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# Modifying SWAT with an energy balance module to simulate snowmelt for maritime regions

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ABSTRACT

Rain-on-snow events are typical in maritime climates, and they can cause serious floods and excessive losses of soils and nutrients. It is assumed that energy balance snowmelt models (EBMs) perform better in simulating these events than temperature index models (TIMs), due to their consideration of physical conditions. In this study, an energy balance snowmelt model was modified and integrated with the Soil and Water Assessment Tool (SWAT) to predict snowmelt for maritime regions. The modified EBM was tested against field measurements and simulations of the currently used TIM in SWAT for eight watersheds across Atlantic Canada. Results indicated that the EBM improved the accuracy of predicting snowmelt compared with the TIM, especially for watersheds with low forest cover, mainly due to improved simulations of rain-on-snow events. In addition, the EBM was able to provide reliable estimates of snow depths important for simulating soil temperatures during winter in Atlantic Canada.


## Software availability

Name of software: SWAT2009 (Soil and Water Assessment Tool)
Developer: USDA Agricultural Research Service (USDA-ARS)
Contact address: 808 East Blackland Road, Temple, TX 76502-6712, USA. Tel. +1 (254) 770-6502; Fax +1 (254) 770-6561; http://swat.tamu.edu/
Year first available: 2009
Hardware required: PC
Software required: Arc View 9.3 for the ARCSWAT GIS interface
Program language: FORTRAN
Program size: 8.86 MB (compiled executable)
Availability and cost: Free download at http://swat.tamu.edu/. The modules associated with the proposed revision may be downloaded from: https://figshare.com/articles/Modifying_SWAT_with_an_Energy_Balance_Module_to_Simulate_Snowmelt_for_Maritime_Region/4232411

## 1. Introduction

Snowmelt plays an important role in hydrologic processes for snow-covered basins (Zeinivand and De Smedt, 2009). Meltwater is the most important component of total water discharge during the snowmelt season (Ohmura, 2001) and has significant influences on flooding, contaminant transport, water supply, and soil erosion (Male, 1981). Knowledge of the timing of snowmelt and quantity of meltwater is crucial in assessing environmental impacts of soil erosion, nutrient leaching, and pollutant loading (Burwell et al., 1975; Harr, 1981; Johnsson and Lundin, 1991). Snowmelt occurs not only during the early spring snowmelt season as a result of increased solar radiation, but also in the pre-snowmelt season due to rain-on-snow events (USACE, 1998). Rain-on-snow is a common feature in various maritime regions, such as western United States, western Europe, and Atlantic Canada, as well as many mountainous areas in the southern hemisphere, due to warm air from oceans bringing heavy rains on snow-covered land (Cohen et al., 2015). Significant rain-on-snow events occur predominantly in northern maritime climates, covering $8.4 \times 10^6$ km$^2$ (Putkonen and Roe, 2003). Under a standard climate change scenario, a global climate

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model predicted a 40% increase in rain-on-snow influenced areas by 2080–2089 (Putkonen and Roe, 2003). Rain-on-snow plays a significant role in generating high stream flows and has greater potential to generate serious floods than does a short period of radiation-induced snowmelt (Kattelmann, 1985, 1987; Singh et al., 1997). As a result, many studies have been conducted to investigate the mechanism and characteristics of rain-on-snow induced runoff (Brunengo, 1990; DeWalle and Rango, 2008; Kattelmann, 1987; Marshall et al., 1999; Meng et al., 1995; Smith, 1974; USACE, 1998).

Physical factors controlling snowmelt have been intensively studied and documented (Anderson, 1968, 1976; DeWalle and Rango, 2008; Male, 1981; USACE, 1998). Two methods are commonly used to estimate snowmelt in hydrological models. One approach is based on simple temperature index models (TIMs) with the assumption that temperature is the major driving force of snowmelt (Ohmura, 2001); another is the energy balance approach taking into account energy exchanges at the snow-air and snow-soil interfaces and energy storage within the snowpack (Dingman, 2015). It is assumed that the energy balance model (EBM) performs better than the TIM in simulation of snowmelt, when the temperature is not the only influential factor. For instance, sensible and latent heat become substantial sources of energy leading to a significant amount of snowmelt, when a combination of warm temperature plus high humidity and wind speed prevail (Debele et al., 2010). Studies have shown that snowmelt generated during rain-on-snow events is most sensitive to turbulent energy exchanges between the air and snow surfaces (van Heeswijk et al., 1996). As a result, the TIM tends to underestimate snowmelt in the pre-snowmelt and snowmelt seasons, because it does not take into account other factors, such as wind speed.

