Journal of Hydrology 388 (2010) 464–479

Contents lists available at ScienceDirect

Journal of Hydrology

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

Variability of snow water equivalent and snow energetics across a large catchment subject to Mountain Pine Beetle infestation and rapid salvage logging

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ARTICLE INFO

Article history:
Received 13 November 2009
Received in revised form 22 April 2010
Accepted 15 May 2010

This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of Günter Blöschl, Associate Editor

Keywords:
Snow
Mountain Pine Beetle
Forest hydrology
Distributed modelling
Catchment scale

SUMMARY

This study examines the effect on stand and catchment scale snow processes due to widespread forest disturbance by the Mountain Pine Beetle (MPB; *Dendroctonus ponderosae*) infestation, for the 1570 km^2 Baker Creek catchment in the B.C. interior where all healthy mature lodgepole pine (*Pinus contorta*) stands which dominated the catchment up until 2000 have since died or been salvage logged. Measurements in 2008 and 2009 indicate that this net canopy reduction has reduced peak snowpack and melt rate differences between remaining stands (including large clearcuts, younger regenerating stands and dead mature pine stands), relative to a healthy forest canopy with smaller clearcuts. The Distributed Hydrology Soil Vegetation Model (DHSVM) was calibrated and run at 200 m resolution across the catchment, and simulated snowmelt rates and snow-covered area compared relatively well to distributed satellite or ground-based measurements. Snowpack and ablation rates were 10–20% higher during the 2008 and 2009 winters than when running the model for the pre-MPB landscape in 2000 using the same input meteorological data, resulting in almost no difference in the snowcover period. A greater snowpack volume which enters the stream network faster inevitably has implications for streamflows, flood risks and water resources, and these are assessed during the next stage of this research project.

1. Introduction

A snowmelt-dominated catchment will increasingly act as a seasonal, natural flood-control mechanism when more spatially diverse combinations of elevation, slope-aspect and forest cover stagger the meltwater release over a period of several weeks or months (Hendrick et al., 1971). The risk of flooding and enhanced streamflows to society and the environment (e.g., stream morphology, water quality and fish habitat) may therefore be reaching a critical level in the Interior Plateau region of British Columbia, since small elevational and slope-aspect gradients due to the gentle rolling topography are now being superimposed on a retreating forest cover dominated by lodgepole pine (*Pinus contorta*), due to the infestation by Mountain Pine Beetle (MPB; *Dendroctonus ponderosae*) since the late-1990's. MPB causes forest cover loss both naturally, when tree death is followed typically by needle removal after 3–5 years (Mitchell and Preisler 1998) and tree blowdown after 15–20 years (Lewis and Hartley, 2006), and anthropogenically as part of subsequent salvage logging operations. Canopy removal has shown to increase ground snowcover accumulation (e.g., Winkler et al., 2005), melt rates (e.g., Boon, 2007), and reduce net evapotranspiration (Ladekarl et al., 2001); the combination of which is likely to explain the increased annual water yields, seasonal streamflows, and earlier peak flows observed from hydrograph data in other catchments with insect-related disturbances (e.g., Bethlahmy, 1975; Potts, 1984). Distributed catchment-scale data of these processes, however, remain lacking for this particular disturbance type. At a decadal timescale, the magnitude and timing of MPB hydrologic and related impacts for the B.C. Interior Plateau region may depend on whether forest managers intensify current rates of salvage logging for greater short-term economic gain, or retain more dead forest. Interannual variability will inevitably depend on the amount of precipitation (e.g. Love, 1955), but also the seasonal weather patterns that control the degree of synchronisation in spatial meltwater delivery and runoff patterns (e.g. Lundquist et al., 2004).

Physically-based, spatially-distributed forest hydrology models of sufficient complexity are able to represent the spatial and temporal interactions between topography, vegetation and meteorology, which control variations in the distributions of snow cover, soil moisture and ultimately streamflows. These models, such as the Distributed Hydrology Soil Vegetation Model (DHSVM), provide a sophisticated method to examine land use disturbances on catchment hydrology, including conventional logging (e.g., Bowling et al., 2000), forest roads (LaMarche and Lettenmaier, 1998) and fire (Lanini et al., 2009). Similar attempts with insect infestation such as the current MPB outbreak are only at a preliminary stage, since stand-level results with which to initialise model

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doi:10.1016/j.jhydrol.2010.05.031

parameter values and verify simulated mass- and energy-balances have only become available since ~2006 (e.g., Teti and Winkler, 2008; Winkler and Boon, 2009; Boon, 2009). Additionally, the algorithms used within most forest hydrology models such as DHSVM may not be suited to MPB canopies which violate many of the underlying physical assumptions. For instance, in terms of snow processes, most canopy cover in dead stands (trunks, branches, snags etc.) is orientated vertically relative to a healthy stand with more randomly orientated foliage, such that scaling relationships optimised for the latter may fail (e.g., snowfall interception efficiency as a function of Plant Area Index; Koivusalo et al., 2006). Other processes, however, may be more easily adapted (e.g., sub-canopy attenuation of short- and long-wave fluxes as a function of solar angle; Pomeroy et al., 2009). The effect on snow surface reflectance from unprecedented needle litter concentrations is unknown, and rapid salvage logging increases the potential of blowing snow processes in large clearcut areas; a process not simulated by forest hydrology models but which controls snow distribution in windy environments with short or no vegetation cover (e.g., Marks et al., 2002; Essery and Pomeroy, 2004).

