Applied Geography 55 (2014) 30–38

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Sensitivity of the Snowmelt Runoff Model to snow covered area and temperature inputs

Jonathan Kult [a], Woonsup Choi [a], Jinmu Choi [b,*]

[a] Department of Geography, University of Wisconsin-Milwaukee, P.O. Box 413, Milwaukee, WI 53201-0413, USA
[b] Department of Geography, Kyung Hee University, 26 Kyunghee-daero, Dongdaemun-gu, Seoul, 130-701, Republic of Korea

ARTICLE INFO

Article history:
Available online

Keywords:
Snowmelt Runoff Model
Temperature lapse rate
Snowmelt runoff
Geographic information systems
Remote sensing

ABSTRACT

Snowpack is an important source of freshwater. Snowmelt runoff models provide a means to predict the timing and magnitude of spring snowmelt. This study assessed the sensitivity of the conceptual, degree-day Snowmelt Runoff Model (SRM) to snow covered area and temperature inputs in a small mountainous catchment in Utah, USA. It was found that snow cover products from the Moderate Resolution Imaging Spectroradiometer (MODIS) underestimate snow covered area during the second half of the melt season, leading to inadequate modeling of spring snowmelt with SRM (Nash-Sutcliffe Efficiency = 0.59; bias of −26.9%). Incorporation of ancillary snow covered area information provided by Landsat ETM+ imagery greatly improved streamflow simulations (Nash-Sutcliffe Efficiency = 0.92; bias of −0.01%). For the temperature input, SRM appeared more sensitive to the elevation and location of the temperature reference station than to the lapse rate scenario used to extrapolate temperatures throughout the watershed. These findings will be useful for snowmelt runoff research and water resource management.

Introduction

Snowmelt from mountain snowpacks provides an important source of freshwater for human consumption, business, and agriculture in the western United States and in many regions worldwide. For example, in the semiarid lands within the Colorado River basin, seasonal runoff patterns are dominated by winter snow accumulation and spring melt (Christensen, Wood, Voisin, Lettenmaier, & Palmer, 2004). In this region, mountain snowpack functions as an ideal water reservoir system, storing winter precipitation as snow and then gradually releasing it to surrounding lowlands during the spring and summer when precipitation is minimal. Many hydrologic models, both physically-based and conceptual, have been developed to predict the timing and magnitude of spring snowmelt (Singh and Frevert, 2006; WMO, 1986).

The idea of snowmelt runoff modeling began with manual snow core sampling along snow courses in the Lake Tahoe region of the Sierra Nevada Mountains in the early 20th century (NRCS, 2008). Snow courses were expanded throughout the 1930s, and snowpack telemetry (SNOTEL) stations developed during the 1960s. In recent decades, a great deal of research has combined remotely sensed snow cover data with either physical or conceptual hydrologic models in order to understand the relationships between snow cover, snowmelt, and basin discharge. Snowmelt runoff models can be lumped or distributed, conceptual or physically-based, and can employ either degree-day or energy balance approaches to simulate the generation of snowmelt over time (Leavesley, 1989). Frequently implemented snowmelt runoff models include the physically-based Utah Energy Balance Snow Accumulation and Melt Model (Tarboton & Luce, 1996), the mass and energy balance Snow Thermal Model (Jordan, 1991), and the conceptual Snowmelt Runoff Model (SRM: Martinec, Rango, & Roberts, 2008).

Many techniques have been developed to estimate snow covered area from remote sensing imagery (Rees, 2006). Spatial and temporal requirements of imagery for snowmelt runoff modeling are a function of watershed size and the rate of snowpack ablation. Numerous recent SRM applications have had success using data from the Moderate Resolution Imaging Spectroradiometer (MODIS) (e.g. Butt & Bilal, 2011; Georgievsky, 2009; Immerzeel, Droogers, de Jong, & Bierkens, 2009; Qiu, You, Qiao, & Peng, 2013; Sirguey, Mathieu, Arnaud, & Fitzharris, 2009; Tahir, Chevallier, Arnaud, Neppel, & Ahmad, 2011; Tekeli et al., 2005). For these studies, conducted in watersheds between 500 and 27,000 km^2 in area, the 500-m resolution of MODIS was sufficient for estimating snow

* Corresponding author.
E-mail addresses: jmkult@uwm.edu (J. Kult), choiw@uwm.edu (W. Choi), jinmuchoi@gmail.com, cjm89@khu.ac.kr (J. Choi).

