed by the climate change.

Conceptual precipitation–runoff models have been used to estimate the effect of climate change on streamflow in glacier-fed basins (Hagg et al., 2007; Akhtar et al., 2008; Konz and Seibert, 2010). However, many of these studies did not adjust the glacier cover to account for transient glacier response to the imposed climatic changes (Singh and Bengtsson, 2005), which limits the temporal scale over which the results could be applied (Stahl et al., 2008). Hagg et al. (2006) and Akhtar et al. (2008) examined the effect of an assumed reduction in glacier area in Central Asia and Hindukush–Karakorum–Himalaya region, respectively; but they did not simulate the transient streamflow response associated with changing glacier area. Horton et al. (2006) updated the glacier area for simulation of future conditions assuming a constant accumulation–area ratio, but also did not address transient responses. Rees and Collins (2006) assumed simplified glacier geometry and removed elevation bands as ice thickness depleted to simulate the transient response associated with glacier retreat.

* Corresponding author. Tel./fax: +86 10 64888920.
E-mail address: luoyi.cas@hotmail.com (Y. Luo).

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Glaciologists have used two main approaches to simulate the transient response of glaciers to climate changes (Stahl et al., 2008). One of the approaches is to use a specified relation between glacier volume and glacier area, which was originally derived empirically (Aizen et al., 2007a). This approach involves using the volume–area scaling relation to estimate future changes in glacier area that would be associated with changes in glacier volume based on simulated future mass balance. Stahl et al. (2008) used a semi-distributed conceptual hydrological model coupled with a glacier response model, HBV–EC (Hamilton et al., 2000), to investigate the sensitivity of streamflow to changes in climate and glacier cover for the Bridge River basin, British Columbia.

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. The Soil Water Assessment Tool (SWAT, Arnold and Fohrer, 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 (e.g., Fontaine et al., 2002; Wang and Melesse, 2005; Zhang et al., 2008).

The objectives of this study include: (1) the development of a glacier processes module for a physically-based distributed hydrological model (SWAT), such that the glacier processes can be simulated in a distributed way at the watershed scale; (2) an evaluation of the glacier module performance in a glaciered watershed in the Tianshan Mountains in northwest China; and (3) a discussion about the glacier-melt-induced streamflow process that is related to the precipitation and temperature and its implications in projecting the climate change impacts.

2. Methods and data

2.1. Description of the SWAT model

SWAT simulates a number of different physical processes at a watershed scale. For modeling purposes, a watershed is partitioned into a number of subbasins. By partitioning the watershed into subbasins, the user is able to reference different areas of the watershed to one another spatially. To account for spatial heterogeneities within subbasins, HRUs lump land areas within the subbasin that are comprised of unique land cover, soil, and management combinations. Water balance is the driving force behind all processes in the watershed. Simulation of the hydrology at a watershed scale can be separated into two major divisions. The first division is the land phase of the hydrologic cycle. The land phase of the hydrologic cycle controls the amount of water to the main channel in each subbasin. The second division is the routing phase during which water moves through tributaries and channels to the outlet.

During the land phase of the hydrologic cycling, plant growth, energy balance, soil evaporation and plant transpiration, water body evaporation, snow pack and snow melt, runoff generation and infiltration are simulated. Soil water dynamics is the core process that couples processes of climate, land surface, aquifer storages, and management practices.

Precipitation falls as snow when the air temperature goes below the snowfall temperature. Snow melt is estimated using the conventional temperature-index or degree-day approach. Snow pack depletion is accounted for by using the depletion curves. Glacier processes are not presently available.

Land phase processes are performed primarily on the basis of the HRUs. SWAT assumes that the land cover area for a HRU remains unchanged during the simulation. To simulate the glacier processes on the platform of SWAT and tackle the transient glacier retreat issue, a dynamic glacier area approach in a HRU is proposed, which is detailed below.

2.2. Descriptions of the glacier module

2.2.1. Glacier mass balance

Scientists often view glaciers as systems that are influenced by a number of inputs and outputs. The main inputs to the glacial system are water in the form of snow. Water leaves the glacial system when ice is converted into water or vapor. To understand why glaciers expand and shrink, advance and retreat, a type of modeling referred to as "glacier mass balance" is often used. The mass balance of a glacier involves two main components: (1) accumulation of snow in the glacier's zone of accumulation; and (2) the ablation of ice in the glacier's zone of ablation. The zone of accumulation resides in the upper reaches of the glacier where yearly additions of snow exceed losses due to melting, evaporation, and sublimation. The surface of this zone is covered by snow throughout the year. Below the zone of accumulation is the zone of ablation. In this zone, the losses of snow and ice from melting, evaporation, and sublimation are greater than the additions of snow. The line that separates these two areas is called the firn limit or snow line.

In the model, the glacier mass balance can be written as

$$\frac{dW_g}{dt} = -(1-f)M - S + F \quad (1)$$

where W_g is the depth of water equivalent of ice in mm H_2O, M is melt rate of ice in mm H_2O day^{-1}, f is ratio for melt water refreezing; S is sublimation rate of ice in mm H_2O day^{-1}, F is glacier accumulation rate in mm H_2O day^{-1}, and t is the time step in day.

It has been noted that a substantial quantity of infiltrated melt water may be refrozen and remain in a cold-based glacier (Munro, 2005), which is the case for glaciers in the Tianshan Mountains. A value of 0.2 for f was determined at an observatory glacier, Qiyi Glacier, in the Qilian Mountains in northwest China (Jiang et al., 2010).

2.2.2. Melt rate

Melt modeling is a crucial element in any attempt to predict runoff from snow-covered or glacierized areas, as well as to assess changes in the cryosphere associated with climate change. Temperature index or degree-day models rest upon a claimed relationship between snow/ice melt and air temperature, which is usually expressed in the form of positive temperatures. Empirically estimated temperature index models and similarly simplified energy based approaches display a physically based nature and are commonly used to evaluate snow and ice melt and runoff, with acceptable results.

The classical degree-day model relates ice or snow melt (mm) to air temperature on a daily basis (Hock et al., 2005):

$$M = \begin{cases} d \cdot (T_{av} - T_{gmlt}), & \text{when } T_{av} > T_{gmlt} \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

where d is the degree-day factor for ice melt in mm day^{-1} °C, T_{av} is daily average air temperature in °C, T_{gmlt} is the threshold value for ice melt in °C. In the SWAT model, the degree-day factor for snow melt is calculated by a sinusoidal function to represent its seasonal change pattern (Neitsch et al., 2005). Some snow/ice melt–runoff models, e.g., HBV–ETH model, determines the snow/ice melt factor