MODELING WINTER HYDROLOGICAL PROCESSES UNDER DIFFERING CLIMATIC CONDITIONS: MODIFYING WEPP

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the dissertation of SHUHUI DUN find it satisfactory and recommend that it be accepted.

Chair

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Abstract

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Water erosion is a serious and continuous environmental problem worldwide. In cold regions, soil freeze and thaw has great impacts on infiltration and erosion. Rain or snowmelt on a thawing soil can cause severe water erosion. Of equal importance is snow accumulation and snowmelt, which can be the predominant hydrological process in areas of mid- to high latitudes and forested watersheds. Modelers must properly simulate winter processes to adequately represent the overall hydrological outcome and sediment and chemical transport in these areas.

Modeling winter hydrology is presently lacking in water erosion models. Most of these models are based on the functional Universal Soil Loss Equation (USLE) or its revised forms, e.g., Revised USLE (RUSLE). In RUSLE a seasonally variable soil erodibility factor (K) was used to account for the effects of frozen and thawing soil. Yet the use of this factor requires observation data for calibration, and such a simplified approach cannot represent the complicated transient freeze-thaw processes and their impacts on surface runoff and erosion.

The Water Erosion Prediction Project (WEPP) watershed model, a physically-based erosion prediction software developed by the USDA-ARS, has seen numerous applications within and outside the US. WEPP simulates winter processes, including snow accumulation, snowmelt, and soil freeze-thaw, using an approach based on mass and energy conservation. However, previous studies showed the inadequacy of the winter routines in the WEPP model. Therefore, the objectives of this study were:

1. To adapt a modeling approach for winter hydrology based on mass and energy conservation, and to implement this approach into a physically-oriented hydrological model, such as WEPP; and
2. To assess this modeling approach through case applications to different geographic conditions.

A new winter routine was developed and its performance was evaluated by incorporating it into WEPP (v2008.9) and then applying WEPP to four study sites at different spatial scales under different climatic conditions, including experimental plots in Pullman, WA and Morris, MN, two agricultural drainages in Pendleton, OR, and a forest watershed in Mica Creek, ID. The model applications showed promising results, indicating adequacy of the mass- and energy-balance-based approach for winter hydrology simulation.

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CHAPTER ONE

INTRODUCTION

1.1. Background

Soil erosion by water is a serious and continuous environmental problem worldwide (Lowdermilk, 1953; Brown and Wolf, 1984; Pimentel, 2000; Trimble and Crosson, 2000; Rustomji et al., 2008; Valentin et al., 2008). Runoff erodes fertile top soil away from productive agricultural land and transports sediment to surface water bodies degrading soil quality (Adams, 1949; Morgan, 1977; Pimentel, 1993; Lal et al., 2004) and polluting water resources (USEPA, 1996). In cold regions, soil freeze and thaw has a great impact on infiltration capacity (Storey, 1955; Boll, 1998; McCauley et al., 2002) and erosion properties (Bullock et al., 1988; Kok and McCool, 1990; Van Klaveren and McCool, 1998) of a soil. Rain or snowmelt on a thawing soil can cause extreme water erosion events (Wade and Kirkbride, 1998; Oygarden, 2001; McCool, 2002). Of equal importance is the snow accumulation and snowmelt process, which can be the predominant hydrological process in some regions, e.g., areas of mid- to high latitudes and forested watersheds (Barnett et al., 2005). Modelers must properly simulate winter processes in order to adequately represent the overall hydrological outcome and sediment and chemical transport in cold regions.

Modeling of winter hydrological processes is presently lacking or inadequate in water erosion models. Most current watershed erosion models are based on the functional Universal Soil Loss Equation (USLE) or its various revised forms, e.g., Revised USLE (RUSLE; Renard et al., 1991). Two such watershed erosion models are the AGricultural Non-Point Source Pollution Model (AGNPS; Young et al., 1987) and the Soil and Water Assessment Tool (SWAT; Neitsch et al., 2005). In RUSLE, for most areas, a seasonally varying soil erodibility factor (*K*) was developed to account for the effects of frozen and thawing soil (Renard et al., 1994). Yet the use of this factor requires observation data for calibration. Furthermore, such a simplified approach cannot represent the complicated transient freeze-thaw processes and their impacts on surface runoff and erosion. Recently, effort has been devoted to adapting the Simultaneous Heat and Water (SHAW; Flerchinger and Saxton, 1989) model into a winter-enhanced AnnAGNPS (Annualized AGNPS; Moore et al., 2006).

The Water Erosion Prediction Project (WEPP) watershed model, a physically-based erosion prediction software developed by the US Department of Agriculture (USDA) to replace the USLE (Laflen et al., 1991,1997), has seen numerous applications within and outside the US (Flanagan et al., 2007). WEPP simulates winter processes, including snow accumulation, snowmelt, and soil freeze and thaw, using an approach based on mass and energy conservation (Savabi et al., 1995). However, previous studies showed the inadequacy of the winter simulation routines in the WEPP model (Kennedy and Sharratt, 1998; McCool et al., 1998; Pannkuk et al., 2000; Greer et al., 2006).