http://dx.doi.org/10.1016/j.apgeog.2014.08.011
0143-6228/

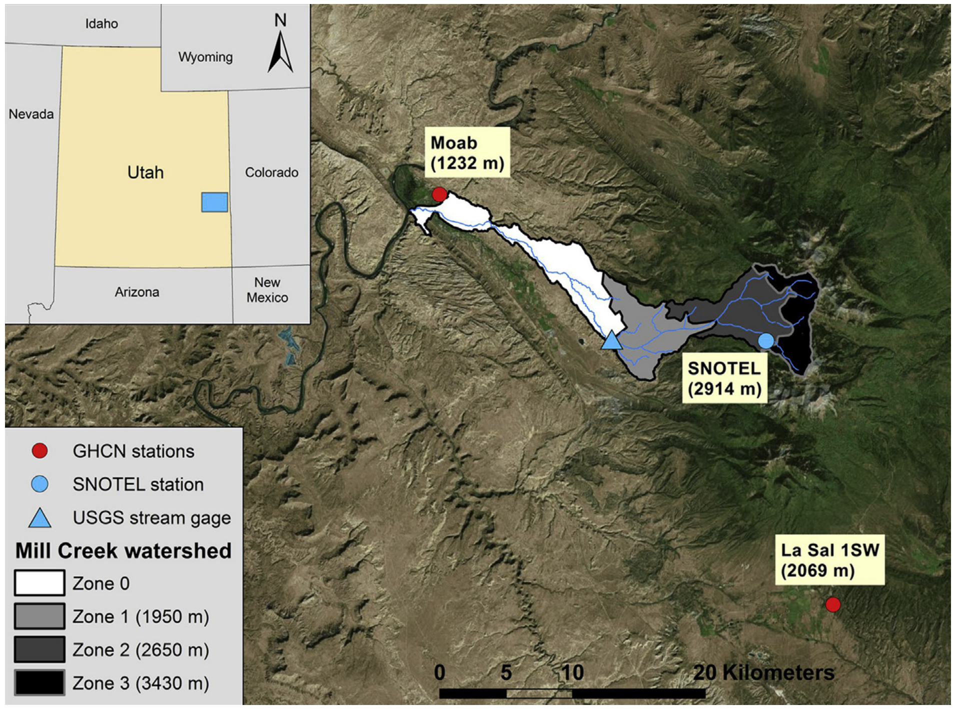

Fig. 1. Mill Creek watershed in the La Sal Mountains of Utah, with locations and elevations of temperature reference stations (circles). The mean hypsometric elevation of each altitudinal zone is given in parentheses in the legend. Zone 0 is below the USGS stream gage (triangle) and is not used in the snowmelt simulations.

covered area. For example, Tahir et al. (2011) used MODIS snow cover products (MOD10A2) with SRM to simulate discharge from glacier- and snow-fed tributaries of the Indus River covering an area of 13,733 km^2 in northern Pakistan. Similarly, Georgievsky (2009) was able to simulate streamflow for several catchments in the Kuban River basin of the western Caucasus Mountains with an average coefficient of determination of 0.84 over multiple accumulation and ablation periods.

The usefulness of MODIS data for determining snow covered area can be expected to decline with decreasing watershed size. Lee, Klein, and Over (2005) applied SRM with MODIS-derived snow covered area to two watersheds in the Rio Grande basin in Colorado and New Mexico, observing good results in the larger (3369 km^2) watershed (bias of 2.6%), but poorer results in the smaller (995 km^2) watershed (bias of −33.1%). The effectiveness of MODIS data for detecting snow in a small (76 km^2) watershed is tested further in this study. Higher resolution (30 m) Landsat ETM+ imagery is used to validate the MODIS-derived snow covered area, as well as modify the MODIS values to improve SRM accuracy.

In addition to snow covered area, the lapse rate parameter is an important component of SRM, particularly in areas of high relief. In SRM, the lapse rate parameter distributes daily average temperatures from a reference station to the mean hypsometric elevation of each zone. Lapse rates indicate the decrease in temperature with elevation in the troposphere, with a commonly-cited global average of 6.5 °C/km. However, lapse rates can be highly variable across space and time (Richard & Gratton, 2001; Rolland, 2003). Continentality, land cover, topography, synoptic meteorological conditions, local climate, and proximity to urban areas can all modify localized thermal structure (Jochner, Sparks, Estrella, & Menzel, 2012; Pape, Wundram, & Loeffler, 2009). Over large spatial domains, this variability may not noticeably affect SRM simulations, and a single long-term average lapse rate may suffice (e.g. Butt & Bilal, 2011; Tahir et al., 2011). For smaller areas, however, the variability of lapse rates in space and time can be expected to have a greater impact on degree-day snowmelt runoff models such as SRM. For example, in the Mill Creek watershed in southeastern Utah, land cover and local climate change rapidly over an area of high relief and complex topography.

The main objectives of this study were (a) to evaluate the spatial and temporal resolutions of remote sensing imagery required for accurate estimation of snow covered area in a small alpine watershed, and (b) to assess the sensitivity of a simple snowmelt runoff model to temperature input in a region with complex temperature-elevation gradients. To accomplish this, a variety of lapse rate scenarios and reference temperature stations were employed for modeling snowmelt in the Mill Creek watershed with SRM. The results will be useful for water resource managers seeking to estimate snowmelt runoff using readily available climate datasets and remote sensing imagery.

The Mill Creek watershed study area is described in Study area Section. Data and methods Section provides the data and methods used to implement SRM, as well as details related to model calibration and performance assessment. Results are presented in Results and discussion Section, along with a discussion of their importance for snowmelt runoff modeling.

Study area

The Mill Creek watershed is located in the La Sal Mountains of southeastern Utah, draining west into Spanish Valley and the town of Moab, and on to the Colorado River (Fig. 1). The U.S. Geological Survey (USGS) gaging station used in this study is located approximately 15 km southeast of Moab. The entire watershed covers an area of 113 km^2, although the area upstream of the USGS gaging station is only 76 km^2.

At Moab, average high temperature in July is 37 °C, whereas average low temperature in January is −6.7 °C. The precipitation range is not large, between 10.4 mm in June and 29.7 mm in October. On the other hand, at La Sal 1SW, average high