This study aims to assess the spatial and temporal variability of Snow Water Equivalent across the Baker Creek catchment on the B.C. Interior Plateau, with small topographic diversity and extensive MPB-related disturbance. Stand-level measurements of SWE and various energy-balance components are used to calibrate the DHSVM model for improved simulation accuracy in representative MPB stands, and the model is run using fine-resolution (200 m) topographic and land cover data, and weather data interpolated from a network of eight automatic weather stations operating in 2008 and 2009. Simulated SWE values in individual stands and across the landscape are tested using ground-based and remotely-sensed data on snowcover properties. The snowpack variability across the current MPB landscape is then compared to the pre-MPB landscape with healthy forest cover, to determine the difference in snow accumulation and ablation rates at the catchment scale resulting from the MPB disturbance. Subsequent research will integrate the spatial and temporal snowmelt distributions resulting from this study within a transient, three-dimensional representation of surface and saturated subsurface flow (Wigmosta et al., 2002), in order to simulate the MPB effects on streamflow characteristics across the catchment. Collectively, these results will be of interest to forest and water resources managers when assessing the risk to infrastructure and other environmental variables, particularly for catchments like Baker Creek which lie towards the extreme end of topographic homogeneity and MPB-disturbance, and may therefore be of most hydrological concern.

2. DHSVM model

The original structure and equations forming the Distributed Hydrological Soil Vegetation Model (DHSVM) are described in full by Wigmosta et al. (2002), and for brevity only those processes controlling the ground snow cover accumulation and melt are summarised here.

2.1. Overview

The modelled landscape is divided into computational grid cells centered on Digital Elevation Model (DEM) data, with each cell or pixel assigned a set of parameter values describing the vegetation and soil characteristics. Vegetation may comprise of overstory vegetation (trees) which cover all or a prescribed fraction F of the pixel, whereas any understorey is assumed to cover the entire pixel. Meteorological conditions are prescribed at a specified reference height, including air temperature T_A, relative humidity RH, precipitation P, wind U and incoming short- and long-wave radiation ($K_\downarrow$ and $L_\downarrow$), of which only U, $K_\downarrow$ and $L_\downarrow$ are attenuated through the canopy. The DEM data in conjunction with specified lapse rates are used to adjust T_A and P topographically, with P partitioned into rainfall P_r and snowfall P_s using threshold values of T_A. Internal model calculations of pixel slope and azimuth angles are used to adjust $K_\downarrow$ but not $L_\downarrow$ to account explicitly for the topographic effects of slope and aspect. The model is then run hourly and generates one-dimensional energy and water balances for each pixel; aggregating these results for all pixels enables the distributions of spatial snow cover (and other hydrological variables such as soil moisture) to be determined. For clarity, common symbols used throughout the text are summarised in Table 1.

2.2. Ground snowpack model

Accumulation and melting of ground snowcover (i.e., under a canopy or in the open) is simulated using the two-layer coupled energy- and mass-balance model of Storck and Lettenmaier (1999) and Storck (2000), that explicitly accounts for the effects of topography and vegetation cover. The energy-balance components are used to simulate snowmelt, refreezing, and changes in the snowpack heat content, whereas the mass-balance components represent snow accumulation, ablation from melting or sublimation (but not wind redistribution), and water yield from the snowpack.

2.3. Canopy snow model

The canopy snow model also introduced by Storck and Lettenmaier (1999) and Storck (2000) is used to represent explicitly the combined canopy processes that govern snow interception, sublimation, mass release, and melt from the forest canopy. The change in intercepted snow amount (ΔI_s) in a certain time step t is simulated as a fixed percentage (interception efficiency I_e) of snowfall:

$$\Delta I_s = I_e \times P_s \quad (1)$$

until a maximum interception capacity (M) based on canopy density is reached:

Table 1
A list of commonly used stand, parameter and meteorological symbols used within the text, with description and units where applicable.

Code	Description	Units
CC	Clearcut stand (<7.5 year)	–
RN	Regenerating stand (7.5–15 year)	–
RG	Attacked juvenile stand (16–50 year)	–
GY	Mature dead pine stand (51+ year)	–
GN	Mature heathy pine stand (51+ year)	
Q_M	Melt energy flux (during melting)	W/m^2
Q_H	Sensible heat flux	W/m^2
Q_E	Latent heat flux	W/m^2
K_*	Net solar radiation	W/m^2
L	Net long-wave radiation	W/m^2
$K_\downarrow$	Incoming solar radiation	W/m^2
$L_\downarrow$	Incoming long-wave radiation	W/m^2
θ	Solar angle	°
τ_{pixel}	Pixel (stand) transmission coefficient	–
κ_{pixel}	Pixel (stand) extinction coefficient	–
I_e	Interception efficiency	–
PAI$_{pixel}$	Pixel (stand) PAI	m^2/m^2
F	Pixel vegetated cover	–
H	Canopy height	m
T_A	Air temperature	°C
Ts	Snow surface temperature	°C
P	Precipitation	mm
U	Wind speed	m/s
RH	Relative humidity	%
$SWE_{T/CC}$	SWE ratio (treed stand:clearcut)	–