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Physically-based modifications to the Sacramento Soil Moisture Accounting model. Part A: Modeling the effects of frozen ground on the runoff generation process

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SUMMARY

This paper presents the first of two physically-based modifications to a widely-used and well-validated hydrologic precipitation–runoff model. Here, we modify the Sacramento Soil Moisture Accounting (SAC-SMA) model to include a physically-based representation of the effects of freezing and thawing soil on the runoff generation process. This model is called the SAC-SMA Heat Transfer model (SAC-HT). The frozen ground physics are taken from the Noah land surface model which serves as the land surface component of several National Center for Environmental Prediction (NCEP) numerical weather prediction models. SAC-HT requires a boundary condition of the soil temperature at the bottom of the soil column (a climatic annual air temperature is typically used, and parameters derived from readily available soil texture data). A noteworthy feature of SAC-HT is that the frozen ground component needs no parameter calibration.

SAC-HT was tested at 11 sites in the U.S. for soil temperature, one site in Russia for soil temperature and soil moisture, eight basins in the upper Midwest for the effects of frozen-ground on streamflow, and one location for frost depth. High correlation coefficients for simulated soil temperature at three depths at 11 stations were achieved. Multi-year simulations of soil moisture and soil temperature agreed very well at the Valdai, Russia test location. In eight basins affected by seasonally frozen soil in the upper Midwest, SAC-HT provided improved streamflow simulations compared to SAC-SMA when both models used *a priori* parameters. Further improvement was gained through calibration of the non-frozen ground *a priori* parameters. Frost depth computed by SAC-HT compared well with observed values in the Root River basin in Minnesota.

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1. Introduction and statement of problem

Heat and moisture transfer processes in the soil aeration zone play an important role in the runoff generation mechanism in regions where seasonal soil freezing/thawing occurs. Cold season processes greatly affect the transformation of snow/rain into runoff, in particular the partitioning of precipitation and snowmelt into surface runoff and infiltrating water. A particular manifestation of this problem occurs in the upper Midwest, where shallow snowpack depths and limited vegetation provide little insulation against the extremely low air temperatures that can occur. These are near optimal conditions for deep penetration of frost. In addition, soil moisture saturation is usually very high during cold season. In such cases, water held in the soil layers is frozen, impeding the percolation of liquid water to lower soil layers and creating an impervious surface layer that generates rapid runoff from subsequent rainfall events. Another aspect of this phenomenon is the rise in streamflow in the spring when the frozen soil thaws and releases water into the channel systems. Often, this can occur on non-rainy days, presenting a perplexing modeling and forecasting problem for hydrologists.

Koren et al. (1999) present examples of the effects of frozen ground and we repeat one of them here to illustrate the problem. Fig. 1 shows the effects of frozen soil in the Root River basin in Minnesota, where winter temperatures and shallow snow packs can generate frozen soil to a depth of two meters. Two distinct rainfall–runoff relationships can be seen in Fig. 1, with the same amount of rain producing much more runoff in the case of frozen ground conditions. The antecedent precipitation index at each

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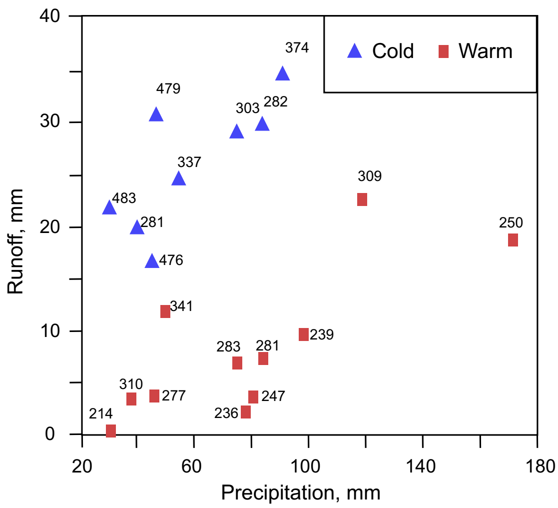

Fig. 1. Precipitation–runoff relationship during periods when soil is estimated to be frozen or unfrozen. Points are labeled with antecedent precipitation index in mm. (*Source:* Koren et al., 1999; reproduced with permission).

point is labeled. The scatter of the points in Fig. 1 show that the different rainfall–runoff regimes are not explained by antecedent precipitation index alone.

