IMPROVING FROST-SIMULATION SUBROUTINES OF THE WATER EROSION PREDICTION PROJECT (WEPP) MODEL


ABSTRACT. Erosion models play an important role in assessing the influence of human activities on the environment. For cold areas, adequate frost simulation is crucial for predicting surface runoff and water erosion. The Water Erosion Prediction Project (WEPP) model is a physically based erosion prediction software program developed by the USDA. One of the major components of WEPP is the simulation of winter processes, which include snow accumulation and melt as well as soil freeze and thaw. WEPP is successfully used in the evaluation of important natural resource issues throughout the U.S. and in a number of other countries. However, previous studies revealed problems in the winter component of the WEPP model, especially the routine for frost simulation. The main purpose of this study was to improve the WEPP model (v2006.5) by changing the soil profile discretization and computation of key thermal and hydraulic parameters in the frost simulation routines so that the model can adequately simulate soil freeze-thaw and winter runoff and erosion. WEPP v2006.5 and the modified version (v2010.1) were applied to experimental plots in Pullman, Washington, and Morris, Minnesota. The simulated snow and frost depths as well as runoff and sediment yield were contrasted and compared with field observations; the results from v2010.1 showed substantial improvement compared to those from v2006.5.

Keywords. Frost, Hydrologic modeling, Runoff, Soil erosion, WEPP, Winter hydrology.

In cold regions, frozen soil has a significant influence on runoff and soil erosion (Horner et al., 1944; Zuzel et al., 1982; Seyfried and Flerchinger, 1994; Stadler et al., 1997; Greer et al., 2006; McCool et al., 2006). A thaw-weakened soil is highly susceptible to water erosion (Kok and McCool, 1990). Severe runoff and soil erosion events are often observed due to the presence of frozen soil and subsequent thawing (Øygarden, 2003; Singh et al., 2009). Long-term field studies in the Palouse region of the U.S. Pacific Northwest showed that more than 70% of water erosion resulted from rainfall or snowmelt events involving soil freezing and thawing, and the largest erosion events occurred on thawing soil (McCool et al., 2006; Singh et al., 2009). Widespread severe erosion due to rapid snowmelt on thawing soils on farmlands in Prince Edward Island, Canada (Edwards et al., 1998) and in the hilly lowlands of eastern Scotland (Wade and Kirkbride, 1998) was also reported. Freeze-thaw degrades the soil cohesive strength (Formanek et al., 1984; Kok and McCool, 1990) and increases the soil erodibility (Van Klaveren and McCool, 1998). Frozen soil can reduce infiltration capacity by reducing the pore space (Boll, 1988; McCauley et al., 2002), thus increasing the surface runoff. In addition, in certain soils (silt or clay), substantial amounts of water may migrate to the freezing front (Miller, 1980; Gatto, 2000) and cause runoff to occur even without rain or snowmelt in areas such as the Palouse region (Kok and McCool, 1990). A frozen layer underneath a thawed surface can cause water to temporarily perch above the frozen layer and lead to extreme but transitory erosion vulnerability (Froese and Cruse, 1997).

Knowledge of frost formation is important for developing sound management practices to reduce runoff and erosion in winter. Proper representation of freezing and thawing processes is also crucial to adequately modeling water erosion. The Water Erosion Prediction Project (WEPP) is a physically based erosion prediction model developed by the USDA (Laflen et al., 1991, 1997). The model has a winter simulation component, which includes the soil freeze and thaw processes (Flanagan et al., 2001). WEPP has been widely applied both in and outside the U.S. (Laflen et al., 1997; Merrit et al., 2003; Flanagan et al., 2007). The model was used for evaluating the impacts of various management practices and natural disturbances in forest settings (Elliot et al., 1995; Elliot and Hall, 1997; Soto and Diaz-Fierros, 1998; Forsyth et al., 2006; Robichaud et al., 2007; Dun et al., 2009). WEPP was also applied to assess water erosion from agricultural lands (Cochrane and Flanagan, 1999; Clark et al., 2006; Cruse et al., 2006; Pieri et al., 2007; Yüksel et al., 2008) and rangeland (Wilcox et al., 1990; Hunt and Wu, 2004; Moffet et al., 2007). However, studies (Kennedy and Sharratt, 1998; McCool et al., 1998; Pannuk et al., 2000; Greer et al., 2006) have shown the winter routines of WEPP to be inadequate in...
simulating (1) frost depth and duration and (2) the impact of frozen soil on soil infiltration capacity, which in turn lead to inadequate simulation of winter runoff and erosion. The main purpose of this study was to improve the WEPP model (v2006.5) so that it more accurately simulates soil freezing and thawing processes as well as winter runoff generation in cold regions where winter hydrology is important. The specific objectives were:

- To modify the algorithms and subroutines of WEPP (v2006.5) that improperly describe soil freezing and thawing processes.
- To assess the performance of the modified model (WEPP v2010.1) at two experimental research sites under different climatic conditions.

**MODEL DESCRIPTION: WEPP v2006.5**

The WEPP model is a distributed-parameter, continuous-simulation, erosion prediction model for hillslope and watershed applications (Flanagan et al., 1995). WEPP includes the following components: climate generation, hydrology and hydraulics, soil dynamics, plant growth and residue decomposition, and erosion (Flanagan and Livingston, 1995). With these components integrated, WEPP has the potential to quantify hydrological and erosion processes under different climatic, vegetation and residue management, soil, and topographic conditions.

In WEPP, a soil profile is discretized into finer, 10 cm layers for the top 20 cm (in consideration of the dynamic changes in soil properties due to tillage) and 20 cm layers for the remainder of the soil profile (for computing the daily water balance). The winter routines of the WEPP model simulate snow accumulation and melt along with soil freeze and thaw on an hourly basis. The winter processes are simulated when a snowpack or a soil frost layer exists or when the daily minimum temperature is below 0°C. Since the focus of this study is on the simulation of soil frost, we include below a summary of the approaches to quantifying soil freeze and thaw, together with detailed description of the methods for determining system surface temperature and frost thickness in the original WEPP v2006.5 after Savabi et al. (1995).