Most watershed-scale hydrological models adopt the TIM approach because the EBM is perceived to require additional meteorological and topographic inputs (Beven et al., 1995; Fontaine et al., 2002; Haith and Shoenaker, 1987; Young et al., 1989). However, many studies have shown that the EBM could perform equivalently or even better than the TIM in snowmelt prediction without extra data requirements (Walter et al., 2005). For example, different forms of the EBM incorporated into the Soil and Water Assessment tool (SWAT) have been tested in several studies (Debele et al., 2010; Fuka et al., 2012; Walter et al., 2005; Zhang et al., 2008). Zhang et al. (2008) compared performance in simulating monthly runoff between three snowmelt models for a large mountainous watershed (a headwater watershed of Yellow River in China). The performance of the EBM was found better than that of TIM, especially when there was little observed data available for model calibration. Debele et al. (2010), in contrast, found that the EBM did not perform better than the TIM in simulating daily runoff for three different watersheds (two small watersheds in Montana in the US, and one large watershed of the Yellow River in China). Since the calibrated parameters of the EBM remained the same for the three study watersheds, the authors concluded that the EBM required calibration for different environmental conditions. Nevertheless, Walter et al. (2005) demonstrated that the EBM performed equivalently or better than the TIM in simulating the snow water equivalent in four study sites (in VT, NY, MN, and ID, USA) without calibration for individual sites. Although many tests have been conducted, none of these has focused on the performance of the EBM in rain-on-snow conditions or in maritime climates. The objectives of this study are to: (1) modify an EBM to integrate with SWAT; (2) test the performance of the EBM in simulating snowmelt, induced by rain-on-snow events, against field measurements and simulations of the TIM in SWAT for eight watersheds across Atlantic Canada; and (3) test the performance of the EBM in simulating snow depths against field measurements from two sites in Atlantic Canada.

## 2. The SWAT model

Soil and Water Assessment Tool is currently one of the most widely used hydrological models for water resource assessment and watershed management (Gassman et al., 2007; Santhi et al., 2006; Yang et al., 2009a, 2009b). It is designed to simulate hydrological processes and predict water quantity and quality as affected by land use, land management practices, and climate change (Arnold et al., 1998; Gassman et al., 2007). The model provides a flexible framework that allows for simulating the impact of a broad range of best management practices, such as those associated with the application of fertilizer and manure, cover crops, filter strips, conservation tillage, irrigation management, and flood-prevention structures (Gassman et al., 2005; Ullrich and Volk, 2009). It is a well-documented open-source model with many modifications for different research purposes (Cools et al., 2011; Green and Van Griensven, 2008; Holvoet et al., 2008; Wu et al., 2013; Wu and Liu, 2012).

The SWAT model currently uses a TIM to predict snowmelt (Fontaine et al., 2002). Specifically, snowmelt is estimated by a time related snowmelt factor, which is a function of two calibration parameters, maximum and minimum snowmelt rates; *Smfmx*, assumed to occur on December 21st in the northern hemisphere and *Smfmn*, assumed to occur on June 21st, respectively. Although the TIM takes into account the impact of seasonal variation in solar radiation, it tends to underestimate snowmelt during rain-on-snow events, which are associated with sensible and latent heat. In addition, the TIM also takes into account effects of cold content and meltwater percolation processes in snowpack by introducing a calibration parameter, i.e., snow temperature lag factor (*Timp*). The effects of unevenly distributed snow cover are accounted for by two parameters, the threshold depth of snow at 100% coverage (*SNOCOVMX*) and a fraction of this threshold depth that provides 50% coverage (*SNO50COV*). To account for orographic effects on snowmelt, SWAT allows up to ten elevation bands in each subbasin. The snow accumulation, spatial depletion, and snowmelt are calculated within each elevation band and weight-averaged in subbasins. However, the TIM of SWAT ignores other important spatial factors, such as land use, aspect, and slope (Debele et al., 2010; Dingman, 2015; Fuka et al., 2012).

## 3. Modification of SWAT

In this study, source code of SWAT2009 was modified using the Compaq Visual FORTRAN Ver. 6.6 (Compaq Computer Corporation, Houston, TX, USA) with respect to the snowmelt module. Specifically, the *snom* file in the source code was replaced with a new file named *snowmelt*, which was coded with an energy balance snowmelt module. Same as *snom*, *snowmelt* was called by the *surface* file to predict snowmelt for individual HRU's. The present version of *snowmelt* did not consider the elevation band feature. An algorithm was developed to calculate the mean aspect values of HRU's based on a digital elevation model (DEM) using ArcGIS 9.3 (Fig. 1). Specifically, an aspect raster was created using the *Aspect* tool based on the DEM. The *Zonal* tool was then used to calculate the mean aspect values based on the HRU polygon generated with the ArcSWAT interface. Then, the mean aspect values were formatted in a text file named *aspect.asp*. Finally, a new FORTRAN file named *readasp* was added to the *main* file to read the mean aspect from the *aspect.asp* for each HRU as input to the *snowmelt* file. The theory of the energy balance module and integration with SWAT are illustrated in the following section.

### *3.1. Energy balanced snowmelt module*

Sources of energy causing snowmelt include both shortwave