Journal of Hydrology 542 (2016) 938–952

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Estimating daily root-zone soil moisture in snow-dominated regions using an empirical soil moisture diagnostic equation

Feifei Pan [a,*], Michael Nieswiadomy [b]

[a] Department of Geography and the Environment, University of North Texas, Denton, TX 76203, USA
[b] Department of Economics, University of North Texas, Denton, TX 76203, USA

ARTICLE INFO

Article history:
Received 12 February 2016
Received in revised form 22 August 2016
Accepted 29 September 2016
Available online 1 October 2016
This manuscript was handled by A. Bardossy, Editor-in-Chief, with the assistance of Roger Moussa, Associate Editor

Keywords:
Soil moisture
Soil moisture diagnostic equation
Snowmelt
Snow water equivalent

ABSTRACT

Soil moisture in snow-dominated regions has many important applications including evapotranspiration estimation, flood forecasting, water resource and ecosystem services management, weather prediction and climate modeling, and quantification of denudation processes. A simple and robust empirical approach to estimate root-zone soil moisture in snow-dominated regions using a soil moisture diagnostic equation that incorporates snowfall and snowmelt processes is suggested and tested. A five-water-year dataset (10/1/2010–9/30/2015) of daily precipitation, air temperature, snow water equivalent and soil moistures at three depths (i.e., 5 cm, 20 cm, and 50 cm) at each of 12 Snow Telemetry (SNOTEL) sites across Utah (37.583°N–41.883°N, 110.183°W–112.9°W), is applied to test the proposed method. The first three water years are designated as the parameter-estimation period (PEP) and the last two water years are chosen as the model-testing period (MTP). Applying the estimated soil moisture loss function parameters and other empirical parameters in the soil moisture diagnostic equation in the PEP, soil moistures in three soil columns (0–5 cm, 0–20 cm, and 0–50 cm) are estimated in the MTP. The relatively accurate soil moisture estimations compared to the observations at 12 SNOTEL sites (RMSE $\leqslant$ 6.23 (%V/V), average RMSE = 4.28 (%V/V), correlation coefficient $\geqslant$0.75, average correlation coefficient =0.89, the Nash-Sutcliffe efficient coefficient Ec $\geqslant$ 0.24, average Ec = 0.72) indicate that the soil moisture diagnostic equation is capable of accurately estimating soil moisture in snow-dominated regions after the snowfall and snowmelt processes are included in the soil moisture diagnostic equation.

1. Introduction

In snow-dominated regions, soil moisture information has many important applications, e.g., (1) estimation of evaporation and evapotranspiration (e.g., Robertson and Gazis, 2006; Christensen et al., 2008; Moyes and Bowling, 2013; Wang et al., 2013; Brown et al., 2014); (2) flood forecasting; without accurate soil moisture information, floods in snow-dominated regions cannot be predicted or modeled accurately (e.g., Koster et al., 2000; Grant et al., 2004; Seyfried et al., 2005; Fassnacht et al., 2006; Mahanama et al., 2012; Rosenberg et al., 2013; Abaza et al., 2014; Broxton et al., 2014; Nied et al., 2014; Salathe et al., 2014); (3) effects of soil moisture on the snowmelt process (e.g., Tague and Peng, 2013; Kormos et al., 2014), early warm-season precipitation (Su et al., 2013), and the accuracy of snow water equivalent measurements (e.g., Ouellette et al., 2013); (4) soil moisture impact on forest wildfire activity (e.g., Westerling et al., 2006); (5) forecasting water supply in groundwater systems (e.g., Barnett et al., 2005); (6) estimation of denudation processes including landslides (e.g., Ekinci et al., 2013), weathering, erosion, and mass movement (e.g., Leisenring and Moradkhani, 2012), such as dust storms and sand storms in China (Wang et al., 2010), and soil movement in periglacial regions (Matsuoka, 2005); (7) modeling ecosystem functions (e.g., Tague et al., 2009), such as greenhouse gas releases from boreal forest soils (e.g., Ullah et al., 2009) and burning in the New Zealand snow-tussock grasslands (Yeates and Lee, 1997).