Simulation of frost in WEPP is driven by surface temperature, which is estimated from an energy balance at the surface of a snow-residue-soil system (fig. 1). The estimated surface temperature is used to determine heat flow to, from, a freezing front (0°C isothermal) due to a temperature gradient. WEPP accounts for thermal resistance of snow, residue, frozen soil, and unfrozen soil in heat transfer. At a freezing front, heat conducted to the surface of the system is balanced by the heat flow from the underlying unfrozen soil and the latent heat released by freezing water. At a thawing front, heat conducted from the surface to the frozen soil is balanced by the latent heat absorbed by thawing ice in the soil. The thickness of soil frozen or thawed is then determined based on the latent heat required and the soil water content at the freezing or thawing front.

There are several assumptions in frost simulation by WEPP. Snow and soil thermal conductivities and water flux are assumed constant during a simulation step, i.e., one hour. Within a simulation step, soil freezing would cause all the water currently in the freezing zone, excluding the residual water, to be converted to ice. In WEPP, the residual water is defined as the amount of soil water corresponding to plant wilting point. Soil temperature one meter below the freezing front is assumed to be 7°C, taken as the mean annual air temperature for the Midwest (NOAA, 2010).

**Estimation of Surface Temperature**

Hourly temperature at the surface of the residue-snow-soil system, \(T_{hrs}(°C)\), was estimated based on an energy balance following equation 1 (Flerchinger, 1987), with the individual terms expanded as equations 2 through 7 and the resultant \(T_{hrs}\) given by equation 8 (Flerchinger, 1987):

\[
R_a(1 - \alpha) + \varepsilon_a \sigma T_{hrsk}^4 - \varepsilon_s \sigma T_{hrs}^4 + \rho_a c_a \frac{(T_{hra} - T_{hrs})}{r_H} - K_{srf} \frac{(T_{hrs} - 0)}{d_{srf}} = 0
\]

\[
\varepsilon_s \sigma T_{hrs}^4 = \varepsilon_s \sigma T_{hsk}^4 + 4 \varepsilon_s \sigma T_{hra}^3 (T_{hrsk} - T_{hra}) - 4 \varepsilon_s \sigma T_{hra}^3 (T_{hsk} - T_{hrs})
\]

\[
R_{net} = \frac{R_a(1 - \alpha)}{t} + (\varepsilon_a - \varepsilon_s) \sigma T_{hra}^4
\]

\[
R_{cof} = \varepsilon_s \sigma T_{hsk}^3
\]

\[
\frac{1}{r_H} \ln \left[ \frac{z_v - z_d + z_m}{z_m} \right] = \frac{\kappa^2}{\rho_a c_a} \ln \left[ \frac{z_v - z_d + z_H}{z_H} \right]
\]

\[
K_{cont} = \frac{\kappa^2}{\rho_a c_a} \ln \left[ \frac{z_v - z_d + z_m}{z_m} \right] \ln \left[ \frac{z_v - z_d + z_H}{z_H} \right]
\]

\[
R_{net} + R_{cof} (T_{hra} - T_{hrs}) + K_{cont} \varepsilon(z) (T_{hra} - T_{hrs}) - K_{srf} \frac{d_{srf}}{T_{hrs}} = 0
\]
where the energy flux terms (W m⁻²) in equation 1 from left to right are incoming solar radiation, longwave radiation from air, longwave radiation from the surface of the residue-snow-soil system, convective heat from air, and conductive heat from the residue-snow-soil system, respectively, and:

\[ R_s \] = solar radiation on a sloping surface (J m⁻²)

\[ \alpha \] = albedo of the surface (-)

\[ t \] = duration for receiving the solar radiation (s)

\[ \sigma \] = Stefan-Boltzmann constant \((5.67 \times 10^{-8}\) W m⁻² K⁻⁴)

\[ \varepsilon_s \] and \[ \varepsilon_a \] = emissivities of the surface and air, respectively (-)

\[ T_{hrs} \] and \[ T_{hra} \] = hourly temperatures of the surface and air, respectively (°C)

\[ T_{hrsK} \] and \[ T_{hraK} \] = hourly temperatures of the surface and air, respectively (K)

\[ \rho_s \] = air density (kg m⁻³)

\[ c_p \] = specific heat (J kg⁻¹ °C⁻¹)

\[ r_H \] = resistance to heat transfer (s m⁻¹)

\[ K_{srf} \] = effective thermal conductivity (W m⁻¹ °C⁻¹)

\[ d_{srf} \] = depth of residue-snow-frozen-soil system (m)

\[ R_{net} \] = net radiation flux (W m⁻²)

\[ R_{cof} \] = radiation coefficient (W m⁻² °C⁻¹)

\[ \kappa \] = von Karman constant (-)

\[ \nu(z) \] = wind velocity (m s⁻¹)

\[ z_v, z_d, z_m, \Delta H \] = height of wind measured, height of zero-plane displacement of the wind profile, momentum roughness of the surface, and surface roughness of the temperature profile (m)

\[ K_{conH} \] = convective heat transfer coefficient (J m⁻³ °C⁻¹).

Hourly air temperature in the WEPP model is estimated following DeWit et al. (1978) from the model input of daily maximum and minimum temperatures. The lowest and highest temperatures of the day are assumed to occur at sunrise and 2:00 p.m., respectively. The temperature between the maximum and minimum values follows two cosine curves.

Daily solar radiation reaching a sloped surface is calculated from measured solar radiation with an adjustment factor for aspect and slope following Swift (1976). Hourly extraterrestrial solar radiation is described by trigonometric functions of station latitude, solar declination, and solar time angle (Jensen et al., 1990). Hourly solar radiation on a sloped surface is then estimated by multiplying the daily solar radiation on a sloped surface by the ratio of hourly to daily extraterrestrial solar radiation with the assumption of a constant atmospheric transmissivity throughout the day.