Zhang et al. (2007) reported that vast geographical regions are impacted by seasonally frozen ground. Land surface models (LSMs) and Soil Vegetation Atmosphere Transfer schemes (SVATs) used for regional scale modeling or coupled with numerical weather prediction models (NWPs) continue to be developed to handle these impacts. For example, Luo et al. (2003) reported the results of 21 LSMs that participated in Phase 2(d) of the Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS 2(d)). One of the specific foci of PILPS 2(d) was the simulation of soil moisture and temperature with and without explicit frozen soil schemes at the Valdai, Russia water balance site. Additionally, Koren et al. (1999) added a physically-based frozen ground scheme to the NOAA National Centers for Environmental Prediction (NCEP) Noah LSM (Chen et al., 1996; Ek et al., 2003) coupled to the Eta mesoscale model. Updated versions of the Noah LSM continue to be used by NCEP in their current operational suite of coupled models.

Beyond LSMs and SVATS, however, Wang et al. (2010) state that with a few exceptions (e.g., Tian et al., 2006; Mou et al., 2008; and later Zhang et al., 2012), frozen soil impacts have been largely ignored in distributed hydrologic models used for basin-scale simulations. We believe that even less attention in this regard has been paid to hydrologic models used for *operational* fine-scale streamflow simulation and forecasting. Those hydrologic models that have been modified for frozen soil have additional parameters that require calibration, which impedes their widespread use in operational forecasting (Anderson and Neuman, 1984; Emerson, 1994; Wang et al., 2010).

Our strategy in this work was to combine the structures/algorithms of two successful models: SAC-SMA and the Noah LSM. The goal was to develop a model whose complexity is commensurate with current and near-future operational meteorological forcings and application scales, and one that would not require calibration of the frozen ground component. The focus of this work is to formulate the physical interaction between conceptual storage-type states and those from a layer-type heat transfer model.

Our work illustrates a convergence of hydrologic and land surface models. First, we retain the structure of SAC-SMA as it is the precipitation/runoff model used by U.S. National Weather Service (NWS) field offices to generate river forecasts at over 4000 points nationwide. Supporting the operational use of SAC-SMA is its good performance in a wide array of validation and intercomparison studies for streamflow simulation. SAC-SMA has been tested at various time steps (e.g., 1–24 h; Reed et al., 2007) and application modes (lumped and distributed – Smith et al., 2012; Reed et al., 2004), and application scales ranging from regional (e.g., Koren, 2006; Finnerty et al., 1997) to Contiguous United States (CONUS)-wide (Xia et al., 2011a,b; Mitchell et al., 2004). SAC-SMA has proven to effectively model a range of runoff-generation mechanisms and responses. We believe our work has broader implications because, in large part, SAC-SMA has a structure common to many so-called conceptual hydrologic models (Clark et al., 2008, 2011).

Second, we select the frozen ground physics implemented in the Noah LSM (Koren et al., 1999), as this scheme has proven successful in operational numerical weather modeling (Ek et al., 2003; Mitchell et al., 2002). Hereafter, we refer to this modified version of the SAC-SMA as the SAC Heat Transfer (SAC-HT) model. This paper serves as a foundation for a companion paper on the modification of SAC-HT to consider canopy resistance for enhanced modeling of evapotranspiration (Koren et al., 2010).

The remainder of this paper is organized as follows. First we present a review of pertinent literature to place our work in context. Section 3 provides a brief discussion of the existing SAC-SMA hydrologic model. Following this, we present a thorough discussion of the physical basis of the development of an efficient mechanism of interaction between storage-type (conceptual hydrological model) states and layer-based (heat transfer model) states. The effect of frozen soil on the runoff generation is discussed in Section 3.2.1. The locations and data for testing SAC-HT are discussed in Section 4. Test results from modeled soil moisture and soil temperature at point, basin, and regional scales are described in Section 5. We complete the paper with sections containing conclusions and recommendations.

2. Literature review

2.1. Hydrologic model modification for frozen ground effects

While considerable theoretical and laboratory analysis of the physical processes of soil freezing/thawing at a point and over a small area has been available for a century, most watershed models do not consider the effect of frozen soil at all, or use empirical index-type relationships to make runoff adjustments under frozen ground conditions. Utilizing results from field experiments, Koren (1980) developed a conceptual approach based on the spatial extent of the frost-induced impermeable layer. He used a gamma distribution of frozen depth and soil moisture to estimate the fraction of impermeable area. A simplified analytical solution was used in the calculation of frozen depth. This parameterization included three empirical parameters which required calibration. Anderson and Neuman (1984) formulated a conceptual modification to SAC-SMA for frozen ground modeling. Their approach first computes a frost index based on air temperature, snow cover (if any), and empirical coefficients for thaw induced by ground heat and water entering the soil. The frost index is then used to reduce the amount of percolation and interflow. As a conceptual model, this approach required the calibration of seven parameters of the frozen ground component. Similarly, Emerson (1994) added modules to the Precipitation Runoff Modeling System (PRMS) model for daily accounting of the heat and water in the soil. This model also required parameter calibration. Wang et al. (2010) added an empirical frozen ground algorithm to a distributed biosphere hydrologic model (SiB2) and tested the resultant model