Although soil moisture information has many vital applications in snow-dominated regions, unlike precipitation and air temperature, the direct in-situ observations of soil moisture are often inadequate in those regions. An alternative approach to produce accurate soil moisture information in snow-dominated regions is to estimate soil moisture using some numerical models. However, modeling soil moisture in snow-dominated regions is challenging because of the following reasons: (1) models need to differentiate between liquid and solid precipitation in the input data of precipitation, because rain water can directly infiltrate into soil, while

* Corresponding author.
E-mail address: feifei.pan@unt.edu (F. Pan).

http://dx.doi.org/10.1016/j.jhydrol.2016.09.063
0022-1694/

snow is solid and accumulates on the ground; (2) estimates of snowmelt are required for modeling soil moisture, while snowmelt usually is not directly measured but rather is estimated from observed snow water equivalent (SWE) if SWE is measured; (3) lack of SWE measurements adds another difficulty in modeling soil moisture in snow-dominated regions, because models also have to simulate SWE; and (4) the freeze-thaw cycle occurring in high latitude or high altitude soils makes soil moisture modeling more challenging.

There are many sophisticated numerical models published in the literature that can capture soil moisture dynamics well in snow-dominated regions, e.g., GISS GCM (Lynch-Stieglitz, 1994), VIC (Liang et al., 1994, 1996), CLSM (Koster et al., 2000), CLM (e.g., Yang and Niu, 2003; Niu and Yang, 2003), and others. However, applying these sophisticated models to simulate soil moisture in snow-dominated regions is a difficult task, requiring a large amount of input data and parameters to run the models and to validate the simulated results. Furthermore, sometimes soil moisture data in snow-dominated regions are not available or difficult to obtain. To solve the problem of the scarcity of soil moisture data in snow-dominated regions, to provide initial and boundary soil moisture conditions for running some sophisticated numerical models, and to produce temporal coverage of spatially distributed soil moisture fields for verifying those models, this study aims to develop a simple and robust empirical approach to estimate daily root-zone soil moisture in snow-dominated regions using the soil moisture diagnostic equation proposed by Pan et al. (2003), Pan (2012), and Pan et al. (2015). In addition to producing soil moisture data for calibrating and validating numerical models, the method proposed in this study can also provide an efficient way to generate soil moisture data for calibrating satellite sensors and remote sensing algorithms to produce remotely sensed soil moisture products, e.g., Advanced Microwave Scanning Radiometer – Earth Observing System Sensor (AMSR-E) on the NASA Aqua satellite (Coopersmith et al., 2015a), the NASA Soil Moisture Active and Passive mission (SMAP) at the global scale (e.g., Cheema et al., 2011), as well as other applications such as irrigation scheduling, agricultural yield estimation, wildfire prediction and prevention, ecosystem management, and water resources management (e.g., Coopersmith et al., 2014, 2015b).

Pan et al. (2003) and Pan (2012) derived a daily soil moisture diagnostic equation (SMDE) based on a linear differential equation suggested by Entekhabi and Rodriguez-Iturbe (1994). As shown in Pan et al. (2003), Pan (2012) and Pan et al. (2015), the soil moisture diagnostic equation is a robust empirical approach to estimate soil moisture with four advantages, i.e., (1) no initial soil moisture is needed; (2) errors in the estimated soil moisture are not cumulative; (3) thus no recalibration is needed; (4) soil moisture can be estimated in a wide range of thicknesses of the soil column. With respect to the last point, for example, Pan et al. (2015) showed that applicability of the SMDE is not just limited to the surface soil moisture, the root zone soil moisture can also be estimated or predicted using the SMDE. In Pan et al. (2015), the SMDE has been successfully applied to estimate soil moisture in 0–10 cm, 0–20 cm, 0–50 cm, and 0–100 cm soil columns.

