Understanding strengths and limitations of temperature-index snowmelt models

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Introduction

This article focuses on two fundamental approaches to seasonal snow and glacier surface melt modeling, specifically the differences between empirical (or temperature-index) and physically-based (or mass- and energy-balance) snow and ice melt models. This article is intended as a concise primer for students, practitioners, and scientists who are new to the field of snow hydrology, deal infrequently with snowmelt modeling, or need to understand the strengths and limitations of the two fundamentally different, yet commonly used, approaches to snow and ice melt modeling.

The Snowcover Energy Balance

To understand the strengths and limitations of these two different snow and ice melt simulation approaches, it is important to conceptually understand the components that comprise the snowcover energy balance. Net radiation (R_n) is comprised of net shortwave (S_n, 0.28-2.5 µm) radiation originating from the sun and reflected by the snow surface, and net longwave (L_n, 4 – 100 µm) radiation emitted by the atmosphere, topography, vegetation, and snow surface. Sensible (H) and latent (LE) heat fluxes result from gradients in air temperature and water vapor density, respectively, combined with turbulent motion of the atmosphere. Ground (G) heat flux results from the conductive heat transfer between the snowpack and ground, and advective (M) heat flux result from the addition of mass, in the form of rain or snow to an existing snowcover. Except for S_n, components of the energy balance can be either positive or negative; that is, the snowpack can gain or lose energy by each process. The net change in the energy budget of a snowcover (ΔQ) over a period of time is therefore given as the sum of all energy balance components:

$$\Delta Q = R_n + H + LE + G + M \qquad \text{Eqn. 1}$$

The accurate simulation of snowpack energetics, and hence melt dynamics, should therefore include either an explicit representation of all energy flux components separately, or an effective proxy that is a reasonable estimate of the net energy flux.

Snowcover Simulation Approaches

There are two distinct approaches to that are commonly used for snowmelt modeling; empirical and physically based. Empirical models are advantageous because they can simulate a variable of interest with relatively little data that is commonly available (e.g.

only air temperature), and require little computational power. A distinct disadvantage of empirical models is that they may not be valid outside of the range of conditions for which they were developed. Conversely, physically based or theoretical models have the distinct advantage that they *should* produce accurate estimates of a variable of interest, if both the forcing data and the equations that represent specific physical processes are accurate and well-parameterized, since they are based on fundamental physics. Physically based models have the disadvantage that they frequently require many environmental variables that may not be commonly collected, and can be computationally expensive. Despite these data requirements, where data are not available, estimation techniques may be used to derive the necessary input variables (Walter et al., 2005).

Temperature-index and accumulated degree-day snowmelt models are classic examples of empirical models, where daily snowmelt rates are estimated from air temperature measurements using a simple statistical regression with as few as 1 or 2 parameters (e.g. Hock, 2003). Near surface air temperature has been shown to be an effective predictor of snowmelt at daily and longer scales because it exerts a strong control on atmospheric longwave radiation which is a major source of energy for melt during the seasonal ablation period (Ohmura, 2001), as well as R_n and H which are which are important sources of energy for melt during the seasonal ablation period (Marks et al., 1998). Conversely, because air temperature does not represent all energy balance components, these general models are likely to fail in conditions outside of their period of calibration. For example, the common lack of correlation between air temperature and LE implies that temperature-index models are likely to fail during conditions such as rain-on-snow events. Likewise, these models may fail following events that perturb net solar radiation, like darkening of the surface following deposition of dark aerosol like dust, or in cold, high environments where shortwave radiation is high and melt can occur even at low air temperatures. While the empirical modeling approach may appear, and often is, too simplistic to accurately describe individual snowmelt events, it has successfully been used to provide reasonable estimates over long time frames. In contrast, physically based snowmelt models are particularly suitable to provide snowmelt estimates based on the specific meteorological conditions at high temporal and spatial resolutions. This approach therefore requires measurements, or estimates, of many variables and parameters including incoming shortwave and longwave radiation, air temperature, humidity, wind speed, soil temperature, snow surface albedo, and roughness length (e.g. Marks et al., 1999), and in some cases corrections for sub-canopy meteorological conditions (Marks et al., 2016).

Simulation Examples

Example 1

A simple temperature-index snowmelt model can be defined as:

$$W = \begin{cases} f_m\left(T_d - T_0\right), & T_d > T_0 \\ 0, & T_d \le T_0 \end{cases}$$

Eqn. 2

where:
W = daily snow melt (mm)
f_m = melt factor (mm day^{-1} K^{-1})
T_d = average daily air temperature (K)
T_0 = threshold melt temperature (K)

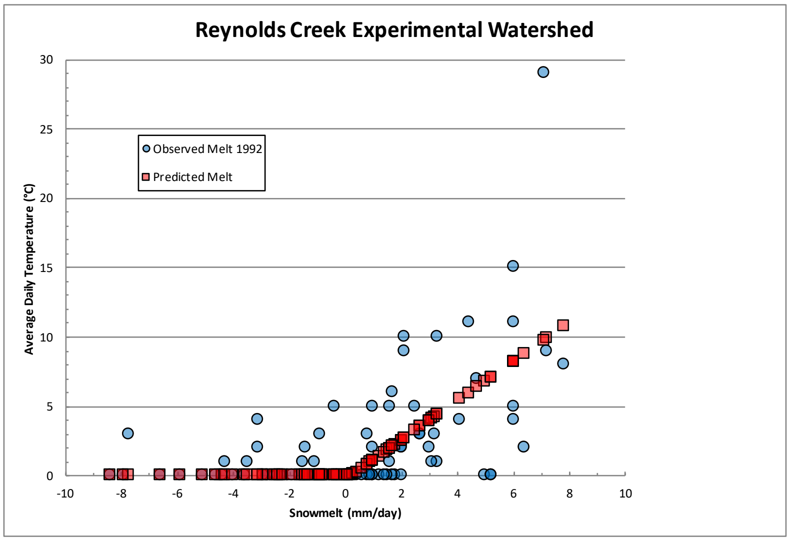

Figure 1. Model parameterization based on snowmelt data observed in 1992.

To apply the model, it must be parameterized, or calibrated, by determining f_m and T_0 using observed data. Figure 1 shows measured air temperature and snowmelt data from the Reynolds Creek Experimental Watershed for 1985 that was an approximately average snow year. The best fit line to Eqn. 2. is shown on the diagram as a solid red line. The model fit indicates that the model generally represents the amount of snowmelt for a given daily average air temperature but has considerable errors on a daily basis. To test the validity of the model, it should be assessed with an independent dataset. Figure 2 shows the simulated snowmelt for 1992, based on the parameters derived for the 1985 dataset. In this case, the model overpredicts snowmelt rates most of the time, although the generally increasing rates with air temperature are predicted, as would be expected. Depending on the specific modeling objectives, this amount of error may be deemed acceptable since the general behavior of the snowpack dynamics

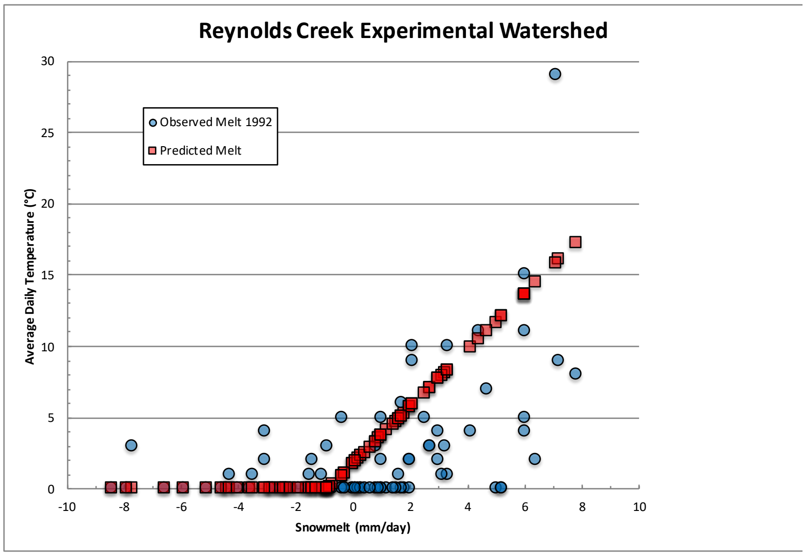

Figure 2. Predicted snowmelt for 1985 based on parameterization developed for 1992.

are reasonably represented, but it is important to note that considerable inter-annual variations in empirical melt factors can and do occur.

Example 2

As noted above, the explicit representation of all snowpack energetic components is needed to accurately represent snowpack dynamics. This is especially important for cases where melt can be partly driven by large contributions of energy fluxes that are typically less dominant, such as latent energy fluxes. An excellent example of this case is the major rain-on-snow (ROS) flood that occurred in the U.S. Pacific Northwest in February 1996. This extreme melt event is detailed in the paper by Marks et al. (1998) that also is an example of the application of a physically-based mass- and energy-balance snowmelt model to understand the spatiotemporal variation of snowmelt processes that contributed to an extreme flood event. A key feature of the event was that the snowmelt was strongly driven by turbulent (sensible and latent) energy fluxes for the first half of the event, and by radiation fluxes during the latter portion of the event as shown and discussed in Marks et al., 1998.

The parameterization for the 1992 winter at the Reynolds Creek Experimental Watershed which experiences a generally similar climate regime was used to simulate the melt dynamics for the 1996 ROS event. A comparison of the daily melt rates simulated with a physically based snowmelt model that was shown to accurately reproduce observations (Marks et al., 1998) and a temperature-index and are shown in Figure 3. In this case, the peak daily melt rate simulated by the temperature-index model was over a factor of 3 less than the amount simulated with the physically based model during the turbulent energy-driven portion of event. In contrast, the melt rates during the second half of the event that was strongly radiation-driven were much more similar. This result is not surprising, since the seasonal snowmelt at the Reynolds Creek Experimental Watershed is typically radiation-driven and well correlated with air temperature; hence the calibration derived for radiation-driven melt fortuitously represented the similar melt conditions even though the calibration was derived for a different year and site that was over 400 km away. The temperature-index model in this case is clearly not an appropriate tool to simulate the extreme ROS event which likewise is not surprising, since such events are partially driven by high vapor pressures and windspeeds which were not correlated with air temperature.

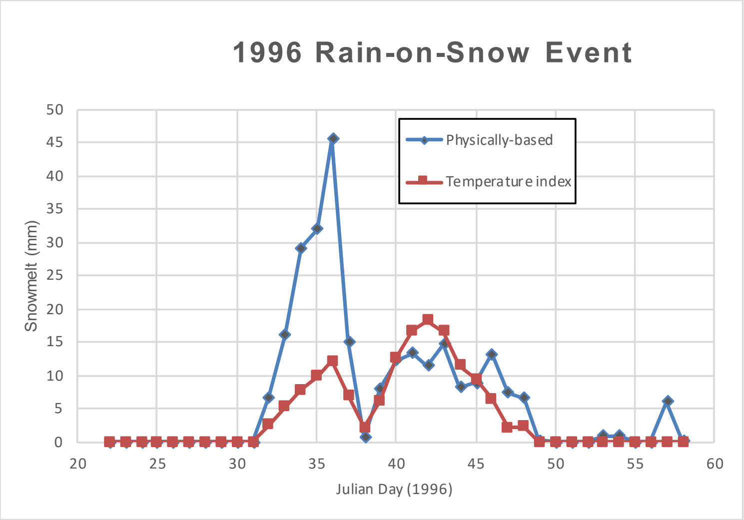

Figure 3. Comparison of a physically-based and temperature-index methods to simulate a major flood event (1st peak)

Summary

The simple examples presented above demonstrate specifically how temperature-index snowmelt models, or more generally, empirical models can effectively simulate a variable of interest when environmental conditions are similar to the calibration period. The examples likewise demonstrate how temperature-index models can be in error, or in some cases fail disastrously, when hydrometeorological conditions differ substantially from calibration periods. Similarly, even when well-performing models are spatially distributed, inaccuracies can also occur due to differing microclimatic conditions in complex terrain and within vegetation canopies, even over very small distances (Kumar et al., 2013). Temperature-index model performance can hence be potentially improved by incorporating additional parameters and/or formulations to more accurately represent net radiation (e.g. Brubaker et al., 1996) and/or serve as proxies for other energy flux components. The accuracy for diverse hydrometeorological and biophysical conditions however, will still be limited by the fact that they do not explicitly simulate the specific components that control snowmelt dynamics. The performance of physically-based models can likewise be limited where accurate and/or distributed input hydrometeorological data and parameters are not available. These limitations should not cause model users to reject particular classes of models, but to carefully and critically evaluate whether a given modeling technique is appropriate for their specific objectives.

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