**Simulation of Frost Thickness**

Frost simulation in WEPP is a combination of mass and energy balance at the freezing or thawing front. Water balance is simulated by tracking the changes in liquid soil water, ice, and the thickness of the frozen soil. Energy balance at the freezing front is described using equations 9 through 11:

\[
\frac{L \Delta d_{fc} \theta}{\Delta t} = Q_{sf} - Q_{uf}
\]

\[
Q_{sf} = K_{srf} \frac{\Delta T_{srf}}{Z_{srf}}
\]

\[
Q_{uf} = K_{uf} \frac{\Delta T_{uf}}{Z_{uf}} + L K_w \frac{\Delta P_{uf}}{Z} + C_{uf} dT_{uf} \frac{Z_{uf}}{\Delta t}
\]

where

\[ L \] = latent heat of fusion (J m⁻³)

\[ \Delta t \] = time interval (s)

\[ \Delta d_{fc} \] = thickness of soil frozen or thawed within \( \Delta t \) (m)

\[ \theta \] = volumetric soil water content (m m⁻³)

\[ Q_{sf} \] and \[ Q_{uf} \] = heat fluxes through the snow-residue-frozen soil zone and from the unfrozen soil beneath the frozen zone, respectively (W m⁻²)

\[ Z_{srf} \] = thickness of the snow-residue-frozen soil zone (m)

\[ \Delta T_{srf} \] = temperature difference between the top of the snow-residue-frozen soil zone and the freezing front (0°C isotherm) (°C)

\[ Z_{uf} \] = distance between the top of the unfrozen soil and the depth of “constant temperature” assumed to be 1 m below the top of the unfrozen soil (m)

\[ \Delta T_{uf} \] = temperature difference between the top of the unfrozen soil and the depth of “constant temperature” assumed to be 1 m below the top of the unfrozen soil (°C)

\[ K_{srf} \] and \[ K_{uf} \] = average thermal conductivities for the snow-residue-frozen soil zone and the unfrozen soil, respectively (W m⁻¹ °C⁻¹)

\[ K_w \] = unsaturated hydraulic conductivity of unfrozen soil (m s⁻¹)

\[ Z \] = soil thickness between the freezing front and the center of the underlying unfrozen soil layer (m)

\[ \Delta P_{uf} \] = difference of water potential between the freezing front and the center of the underlying unfrozen soil layer (m)

\[ C_{uf} \] = heat capacity of the unfrozen soil (J m⁻³ °C⁻¹)

\[ dT_{uf} \] = change in temperature of a unit volume of unfrozen soil within \( \Delta t \) (°C).

When surface temperature is below 0°C, cold from the surface of the snow-residue-soil system is balanced with the energy sources at the freezing front in the sequence of (1) heat conducted from the underlying unfrozen soil, (2) latent heat released from freezing the water migrated to the freezing front, and (3) heat released from freezing the water held in place at the freezing front, which results in an increase in the thickness of frozen soil.

When surface temperature is above 0°C, heat from the surface of the snow-residue-soil system and from the unfrozen soil is consumed by thawing the top-most and bottom-most frozen soil, respectively. If a frost “sandwich”
occurs, cold from the surface is balanced by freezing the top-most unfrozen soil (fig. 1).

**LIMITATIONS OF THE FROST SIMULATION ROUTINES IN WEPP v2006.5**

Major limitations in the frost simulation routines of WEPP v2006.5 included: (1) coarse discretization of the entire soil profile into two layers (tillage and non-tillage) without using the finer soil profile discretization for daily water balance, and accounting for only one frost “sandwich” layer; (2) assumption of a constant temperature of 7°C for the unfrozen soil 1 m below the freezing front; (3) inadequate adjustment of saturated hydraulic conductivity of frozen soil (Greer et al., 2006); and (4) programming errors in computing unsaturated hydraulic conductivity, soil water potential, and upward water movement to a freezing front, and in incorrect use of energy flux for the amount of energy.

**IMPROVEMENTS OF THE FROST SIMULATION ROUTINES IN WEPP v2010.1**

The framework of the frost simulation in WEPP v2006.5 was retained, and the major limitations were rectified. Specific improvements were made to (1) adequately discretize the snow-residue-soil system; (2) better represent soil temperature below the bottom-most frozen zone, unsaturated hydraulic conductivity and water characteristic, saturated hydraulic conductivity of frozen soil, and thermal conductivity of snow and soil; and (3) properly integrate the frost simulation routines and other water balance routines of WEPP. The equations and associated assumptions presented in the following sections pertain to WEPP v2010.1 unless specified otherwise.

**Discretization**

Snow and surface residue were each treated as a single layer. A soil profile was divided into 1 cm computational layers in the top 20 cm tillage zone and 2 cm layers in the remainder, at one-tenth of the original resolution. The amount of ice, the thickness of frozen soil, and the soil water content of unfrozen soil in each layer were explicitly tracked. The fine discretization helps to simulate the liquid soil water and ice as well as the occurrence and location of a frost “sandwich” more accurately.

**Temperature of Soil Below the Bottom-Most Frozen Zone**

The temperature of the unfrozen soil was estimated following Campbell and Norman (1998), an analytical solution of 1-d heat transfer for uniform soil (eq. 12), and the soil temperature gradient at a given time of a year was estimated as the partial derivative of soil temperature with respect to soil depth (eq. 13):

\[
T(z, t) = T_{\text{avg}} + A_0 \exp(-z/D)\sin[\omega(t - t_0) - z/D] \quad (12)
\]

\[
\frac{\partial T(z, t)}{\partial z} = A_0 (-1.0/D) \exp(-z/D) \{\sin[\omega(t - t_0)] - z/D + \cos[\omega(t - t_0) - z/D]\} \quad (13)
\]

where

- \( T_{\text{avg}} \) = annual mean temperature at the soil surface (°C)
- \( A_0 \) = amplitude of fluctuation of the temperature at the soil surface (°C)
- \( \omega = 2\pi/365 \) (rad d⁻¹)
- \( D \) = damping depth (m)
- \( z \) = soil depth (m)
- \( t \) = time in Julian day (d)
- \( t_0 \) = temporal phase shift (d).

Equations 12 and 13 suggest that, for a given time, the temperature of the soil beneath the bottom-most frozen zone increases with increasing depth, whereas the temperature gradient decreases with depth. Soil temperature at 1 m below the bottom-most frozen zone was thus used to estimate heat conducted from unfrozen soil to a freezing or thawing front.

A typical damping depth of 2 m for temperature changes on a yearly time scale (Campbell and Norman, 1998) was used in the modified frost routines. Other parameters in equation 12, i.e., \( T_{\text{avg}}, A_0, \) and \( t_0 \) were estimated from monthly mean temperature approximated by a sine curve. No heat transfer from the unfrozen soil occurs if the estimated temperature for the soil 1 m below the bottom-most frozen zone is below 0°C.