The main objective of this study is to test if the soil moisture diagnostic equation can be used to accurately estimate daily root-zone soil moisture in snow-dominated regions through including snowfall and snowmelt processes in the soil moisture diagnostic equation. The second goal of this study is to demonstrate if the sinusoidal soil moisture loss function also works well in snow-dominated regions to represent soil water loss due to evapotranspiration and drainage, as shown in Pan (2012). The arrangement of this paper is as follows. Section 2 describes the soil moisture diagnostic equation including snowfall and snowmelt processes, and the application of the soil moisture diagnostic equation to estimate soil moisture. Section 3 contains information about 12 SNOTEL sites across Utah used in this study for demonstrating the ability of the soil moisture diagnostic equation in estimating root-zone soil moisture in snow-dominated regions. Section 4 presents results and discussion. Conclusions are given in Section 5.

2. Method

2.1. Derivation of a daily soil moisture diagnostic equation with snow processes

Pan et al. (2003) first derived the daily soil moisture diagnostic equation (SMDE) based on a linear stochastic differential equation (Entekhabi and Rodriguez-Iturbe, 1994). Using the same approach, we can derive a similar soil moisture diagnostic equation including snowfall and snowmelt processes based on a simplified soil moisture dynamic equation given as follows:

$$z\frac{d\theta}{dt} = -\eta\theta + \gamma W \tag{1}$$

where z is the thickness of a soil column (from land surface down to depth z), θ is soil moisture of the soil column, $-\eta\theta$ is the loss of soil moisture, η is the loss coefficient, W is the liquid water input rate including liquid precipitation and snowmelt, and γ is the infiltration coefficient representing the ratio of infiltration to liquid water input. Eq. (1) states that the soil moisture time-change rate is equal to infiltration minus soil moisture loss. Vertical drainage and evaporation or evapotranspiration (ET) are two principal processes controlling soil water loss. Rearranging terms in Eq. (1) yields:

$$\frac{zd\theta}{-\eta\theta + \gamma W} = dt \tag{2}$$

For a time series of soil moisture at a point illustrated in Fig. 1, Eq. (2) can be integrated between time t_2 and t_1 as follows:

$$\int_{t_2}^{t_1} \frac{zd\theta}{-\eta\theta + \gamma W} = \int_{t_2}^{t_1} dt \tag{3}$$

where $t_2 < t_1$. For a time step less than or equal to one day the loss coefficient and the infiltration coefficient can be assumed to be constants between time t_2 and t_1. W in Eq. (3) is the observed or estimated liquid water input between time t_1 and t_2 and independent of soil moisture. With the above assumptions, Eq. (3) becomes:

$$-\frac{z}{\eta_1} ln\left[\frac{\theta_1 - \gamma W_1/\eta_1}{\theta_2 - \gamma W_1/\eta_1}\right] = t_1 - t_2 \tag{4}$$

where η_1 and W_1 are the loss coefficient and total liquid water input between time t_1 and t_2, respectively. Rearranging Eq. (4) yields:

$$\theta_1 = \theta_2 e^{-\frac{\eta_1}{z}(t_1-t_2)} + \frac{\gamma W_1}{\eta_1}\left[1 - e^{-\frac{\eta_1}{z}(t_1-t_2)}\right] \tag{5}$$

For a daily time step (i.e., t_1-t_2 = 1 day), Eq. (5) can be written as:

$$\theta_1 = \theta_2 e^{-\frac{\eta_1}{z}} + \frac{\gamma W_1}{\eta_1}\left(1 - e^{-\frac{\eta_1}{z}}\right) \tag{6-1}$$

where η_1, W_1, θ_1, θ_2 are daily soil moisture loss coefficient, liquid water input of day 1, soil moisture of day 1, and soil moisture of day 2 (which is one day before day 1), respectively. Similarly, we can have soil moisture of day 2 (θ_2) as a function of η_2, W_2, and θ_3:

$$\theta_2 = \theta_3 e^{-\frac{\eta_2}{z}} + \frac{\gamma W_2}{\eta_2}\left(1 - e^{-\frac{\eta_2}{z}}\right) \tag{6-2}$$

and soil moisture of day n − 1 (θ_{n-1}) as a function of η_{n-1}, W_{n-1}, and θ_n: