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Infiltration under snow cover: Modeling approaches and predictive uncertainty

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A R T I C L E I N F O

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A B S T R A C T

Groundwater recharge from snowmelt represents a temporal redistribution of precipitation. This is extremely important because the rate and timing of snowpack drainage has substantial consequences to aquifer recharge patterns, which in turn affect groundwater availability throughout the rest of the year. The modeling methods developed to estimate drainage from a snowpack, which typically rely on temporally-dense point-measurements or temporally-limited spatially-dispersed calibration data, range in complexity from the simple degree-day method to more complex and physically-based energy balance approaches. While the gamut of snowmelt models are routinely used to aid in water resource management, a comparison of snowmelt models' predictive uncertainties had previously not been done. Therefore, we established a snowmelt model calibration dataset that is both temporally dense and represents the integrated snowmelt infiltration signal for the Vers Chez le Brandt research catchment, which functions as a rather unique natural lysimeter. We then evaluated the uncertainty associated with the degree-day, a modified degree-day and energy balance snowmelt model predictions using the null-space Monte Carlo approach. All three melt models underestimate total snowpack drainage, underestimate the rate of early and midwinter drainage and overestimate spring snowmelt rates. The actual rate of snowpack water loss is more constant over the course of the entire winter season than the snowmelt models would imply, indicating that mid-winter melt can contribute as significantly as springtime snowmelt to groundwater recharge in low alpine settings. Further, actual groundwater recharge could be between 2 and 31% greater than snowmelt models suggest, over the total winter season. This study shows that snowmelt model predictions can have considerable uncertainty, which may be reduced by the inclusion of more data that allows for the use of more complex approaches such as the energy balance method. Further, our study demonstrated that an uncertainty analysis of model predictions is easily accomplished due to the low computational demand of the models and efficient calibration software and is absolutely worth the additional investment. Lastly, development of a systematic instrumentation that evaluates the distributed, temporal evolution of snowpack drainage is vital for optimal understanding and management of cold-climate hydrologic systems.

1. Introduction

Infiltration resulting from snowmelt represents the temporal redistribution of liquid precipitation. This is extremely important because the rate and timing of snowpack drainage has substantial consequences to aquifer recharge patterns, which in turn affect groundwater availability throughout the rest of the year. In spite of its significance, direct measurement and modeling of snowpack outflow remains challenging due to the inherent limitations of monitoring instrumentation.

A number of field methods have been used to measure water drainage from snow packs (loss of snow water equivalence, SWE) including snow pillows (Archer and Stewart, 1995; Butcher and McManamon, 2011; Trujillo and Molotch, 2011), and snowmelt lysimeters (Jost et al., 2012; Kattelmann, 1989, 2000; Tekeli et al., 2005), both of which can render temporally dense point data. Extrapolation throughout a watershed of point measurements such as these is difficult due to the considerable spatial variability that exists in both snow depth and corresponding SWE and heterogeneous infiltration processes resulting from different soil types and structures across a watershed. Further, snow lysimeters have structural configurations that impose bias to the output data, such as sidewalls which are used to mitigate gains or losses from lateral

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flow within a snowpack (Haupt, 1969; Martinec, 1986). Snow pillow data can also be skewed due to snow bridging. Snow courses (Marks et al., 2001; Rice and Bales, 2010) produce a more distributed understanding of SWE, however they are highly laborious and are typically done at a coarse time resolution. Assessment of SWE evolution is further complicated when considering that spatial variability in recharge from snowmelt also results from irregularity in the amount of water released from the base of the snowpack. This ensues from complicated, preferential pathways in which melt water travels through a snowpack before percolating to the base (Kattelmann, 1989). Ultimately, snow hydrologists still must rely on limited and possibly biased field data to obtain basic liquid inputs for snowmelt modeling (DeWalle and Rango, 2008).

Numerous modeling methods have been developed to evaluate snow processes, with complexities ranging between simple index models and physically based multi-layer models which simulate a snowpack's energy balance (Etchevers et al., 2004). The ongoing debate regarding the relative merits of these modeling end members (Franz et al., 2010) has manifested in several model intercomparisons (Feng et al., 2008; Magnusson et al., 2011; Rutter et al., 2009). In its simplest form, the degree-day (DD) method of modeling snowmelt is based on the assumption that snowmelt during a time interval is proportional to positive air temperature, with the proportionality factor being the degree-day factor C (Hock, 1999), an association first presented in (Linsley, 1943). The relative contributions of the different energy balance components can shift in space and time affecting the parameter C. These changes include cloud cover, snowpack conditions, shift in season or progression of day, aspect, slope and vegetation cover (Hock, 2003). That withstanding, Ohmura (2001) was able to show the computational validity of melt rate parameterization using air temperature, and that the degree-day method "works" because temperature information is transferred to earth's surface mainly through long wave atmospheric radiation, which is by far the most important heat source for melt. Several studies have demonstrated improvements to the DD method via incorporation of solar radiation (Hock, 1999, 2003; Jost et al., 2012) and progression of day (Tobin et al., 2013). Overall though, the efficacy of this index method is usually attributed to the way in which air temperature effectively integrates the influence of a range of meteorological variables, or energy fluxes (Hodgkins et al., 2012). Acquiring air temperature data is relatively easy and inexpensive. In contrast, more rigorous energy balance models are data intensive and usually require expensive instrumentation. At a minimum, physically based assessments take into account air temperature, relative humidity, wind speed, precipitation, global and incoming long wave radiation. With this breadth of information researchers can explicitly model changes in heat storage of a snowpack and solve for snow surface temperature using a heat budget formula (Jost et al., 2012), thereby more concisely modeling accumulation and ablation. The physics behind the energy balance method has been well documented (Anderson, 1968; Cline, 1995; Herrero et al., 2009; Male and Gray, 1981; Marks and Dozier, 1992). An exhaustive overview of snow models is presented by Yang (2008) and updated regularly on the Snow Modelers Internet Platform.

Choice of modeling method is in part dictated by data and computational availability. The empirical degree-day method requires little data and is easily applied in distributed modeling efforts, but does not explicitly take into consideration climatic forcing functions operating during snow accumulation and ablation. In contrast, the computationally intensive physically-based energy balance methods offers more insight into the processes controlling the energy balance (Hodgkins et al., 2012) but requires vast amounts of data, which in consequence hinders distributed application, needed for up-scaling of point-processes. Further, uncertainty may be introduced when adopted model parameters are unknown. Thus, to some degree, these modeling end members serve different needs within the modeling community.

Most numerical models are employed to aid in environmental management, and as such the uncertainty associated with predictions made by such models must be assessed (Gallagher and Doherty, 2007; Jost et al., 2012). However, given the issues with the above-discussed field methods for collection of calibration data and the lack of data for comparison, it has been difficult to quantify 1. to what extent these branches of snowmelt models provide robust estimates of snowpack outflow and 2. how well these models perform at different time scales. That said initial attempts on this front have been made. Seibert (1997) examined parameter uncertainty within the HBV model using a Monte Carlo approach. Since ranges in parameters can provide an almost equally good model fit, Seibert concluded that model predictions should be given a probability distribution rather than a single value, which is in keeping with assertions made by Melching et al. (1990) and Beven and Binley (1992). Franz et al. (2010) applied the Bayesian Model Averaging (BMA) method to an ensemble of twelve snow models, that varied in their heat and melt algorithms, parameterization, and/or albedo estimation method, to quantify the uncertainty associated with these sources of error in the stream flow forecasting process associated with snowmelt. Here the individual models BMA predictive mean, and BMA predictive variance were evaluated. An individual snow model would often outperform the BMA predictive mean. However, observed snow water equivalent was captured within the 95% confidence intervals of the BMA variance on average 80% of the time. Franz et al. concluded that consideration of multiple snow structures would provide useful uncertainty information for probabilistic hydrologic prediction. Slater et al. (2013) investigated uncertainty surrounding SWE reconstruction, when using remote sensing, and found that errors in model forcing data were at least as important, if not more so, than image availability when reconstructing SWE. Even though a few isolated studies have look at uncertainties surround snow processes models, uncertainty assessment of model performance is not routinely quantified for recharge estimates associated with snowmelt. So far, there have been no systematic comparisons of the uncertainties arising from different snowmelt modeling approaches at either the parametric or structural levels.

This paper presents a comparison of three snow-process models' ability to predict recharge from snowmelt and a short discussion pertaining to the application of these results at different temporal scales. This study was not intended to be an exhaustive analysis of either parameters nor model structure uncertainty but rather help shed light on how well snow process models are able to predict recharge, either at the event or seasonal scale. To generate snowmelt model calibration data, we used a large and natural lysimeter as proposed by Kattelmann (2000). This researcher stated that snowmelt runoff from a larger "natural lysimeter", a well defined catchment with an easily-monitored drainage point, would provide a conceptually better basis for evaluating output from snowmelt models than the somewhat artificial sampling of snowpack outflow by lysimeters and snow pillows. In following, the karstified Vers Chez les Brant (VCB), which can be viewed as an oversized, real-world lysimeter, consists of a 1600 m^2 watershed that drains infiltrating water to a cave discharge point (VCB1) 53 m below the ground surface (Meeks and Hunkeler, 2015). We used this rather unique natural lysimeter to evaluate the uncertainty surrounding modeled snowmelt predictions. We used a simple, albeit physically based vadose zone model, to back calculate snowmelt from the observed cave drainage. The back-calculated snowmelt does not retain any of the aforementioned data biases imposed by traditional lysimeters or snow pillows, has a fine time resolution, and represents the integrated behavior of snowmelt across the VCB recharge zone. This