**Unsaturated Hydraulic Conductivity and Water Characteristic**

The unsaturated hydraulic conductivity and the matric potential of unfrozen soil were determined from the volumetric soil water content and soil texture of individual computational layers following Saxton and Rawls (2006). The WEPP model simulates water migration to the freezing front if the soil water potential at the freezing front is lower than that of the unfrozen soil in the layer beneath. Soil water potential of a frozen soil was estimated from soil temperature using the generalized form of the Clausius-Clapeyron equation following Watanabe and Wake (2008). We assumed that the soil temperature at the freezing front is the same as the freezing depression temperature, typically ranging from 0.01°C to 2.5°C as a function of volumetric soil water content and soil texture (Kozlowski, 2004). Such a temperature range of a freezing front would correspond to a water potential range of -1.2 m to -310 m based on Watanabe and Flury (2008).

**Saturated Hydraulic Conductivity of Frozen Soil**

It was assumed that the ice in the soil occupies pore spaces in the same manner as air in the unsaturated soil. Hence, the method of estimating unsaturated hydraulic conductivity of an unfrozen soil by Saxton and Rawls (2006) was adapted to estimate the saturated hydraulic conductivity of a frozen soil. Specifically, the saturated hydraulic conductivity of a frozen soil is taken as the unsaturated hydraulic conductivity at the soil water content that is equal to the soil’s porosity minus the ice content.

Ice content of a computational layer in frost simulation was calculated by dividing the depth of water in solid form by the thickness of the computational layer. Hence, the calculated ice content was dependent on the initial soil water content before soil was frozen and the thickness of frozen soil in the layer: the smaller the initial soil water content or the thinner the frozen soil, the smaller the ice content and therefore the larger the saturated hydraulic conductivity of the frozen soil. The vertical and horizontal hydraulic conductivities of a larger soil layer for water balance computation were respectively the harmonic mean and arithmetic mean of the saturated hydraulic conductivities of the frost computational layers enclosed in the larger layer. The saturated hydraulic conductivity of the larger soil layer
was adjusted for crusting, tillage, crop, and rainfall in infiltration simulation and was adjusted based on soil texture and saturation level in percolation and subsurface lateral flow calculation (Flanagan and Nearing, 1995).

**Thermal Conductivity of Snow and Soil**

Snow thermal conductivity was estimated following Sturmi et al. (1997) based on snow density as follows:

\[ K_{\text{snow}} = 0.023 + 0.234 \left( \rho_{\text{snow}} / 1000 \right) \]

\[ \rho_{\text{snow}} \leq 156 \]

\[ K_{\text{snow}} = 0.138 - 1.01 \left( \rho_{\text{snow}} / 1000 \right) + 3.233 \left( \rho_{\text{snow}} / 1000 \right)^2 \]

\[ \rho_{\text{snow}} > 156 \]

(14)

where \( K_{\text{snow}} \) is the snow thermal conductivity (W m \(^{-1}\) °C\(^{-1}\)), and \( \rho_{\text{snow}} \) is the snow density (kg m\(^{-3}\)).

Soil density is the major factor that impacts thermal conductivity of a snow cover. Other factors, e.g., snow microstructure (Satyawali and Singh, 2008), may also play a role. A proportionality coefficient, \( K_{fsoil} \), was included in the modified WEPP for users to adjust the snow thermal conductivity estimated from equations 14 and 15. The default value of \( K_{fsoil} \) was set to 1.0.

The thermal conductivity values for frozen soils (1.75 and 2.10 W m \(^{-1}\) °C\(^{-1}\) for tilled and untilled soil, respectively; Savabi et al., 1995) in WEPP v2006.5 were used in v2010.1. A proportionality coefficient, \( K_{fsoil} \), was also adopted from WEPP v2006.5:

\[ K_{\text{soil}} = \left( 0.5906 + 7.4493 \theta - 8.7484 \theta^2 \right) \times (0.0014139 \rho_\theta - 1.0588) \]

(16)

where \( K_{\text{soil}} \) is thermal conductivity of unfrozen soil (W m \(^{-1}\) °C\(^{-1}\)), \( \theta \) is soil water content (m\(^3\) m\(^{-3}\)), and \( \rho_\theta \) is soil bulk density (kg m\(^{-3}\)).

The equations between thermal conductivity versus soil water content vary among different soil types (Campbell and Norman, 1998). Equation 16 yielded a curve most agreeable to that of a sandy soil reported by Campbell and Norman (1998). A proportionality coefficient, \( K_{fsoil} \) (default 1.0 for sandy soil), was therefore added as an input in WEPP v2010.1 for users to adjust the estimated unfrozen soil thermal conductivity for site-specific soils. A \( K_{fsoil} \) value less than 1 should be used for other soil types following Campbell and Norman (1998).

**Integrating Frost Simulation Routines with Other Water Balance Components of WEPP**

Soil freeze and thaw affect soil hydraulic and erodibility parameters. In WEPP, these parameters include hydraulic conductivity, interrill and rill erodibility, as well as critical shear stress. The results of frost simulation were used by the WEPP water balance and erosion routines to update soil water content and to adjust hydraulic properties (Saxton and Rawls, 2006) and erosion parameters based on ice content (Savabi et al., 1995).

Updating of soil water content of an individual frost computational layer was carried out at the beginning of a daily frost simulation, and updating of both soil water and ice content and interactions with other water balance components was carried out at the end of a daily frost simulation. In the absence of frost, initial soil water content of a computational layer in the frost simulation was presumed the same as the soil water content in the larger, enclosing layer used in other water balance calculations. When frost is present, the increased (due to infiltration) or decreased (due to percolation) water in an enclosing layer is evenly distributed to each frost computational layer. Soil water and ice content of the larger layer are updated from the cumulative water and ice amount of all the enclosed frost computational layers at the end of a daily frost simulation.

**SITE DESCRIPTION**

Two study sites under different climatic conditions were chosen to assess the performance of the winter routines in WEPP v2010.1. One site was the Palouse Conservation Field Station (PCFS; 46° 45′ N, 117° 12′ W), located 3 km northwest of Pullman, Washington. Long-term experimental runoff plots have been installed at the PCFS since the 1970s (McCool et al., 2002). Data from these experimental plots included weather, snow and frost depths, and runoff and sediment yield from fall 1983 to spring 1990. A 24 h chart-type recording rain gauge near the runoff plots provided the break-point rainfall data for this study (Lin and McCool, 2006). Other weather data, including temperature, wind, humidity, and solar radiation, were from the NOAA Pullman 2 NW, 0.6 km to the east of the runoff plots and the closest weather station with the majority of the required WEPP climate inputs. The NOAA Pullman 2 NW station and the runoff plots are at the same elevation of 762 m a.s.l. and are separated by a ridge at 797 m a.s.l. in an area of extended rolling hills. Snow depth was measured with snow stakes, and frost depth was measured with frost tubes (McCool and Molnau, 1984) installed at three locations (top, middle, and bottom) along the edge of each plot. Runoff and sediment yield were measured using sediment delivery tank (McCool et al., 2006). In this study, one plot at the PCFS site was chosen for WEPP simulations.

The other study site (45° 41′ N, 95° 48′ W) was located near Morris, Minnesota. Weather data, snow and frost depths, as well as soil temperature and soil water content were collected from no-till corn plots with different residue managements during the winter (November to March) of 1993-1996 (Kennedy and Sharratt, 1998; Sharratt, 2002). Precipitation data were from a tipping-bucket rain gauge (0.254 mm per tip) in an automatic weather station. Snow depth was measured using snow stakes, and frost depth was determined with frost tubes (Sharratt, 2002). Runoff and sediment yield were not monitored at these plots. For this study, one plot was selected for WEPP modeling.

The PCFS is in a Mediterranean climate zone with a wet winter and dry summer. The long-term mean annual temperature is 8.3°C, and the long-term mean annual precipitation is 533 mm (NRCS, 2010a, 2010b). Rapid fall and rise in temperature can occur multiple times during the winter. Snow cover is transient, with accumulated snow subject to rapid melting by the warm fronts. On average, frost depth in the soil can reach 0.2 to 0.5 m (WRCC, 2008), and it can reach 0.9 m under severe conditions. Numerous freeze-thaw cycles may occur (McCool, 1990). In contrast, the Morris research site is typified by a continental climate with a long-term mean annual temperature of 6.1°C and a long-term mean annual precipitation of 635 mm (NRCS, 2010a,
Table 1. Monthly means of observed climate data during 1983-1990 at Pullman, Washington.

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<th>Maximum Temperature (°C)</th>
<th>Minimum Temperature (°C)</th>
<th>Solar Radiation (Langley d⁻¹)</th>
<th>Wind Velocity (m s⁻¹)</th>
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<td>526</td>
<td>3.1</td>
<td>6.2</td>
</tr>
<tr>
<td>9</td>
<td>25</td>
<td>22.2</td>
<td>6.0</td>
<td>388</td>
<td>2.8</td>
<td>4.1</td>
</tr>
<tr>
<td><strong>Yearly[a]</strong></td>
<td>505</td>
<td>14.5</td>
<td>2.4</td>
<td>352</td>
<td>3.4</td>
<td>1.1</td>
</tr>
</tbody>
</table>

[a] Yearly precipitation refers to the total, and the rest of the yearly values are means of monthly values.

Table 2. Monthly means of observed climate data during 1993-1996 at Morris, Minnesota.

<table>
<thead>
<tr>
<th>Month</th>
<th>Precipitation (mm)</th>
<th>Maximum Temperature (°C)</th>
<th>Minimum Temperature (°C)</th>
<th>Solar Radiation (Langley d⁻¹)</th>
<th>Wind Velocity (m s⁻¹)</th>
<th>Dewpoint Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>64</td>
<td>13.0</td>
<td>2.5</td>
<td>191</td>
<td>4.1</td>
<td>2.5</td>
</tr>
<tr>
<td>11</td>
<td>24</td>
<td>2.3</td>
<td>-6.6</td>
<td>123</td>
<td>4.6</td>
<td>-6.6</td>
</tr>
<tr>
<td>12</td>
<td>19</td>
<td>-4.2</td>
<td>-13.1</td>
<td>108</td>
<td>4.3</td>
<td>-13.1</td>
</tr>
<tr>
<td>1</td>
<td>26</td>
<td>-10.9</td>
<td>-21.1</td>
<td>147</td>
<td>4.7</td>
<td>-21.1</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>6.2</td>
<td>-17.7</td>
<td>231</td>
<td>5.0</td>
<td>-17.7</td>
</tr>
<tr>
<td>3</td>
<td>41</td>
<td>1.5</td>
<td>-7.5</td>
<td>306</td>
<td>4.6</td>
<td>-7.5</td>
</tr>
<tr>
<td>4</td>
<td>75</td>
<td>9.6</td>
<td>-0.8</td>
<td>378</td>
<td>4.6</td>
<td>-0.8</td>
</tr>
<tr>
<td>5</td>
<td>64</td>
<td>19.4</td>
<td>7.4</td>
<td>364</td>
<td>4.4</td>
<td>7.4</td>
</tr>
<tr>
<td>6</td>
<td>23</td>
<td>24.7</td>
<td>8.9</td>
<td>257</td>
<td>3.2</td>
<td>8.9</td>
</tr>
<tr>
<td>7</td>
<td>28</td>
<td>26.3</td>
<td>9.4</td>
<td>630</td>
<td>3.2</td>
<td>9.4</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>29.5</td>
<td>9.9</td>
<td>537</td>
<td>3.1</td>
<td>9.9</td>
</tr>
<tr>
<td>9</td>
<td>26</td>
<td>23.4</td>
<td>6.4</td>
<td>387</td>
<td>2.7</td>
<td>6.4</td>
</tr>
<tr>
<td><strong>Yearly[a]</strong></td>
<td>413</td>
<td>10.7</td>
<td>-1.9</td>
<td>340</td>
<td>4.0</td>
<td>-1.9</td>
</tr>
</tbody>
</table>

[a] Yearly precipitation refers to the total, and the rest of the yearly values are means of monthly values.

Snow cover persists from early December to late March, and soil frost may start to form from mid-November and last to mid-May in the following spring. Soil frost penetrated up to 1.2 m as observed in a field study during 1993-1996 (Sharratt, 2002). Note that annual mean temperature of the two study sites differed by only 2.2°C; however, Morris had much greater temperature change within a year and much colder winters than Pullman (tables 1 and 2).

The soil at the PCFS was Palouse silt loam (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls) under continuous bare fallow condition. The chosen plot for WEPP simulation (hereafter referred to as the PCFS plot) was 22.3 m long and 3.7 m wide on a 21% south-facing slope (McCool et al., 1995). The soil at the Morris research site was Barnes loam (fine-loamy, mixed, superactive, frigid Calcic Hapludolls). The study plot (hereafter referred to as the Morris plot) was 12 m long and 18 m wide on a 2% east-facing slope in a no-tillage corn field. Standing stubble and flat residue were removed from the plot after each harvest (Sharratt, 2002).

WEPP SIMULATIONS AND MODEL PERFORMANCE ASSESSMENT

WEPP hillslope simulation requires four input files: climate, topography, soil, and management. The climate inputs included observed daily precipitation, maximum and minimum air temperature, solar radiation, wind speed and direction, and dewpoint temperature. Topographic inputs for both study plots included a uniform slope configuration with respective slope gradients, slope aspects, and plot dimensions. Management was continuous-tilled fallow for the PCFS plot (Lin and McCool, 2006) and no-tillage corn with 100% residue removal for the Morris plot (Kennedy and Sharratt, 1998).

The particle size distribution data in the soil inputs (tables 1 and 2) were from field and lab measurements as reported by Lin and McCool (2006) and Kennedy and Sharratt (1998). Other soil input parameters were from the WEPP database for Palouse silt loam and Barnes loam. The erosion parameters (rill and interrill erodibilities and critical shear stress) are crucial WEPP inputs affecting erosion prediction. Previous studies showed that these parameters are strongly impacted by crop and tillage management and should be calibrated to site-specific surface conditions (McCool et al., 1998; Pannuk et al., 2000; Greer et al., 2006; Singh et al., 2009). In this study, rill erodibility and critical shear stress for the top soil layer for the Palouse silt loam were adjusted to best reproduce field-observed average annual runoff and erosion at the PCFS plot where field-observed runoff and erosion data were available.
Cannell and Gardner (1959) reported that lab-measured freezing point depression for the Palouse silt loam varied from 0.02°C to 0.06°C, corresponding to a water potential at the freezing front of -2.5 to -7.5 m by the Clausius-Clapeyron equation. In this study, water potential at the freezing front was set to -5 m (the average of -2.5 and -7.5 m) for both the PCFS and Morris plots.

Soils at the two study plots were silt loam and loam, respectively. Thermal conductivities for loam soils range from 0.02 to 0.79 W m⁻¹ °C⁻¹, corresponding to a water potential at the freezing front of -2.5 to -7.5 m by the Clausius-Clapeyron equation. In this study, water potential at the freezing front was set to -5 m (the average of -2.5 and -7.5 m) for both the PCFS and Morris plots.

A calibrated $K_{f\text{soil}}$ value of 1.5 (default value of 1.0) was found to better reproduce the field-observed frost depth at the PCFS plot. The increase in thermal conductivity was likely attributed to two reasons. First, snow depths at the PCFS plot were shallow, rarely exceeding 200 mm, during the study period. Second, the shallow snow cover in combination with rapid and frequent freeze and thaw created non-uniformity of snow cover (depth and density), which in turn led to large spatial variation in snow thermal conductivity.

**RESULTS AND DISCUSSION**

**WEPP v2010.1 and v2006.5 Results for the PCFS Plot**

There was a good agreement between WEPP v2010.1 simulated and field-observed snow and frost depths at the PCFS plot (figs. 2a and 2b). WEPP v2010.1 properly reproduced the snow depth as well as the occurrence and duration of the major snow cover and frost presence for the winter seasons of 1985-1988 for the study plot. The model rendered an overestimate of snow depth for 1984, and an underestimate for frost depth. An over- or under prediction of snow will directly impact the predicted frost depth. In addition, the model underestimated snow depth for 1989. Wilcoxon signed-rank tests showed that WEPP-simulated snow and frost depths both differed from field observations. The PBIAS of -8% for snow depth and -14% for frost depth (table 5) suggest underestimates of both quantities by WEPP v2010.1. Adequate prediction of frost penetration depends on many factors, including proper prediction of soil surface temperature, soil water content, and thermal properties of residue and snow on the ground. The monthly mean of daily maximum temperatures at the PCFS fluctuated around 0°C in December during the study period (table 1), posing a challenge for simulating the dynamics of both snow cover and soil freeze-thaw.
Figure 2. Comparison of WEPP-simulated and field-observed snow (upper panels) and frost (lower panels) depths for the Palouse Conservation Field Station (PCFS) plot near Pullman, Washington.

Table 5. Statistical tests comparing WEPP simulation results and field observations for the Palouse Conservation Field Station (PCFS) plot near Pullman, Washington.[a]

<table>
<thead>
<tr>
<th>WEPP Version</th>
<th>Parameters[b]</th>
<th>Simulated[c]</th>
<th>SEE</th>
<th>PBIAS (%)</th>
<th>Wilcoxon Test[d]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td></td>
<td>S-Statistic</td>
</tr>
<tr>
<td>v2010.1</td>
<td>Snow depth, mm (145)</td>
<td>109 (118)</td>
<td>84 (73)</td>
<td>76</td>
<td>-8</td>
</tr>
<tr>
<td></td>
<td>Frost depth, mm (254)</td>
<td>102 (118)</td>
<td>69 (77)</td>
<td>71</td>
<td>-14</td>
</tr>
<tr>
<td></td>
<td>Event runoff, mm (253)</td>
<td>5.3 (6.3)</td>
<td>5.9 (7.5)</td>
<td>8.0</td>
<td>-7</td>
</tr>
<tr>
<td></td>
<td>Event sediment yield, t ha⁻¹ (253)</td>
<td>2.7 (4.9)</td>
<td>14.8 (9.9)</td>
<td>10.5</td>
<td>-25</td>
</tr>
<tr>
<td></td>
<td>Annual runoff, mm (7)</td>
<td>118 (133)</td>
<td>42 (48)</td>
<td>59</td>
<td>-11</td>
</tr>
<tr>
<td></td>
<td>Annual sediment yield, t ha⁻¹ (7)</td>
<td>60 (104)</td>
<td>22 (59)</td>
<td>99</td>
<td>-42</td>
</tr>
<tr>
<td>v2006.5</td>
<td>Snow depth, mm (145)</td>
<td>39 (118)</td>
<td>14 (73)</td>
<td>120</td>
<td>-67</td>
</tr>
<tr>
<td></td>
<td>Frost depth, mm (254)</td>
<td>175 (118)</td>
<td>18 (77)</td>
<td>87</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>Event runoff, mm (180)</td>
<td>2.4 (6.3)</td>
<td>3.5 (7.5)</td>
<td>9.0</td>
<td>-71</td>
</tr>
<tr>
<td></td>
<td>Event sediment yield, t ha⁻¹ (180)</td>
<td>5.0 (4.9)</td>
<td>13.2 (9.9)</td>
<td>11.8</td>
<td>-51</td>
</tr>
<tr>
<td></td>
<td>Annual runoff, mm (7)</td>
<td>18 (133)</td>
<td>12 (50)</td>
<td>142</td>
<td>-86</td>
</tr>
<tr>
<td></td>
<td>Annual sediment yield, t ha⁻¹ (7)</td>
<td>39 (104)</td>
<td>49 (59)</td>
<td>98</td>
<td>-62</td>
</tr>
</tbody>
</table>

[a] SD = standard deviation (root mean square), SEE = standard error of the estimate, and PBIAS = percent bias.
[b] Values in parentheses are sample sizes. For snow and frost depth, the sample sizes are the number of days with observations. For runoff and sediment yield, the sample sizes are the days when runoff was observed or for which runoff was predicted.
[c] Values in parentheses are field-observed values.
[d] Significance level α= 0.05.

There were no significant differences between WEPP v2010.1 and field-observed annual runoff and sediment yields (tables 5 and 6). The simulated event-by-event runoff was also not significantly different from the field observations, with PBIAS of -7%. However, event-by-event sediment yields were significantly different from the field-observed values, with PBIAS of -25%, indicating an underestimate for sediment yield by WEPP.

WEPP v2010.1 reproduced the large runoff events typically observed in winter (fig. 3a). However, WEPP did not predict some of the small runoff events observed during winter, and WEPP predicted events that were not observed, especially during summer when the winter routines were not in effect (fig. 3a). Improving WEPP’s winter routines was an integral part of our goal to improve the model’s overall ability in continuous simulation of water erosion. That the summer events were not always properly simulated suggests further assessment of WEPP application for summer season under Mediterranean climatic conditions. The incorrect simulated timing of the small runoff events in winter was likely due to
Table 6. Observed and simulated yearly runoff and sediment yield for the Palouse Conservation Field Station (PCFS) plot near Pullman, Washington.

<table>
<thead>
<tr>
<th>Water Year (Oct. to Sept.)</th>
<th>Precipitation (mm)</th>
<th>Runoff (mm)</th>
<th>Sediment Yield (t ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Simulated</td>
<td></td>
</tr>
<tr>
<td></td>
<td>v2010.1</td>
<td>v2006.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>Simulated</td>
<td>Observed</td>
</tr>
<tr>
<td></td>
<td>v2010.1</td>
<td>v2006.5</td>
<td></td>
</tr>
<tr>
<td>1984</td>
<td>596</td>
<td>228</td>
<td>133</td>
</tr>
<tr>
<td></td>
<td>v2010.1</td>
<td>v2006.5</td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td>515</td>
<td>119</td>
<td>152</td>
</tr>
<tr>
<td></td>
<td>v2010.1</td>
<td>v2006.5</td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td>536</td>
<td>147</td>
<td>169</td>
</tr>
<tr>
<td></td>
<td>v2010.1</td>
<td>v2006.5</td>
<td></td>
</tr>
<tr>
<td>1987</td>
<td>415</td>
<td>71</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>v2010.1</td>
<td>v2006.5</td>
<td></td>
</tr>
<tr>
<td>1988</td>
<td>424</td>
<td>108</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>v2010.1</td>
<td>v2006.5</td>
<td></td>
</tr>
<tr>
<td>1989</td>
<td>559</td>
<td>125</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>v2010.1</td>
<td>v2006.5</td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>492</td>
<td>134</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>v2010.1</td>
<td>v2006.5</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>505</td>
<td>133</td>
<td>118</td>
</tr>
<tr>
<td></td>
<td>v2010.1</td>
<td>v2006.5</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>Simulated</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>v2010.1</td>
<td>v2006.5</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>39</td>
</tr>
</tbody>
</table>

Figure 3. Comparison of WEPP-simulated and field-observed runoff (upper panels) and sediment yield (lower panels) for the Palouse Conservation Field Station (PCFS) plot near Pullman, Washington.

The inadequate simulation of the rapid snowmelt and soil freeze-thaw processes in the Palouse region. The incorrect simulated summer runoff may be due to the improper characterization of seasonal changes in soil hydraulic properties.

WEPP v2010.1 reproduced the occurrence of the major observed erosion events (fig. 3b). However, the amount of sediment yield was either under- or overpredicted. The critical shear stress (0.08 N m⁻²) calibrated in this study was at the lower end of the range (0 to 2.1 N m⁻²) of field-measured values (Elliot et al., 1989), and the calibrated rill erodibility (1.2 × 10⁻² s m⁻¹) was higher than the default value (9.0 × 10⁻³ s m⁻¹) in the WEPP database. The calibrated values differed from the field-measured values likely because the latter were obtained from field experiments conducted during summer without the impact of soil freeze and thaw (Elliot et al., 1989). The inability of WEPP to reproduce all field-observed erosion events suggests the complexity of the dynamic changes in soil properties and the need for improving the representation of such dynamics.

The performance of WEPP v2006.5 was generally inadequate (figs. 2 and 3). Snow depths simulated by WEPP v2006.5 were underestimates with a PBIAS of -67% and differed significantly from the field observations (table 5). The snow cover period simulated by WEPP v2006.5 was much shorter than the observed value (fig. 2c). Frost depth simulated by WEPP v2006.5 differed significantly from the observed value (table 5). WEPP v2006.5 simulated a frost penetration mostly around 180 mm and a longer frost period (fig. 2d) than observed due to an error in estimating energy balance at the freezing front.
Using the same WEPP inputs as in WEPP v2010.1, WEPP v2006.5 underestimated annual runoff and sediment yield (figs. 3c and 3d) with PBIAS of -86% and -62%, respectively (table 5). Simulated annual runoff and sediment yields were both significantly different from field observations. WEPP v2006.5 simulated fewer runoff and erosion events and lower sediment yield for all but one extreme event than WEPP v2010.1 (fig. 3). The observed extreme event occurred in December 1983 with 28 mm of runoff and 21 t ha⁻¹ of sediment yield. WEPP v2006.5 simulated 20.1 mm runoff and 85 t ha⁻¹ sediment yield due to a simulated rain-on-snow-on-thawing-soil condition. The simulated and observed runoff was compatible. However, the simulated sediment yield is much larger than the observed value. Both WEPP v2006.5 and v2010.1 generated summer runoff and erosion events that were not observed in the field. Compared to v2010.1, v2006.5 reproduced less winter runoff and erosion events (fig. 3).

**WEPP v2010.1 AND V2006.5 RESULTS FOR THE MORRIS PLOT**

WEPP v2010.1 satisfactorily simulated snow depth and snow cover for the Morris plot (fig. 4a). No significant difference between the WEPP v2010.1 simulated and field-observed snow depths was detected by Wilcoxon signed-rank test (table 7). Simulated frost depths differed from field observations from the Wilcoxon signed-rank test (table 7). WEPP v2010.1 overestimated frost depth with a PBIAS of 27% (table 7). The model properly simulated the frost penetration rate and maximum frost depth (fig. 4b). It also properly simulated the thawing rates as well as periods when frost was observed.

The Wilcoxon test indicated no significant difference between WEPP v2006.5 simulated and field-observed snow depth for the Morris plot (table 7, fig. 4c). WEPP v2006.5 significantly underestimated frost duration and penetration (table 7, fig. 4d). Both WEPP v2006.5 and v2010.1 adequately captured the observed snow accumulation and

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**Figure 4. Comparison of WEPP-simulated and field-observed snow (upper panels) and frost (lower panels) depths for the Morris plot at Morris, Minnesota.**

**Table 7. Statistical tests comparing WEPP simulation results and field observations for the Morris plot at Morris, Minnesota.**

<table>
<thead>
<tr>
<th>WEPP Version</th>
<th>Parameters[b]</th>
<th>Simulated[c]</th>
<th>PBIAS (%)</th>
<th>Wilcoxon Test[^d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>v2010.1</td>
<td>Snow depth, mm (87)</td>
<td>180 (178)</td>
<td>73 (84)</td>
<td>-8</td>
</tr>
<tr>
<td></td>
<td>Frost depth, mm (157)</td>
<td>591 (496)</td>
<td>321 (311)</td>
<td>27</td>
</tr>
<tr>
<td>v2006.5</td>
<td>Snow depth, mm (87)</td>
<td>178</td>
<td>120</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Frost depth, mm (157)</td>
<td>115</td>
<td>98</td>
<td>-79</td>
</tr>
</tbody>
</table>

[a] SD = standard deviation (root mean square), SEE = standard error of the estimate, and PBIAS = percent bias.
[b] Values in parentheses are sample sizes.
[c] Values in parentheses are field-observed values.
[^d] Significance level α = 0.05.
melt, yet WEPP v2010.1 better reproduced frost penetration and frost duration (fig. 4).

SUMMARY AND CONCLUSIONS

This study aimed to modify the algorithms and subroutines of WEPP v2006.5 that inadequately describe soil freezing and thawing processes so that WEPP can be applied to adequately simulate soil freezing and thawing processes as well as winter runoff generation in cold regions where winter hydrology is important, and to assess the performance of the modified model by applying it to two experimental research sites under different climatic conditions.

Limitations of the frost simulation routines in WEPP v2006.5 were identified, and new frost simulation routines were developed and implemented in WEPP v2010.1. Specifically, improvement was made in (1) discretization of a snow-residue-soil system; (2) computation of soil temperature, soil water movement in unsaturated soil, and saturated hydraulic conductivity of frozen soil; and (3) integration of the frost-simulation routines and other water balance routines of WEPP. The refined WEPP model has the ability to account for multiple sandwiched frost layers and soil water migration to the freezing front. Further, the model allows for interaction between hourly frost simulation and other daily water balance computations. Comparison of the results from WEPP v2006.5 and v2010.1 shows that the new version can be used to more realistically simulate winter hydrologic processes in cold regions.

Model performance assessment was carried out by applying the WEPP model to experimental research sites at Pullman, Washington, and Morris, Minnesota. Considerably different snow and frost characteristics were observed from the study plots at the Pullman and Morris research sites. Pullman is typified by rapid snow melt and numerous freeze-thaw cycles under a Mediterranean climate, and Morris is typified by long-lasting snow cover and frost presence under continental climate. Comparison of WEPP model results from v2006.5 and v2010.1 showed that WEPP v2010.1 had substantial improvement in simulating snow and frost depth for both study sites as well as in predicting winter runoff events and annual runoff and sediment yield from the Pullman site.

WEPP v2010.1 simulated contrasting snow and frost characteristics for the two study sites, consistent with field observations. With the new frost routines, WEPP v2010.1 more adequately simulated the major winter processes at the study sites. WEPP-simulated snow and frost depths, snow cover period, and frost duration were in reasonable agreement with field observations for both study sites. WEPP simulated the runoff events for the Pullman site reasonably well.

WEPP v2010.1 showed great potential for evaluating winter hydrologic and erosion processes in cold regions, which is a marked improvement in accuracy over WEPP v2006.5. However, it was not able to fully describe the dynamic winter processes in the field at the daily time scale. Snow accumulation and melt, and soil freeze-thaw are complex processes that are impacted by numerous factors, including weather characteristics, surface conditions, and soil type. Future efforts should be devoted to further improving the ability of WEPP in simulating snow pack dynamics and the transient change of soil hydraulic conductivity and erodibility parameters.

ACKNOWLEDGEMENTS

We are grateful to Drs. W. J. Elliot, G. N. Flerchinger, and C. O. Stöckle for their valuable discussions on winter hydrologic processes and for their comments that helped to improve the technical rigor and editorial clarity of the manuscript. We thank Mr. J. R. Morse and Drs. C. Lin and B. S. Sharratt for their suggestions about WEPP input preparation and discussions on field observations. We are also thankful to the anonymous reviewers and the ASABE associate editor for their constructive comments and suggestions that substantially helped to improve the manuscript.

REFERENCES


