Journal of Hydrology 553 (2017) 199–213

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Influence of snowpack and melt energy heterogeneity on snow cover depletion and snowmelt runoff simulation in a cold mountain environment

Chris M. DeBeer [a,*], John W. Pomeroy [b]

[a] Global Institute for Water Security, University of Saskatchewan, Saskatoon, Saskatchewan, Canada
[b] Centre for Hydrology, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

ARTICLE INFO

Article history:
Received 27 January 2017
Received in revised form 11 July 2017
Accepted 25 July 2017
Available online 29 July 2017
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Masaki Hayashi, Associate Editor

Keywords:
Mountain
Snowmelt
Snow cover depletion
Runoff
Modelling

ABSTRACT

The spatial heterogeneity of mountain snow cover and ablation is important in controlling patterns of snow cover depletion (SCD), meltwater production, and runoff, yet is not well-represented in most large-scale hydrological models and land surface schemes. Analyses were conducted in this study to examine the influence of various representations of snow cover and melt energy heterogeneity on both simulated SCD and stream discharge from a small alpine basin in the Canadian Rocky Mountains. Simulations were performed using the Cold Regions Hydrological Model (CRHM), where point-scale snowmelt computations were made using a snowpack energy balance formulation and applied to spatial frequency distributions of snow water equivalent (SWE) on individual slope-, aspect-, and landcover-based hydrological response units (HRUs) in the basin. Hydrological routines were added to represent the vertical and lateral transfers of water through the basin and channel system. From previous studies it is understood that the heterogeneity of late winter SWE is a primary control on patterns of SCD. The analyses here showed that spatial variation in applied melt energy, mainly due to differences in net radiation, has an important influence on SCD at multiple scales and basin discharge, and cannot be neglected without serious error in the prediction of these variables. A single basin SWE distribution using the basin-wide mean SWE ($\overline{\mathrm{SWE}}$) and coefficient of variation (CV; standard deviation/mean) was found to represent the fine-scale spatial heterogeneity of SWE sufficiently well. Simulations that accounted for differences in ($\overline{\mathrm{SWE}}$) among HRUs but neglected the sub-HRU heterogeneity of SWE were found to yield similar discharge results as simulations that included this heterogeneity, while SCD was poorly represented, even at the basin level. Finally, applying point-scale snowmelt computations based on a single SWE depth for each HRU (thereby neglecting spatial differences in internal snowpack energetics over the distributions) was found to yield similar SCD and discharge results as simulations that resolved internal energy differences. Spatial/internal snowpack melt energy effects are more pronounced at times earlier in spring before the main period of snowmelt and SCD, as shown in previously published work. The paper discusses the importance of these findings as they apply to the warranted complexity of snowmelt process simulation in cold mountain environments, and shows how the end-of-winter SWE distribution represents an effective means of resolving snow cover heterogeneity at multiple scales for modelling, even in steep and complex terrain.

1. Introduction

Many of the world's major river systems originate in high mountain areas where runoff from snowmelt in headwater basins represents a major, if not dominant source of flow in streams and rivers (Viviroli et al., 2011). The hydrological regime of these systems is sensitive to climatic change, especially in temperate locations where winter temperatures approach 0 °C, as even modest warming can lead to more frequent mid-winter melt events, a shift from snowfall to rainfall, increased occurrence of rain-on-snow peak flow events, earlier spring flows, and reduced late spring and summer flows (Barnett et al., 2005; Adam et al., 2009; Pomeroy et al., 2015). Indeed, many of these changes have already been observed in different mountain environments worldwide (Cayan et al., 2001; Mote et al., 2005; Stewart et al., 2005;

* Corresponding author.
E-mail address: chris.debeer@usask.ca (C.M. DeBeer).

http://dx.doi.org/10.1016/j.jhydrol.2017.07.051
0022-1694/© 2017 The Author(s). Published by Elsevier B.V.

Martin and Etchevers, 2005; Birsan et al., 2005; Hamlet et al., 2005; 2007; Hamlet and Lettenmaier, 2007; McCabe et al., 2007; Moore et al., 2007; Barnett et al., 2008; Renard et al., 2008; Stewart, 2009; Yang et al., 2002, 2003, 2007; Harder et al., 2015), posing a significant challenge for water management and decision making. This underscores the need for better understanding of past hydro-climatic changes, diagnosis of system behaviour and responses, and prediction of future changes, which requires improved modelling tools to represent snow accumulation, ablation, and runoff processes in mountain areas.

Simulating these processes in a robust and physically realistic manner is challenging, but essential for capturing process responses and interactions, and non-linear scaling behaviour (e.g., Blöschl, 1999). Mountain snow cover and surface energetics exhibit considerable spatial heterogeneity that influence the patterns of snow cover depletion (SCD) and meltwater generation, in turn controlling surface–atmosphere energy fluxes and the timing and magnitude of snowmelt runoff (Liston 1995; Essery 1997; Luce et al., 1998; Tarboton et al., 2000; Anderton et al., 2002; Marks et al., 2002; Lott and Lundquist, 2008). Fully distributed, fine-scale simulations using detailed process-based models represent a useful approach for gaining hydrological insights in well-studied research basins (e.g., Marks et al., 1999; Lehning et al., 2006; Reba et al., 2011; Kormos et al., 2014). For simulations of a recent flood in the Canadian Rockies, it was shown that inclusion of winter snow redistribution and snowmelt energy balance calculations was essential to simulations of rain-on-snow flooding (Pomeroy et al., 2016). More often, however, land surface schemes and hydrological models applied over large regions employ sub-grid process parameterizations to account for small-scale snow cover heterogeneity. Several recent snow model intercomparison studies have examined the capabilities of models of varying complexity and parameterization approaches to simulate snowpack evolution from local meteorological observations (Essery et al., 2009, 2013; Rutter and Essery, 2009; Chen et al., 2014; van den Hurk et al., 2016). Some of these have pointed, in general, to the importance of snow albedo, storage and refreezing of liquid water within the snow, and turbulent fluxes for model performance and correctly capturing land–atmosphere interactions.

Some fundamental problems or limitations commonly encountered in large-scale, coarse-resolution modelling applications include assumptions of spatially uniform snowpack energy balance and melt rates, and the use of a single unimodal frequency distribution of snow water equivalent (SWE) over vastly large computational units (Donald et al., 1995; Liston, 1999; 2004; Luce et al., 1999; Luce and Tarboton, 2004; Liston and Hiemstra, 2011; Egli et al., 2012; Helbig et al., 2015). No model includes representation at the sub-grid level of the fine-scale differences in snowpack internal energy, warming and ripening, overnight cooling and refreezing, and the associated effects on melt rates and timing, SCD, and snowmelt runoff over a heterogeneous snow cover, yet this has been shown to be important in controlling snow ablation patterns in many environments (Gray, 1974; Male and Gray, 1975; Norum et al., 1976; Marsh and Pomeroy, 1996; Fierz et al., 1997, 2003; Pohl and Marsh, 2006). It is common in mountain environments for new snowfall to occur during the melt period and restore near-complete snow cover, but only conceptual approaches exist for handling the new snowfall in large-scale models (e.g., Luce et al., 1999; Moore et al., 1999) and these are generally arbitrarily defined and site-specific. Further, over highly complex terrain there are always some parts of the landscape (i.e., cliffs and very steep areas) that remain snow-free (Blöschl et al., 1991; Kirnbauer et al., 1991; Mittaz et al., 2002), but most models assume 100% areal snow coverage beyond a certain (fixed) mean snow depth.

It has been previously shown that snow process modelling applications in mountainous environments can be improved by objectively choosing landscape-based computational units that are consistent with the primary underlying sources of spatial variability in snow accumulation and melt energy (Dornes et al., 2008a, 2008b; DeBeer and Pomeroy, 2009, 2010). The use of arbitrary coarse-resolution grids in complex terrain inappropriately combines snow accumulation and ablation process heterogeneity and causes unnecessary scaling problems (Seyfried and Wilcox, 1995; Blöschl, 1999). Dornes et al. (2008a, 2008b) demonstrated that simulations of snow cover ablation and basin runoff, when stratified by slope- and aspect-based landscape units, were greatly improved over spatially aggregated simulations in a small sub-arctic mountain basin in the Yukon Territory, Canada. DeBeer and Pomeroy (2009) showed that simulated snow covered area (SCA) was improved relative to observations in a Canadian Rocky Mountain cirque basin by considering snow cover distribution and melt energetics separately over different slope units rather than applying uniform energy to a single basin SWE distribution. DeBeer and Pomeroy (2010) took this further and examined how the variability influenced the contributing areas and locations for meltwater generation over the basin, focusing not only on differences in melt energetics and SWE distributions among different slopes, but also on spatial differences in snow mass and internal energy content over individual slopes to assess the combined effects on simulated melt timing and rate, SCD, and meltwater contributing area. The meltwater contributing area is not necessarily equal to the SCA (Marsh and Pomeroy, 1996), as has generally been assumed for snowmelt runoff models (e.g., Martinec et al., 1998). DeBeer and Pomeroy (2009, 2010) presented a framework for simulating SCD and meltwater production that is based on the theoretical lognormal distribution of SWE, requiring only the mean ($\overline{SWE}$) and the coefficient of variation (CV; standard deviation/mean), and having the advantage that it is relatively simple yet physically robust and readily transportable outside of well-studied research basins.

Here DeBeer and Pomeroy's framework is applied within a process-based hydrological model to derive the snowmelt hydrograph of a small alpine headwater basin in the Canadian Rocky Mountains. The purpose is to examine the influence of spatial representation of snow cover and melt energy heterogeneity on both simulated SCD and snowmelt runoff from the basin, and thereby provide insight on appropriate modelling strategies and complexity for such applications in cold mountain environments.

2. Study area and field observations

This study was conducted within a 1.2 km^2 alpine headwater basin—Upper Marmot Creek, within the Marmot Creek Research Basin, in the Front Ranges of the Canadian Rocky Mountains, Alberta, Canada (Fig. 1). Upper Marmot Creek Basin is centered at 50.96°N and 115.21°W. DeBeer and Pomeroy (2009, 2010), Pomeroy et al. (2016) and Fang and Pomeroy (2016) describe some physical characteristics of the Upper Marmot Creek Basin and its climatic regime, while Harder et al. (2015) describe the hydrological regime of Marmot Creek. Upper Marmot Creek Basin is a glacial cirque comprised of several distinct slopes of different orientation (north, south, and east facing), mostly covered by alpine meadow, talus, and rock outcrops. The ground is seasonally frozen and parts of the basin are underlain with glacial and post-glacial deposits that have a large storage capacity, supplying baseflow throughout much of the year (Stevenson, 1967). Treeline here occurs between about 2100 and 2300 m, where forests of spruce, fir, and larch transition into krummholz formation stands and shrub patches. There are several steep cliffs in the upper part of the basin that remain