1.2. Objectives

The goal of this dissertation was to adapt a modeling approach for winter hydrology based on mass and energy conservation, and to implement this approach into a physically-oriented hydrological model, such as the USDA's WEPP model; and to assess this modeling approach through case applications to different geographic and environmental conditions. To achieve this goal, I assessed the performance of WEPP v2004.7 with an alternative soil frost simulation routine developed by Lin and McCool (2006) based on an energy-budget approach. This alternative approach could reproduce major winter processes (e.g., snow and frost depths, runoff and erosion) for certain observed periods, yet it cannot consistently represent all the complicated winter phenomena observed in the field. I next adapted an approach for frost simulation based on mass- and energy conservation, as was in the WEPP model. I developed new soil frost simulation routines following the mass-energy-balance- conservation approach and integrated these routines into WEPP (v2008.9). Additionally, I examined and modified WEPP's routines for snow accumulation and snowmelt, which is another important winter process. This latter effort contributed particularly to improving snow simulation under forest settings or for crop- and rangelands with thick and long-lasting snowpacks.

The performance of the modified winter hydrology routines in the WEPP model (v2008.9) was evaluated through case applications to four study sites at different spatial scales under different climatic conditions, including the experiment plots near Pullman, WA and Morris, MN; two small agricultural drainages near Pendleton, OR; and a forest watershed near Mica Creek, ID. These studies were carried out collaboratively. The goal and objectives of the respective case studies were:

1. To examine the performance of WEPP v2004.7 with an alternative frost simulation routine developed by Lin and McCool (2006) based on an energy-budget approach using long-term erosion research plots established and monitored at the USDA Palouse Conservation Field Station (PCFS), Pullman, WA. The specific objectives were to (i) evaluate winter hydrological and erosion processes as affected by continuous tilled bare fallow(CTBF) and no-tillage (NT) seeding in the U.S. Pacific Northwest; and (ii) assess the suitability of WEPP with this alternative frost simulation routine for quantifying the field-observed winter processes.
2. To improve WEPP v2006.5 so that it 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. The specific objectives were: (i) to modify the algorithms and subroutines of

WEPP v2006.5 that improperly describe soil freezing and thawing processes; and (ii) to assess the performance of the modified model (WEPP v2008.9) by applying it to two research experimental sites under different climatic conditions of Pullman, WA and Morris, MN.

3. To assess the performance of the WEPP v2008.9 model in simulating small drainages under different dryland cropping systems in Northeastern Oregon. The specific objectives were to evaluate the abilities of WEPP to simulate: (i) spatial variability in soil water content and ET throughout two headwater catchments; (ii) surface runoff and sediment yield at the outlet of the catchments; and (iii) crop yield and biomass production in two- and four-year winter wheat cropping rotations.
4. To assess the performance of the WEPP v2008.9 model in simulating the major components in water balance under forest settings using field data. The specific objectives were: (i) to present field-observed water balance and major components, including streamflow, tree transpiration, and transient soil water content, for Mica Creek Experimental Watershed (MCEW) located in Shoshone County, northern Idaho; and (ii) to evaluate the suitability of WEPP in simulating these hydrologic processes under forest settings by applying the model to the watershed.

1.3 Thesis Outline

This dissertation includes six chapters: an introduction, four major technical chapters, and a conclusion. Ch.1 introduces the main objectives of the dissertation. Ch. 2 reports a study involving field experimentation and WEPP simulation of winter hydrological and erosion processes under two contrasting tillage treatments in the US Palouse Region. Specifically, an alternative energy-budget approach for frost simulation implemented in WEPP v2004.7 was evaluated using frost-tube data, and WEPP-simulated winter runoff and erosion were compared with field observations. This chapter has been accepted for publication in *Vadose Zone J*.

Ch. 3 presents a frost simulation routine based on mass- and energy conservation and the implementation of this routine into a physically-based hydrology and water erosion model, Water Erosion Prediction Project (WEPP, v2008.9). The adequacy of this routine was examined by applying WEPP to two study sites under different climatic conditions of Pullman, WA and Morris, MN. This chapter has been adapted for submission to *Trans. ASABE*. References for Ch. 1 and 3 are listed at the end of the chapter.

Ch. 4 investigates the adequacy and performance of WEPP v2008.9 for runoff and water erosion prediction for two small drainages of Northeastern Oregon under dryland farming. A technical manuscript based on this chapter has been submitted to *J. Soil Water Conserv*.

Ch. 5 presents a study applying WEPP v2008.9 to quantify field-observed water balance under forest setting in the US Pacific Northwest. The work has been adopted for publication in *Hydrol. Process*.

Ch. 6 summarizes the major conclusions of this doctoral study. The appendices include the (A) Limitations of the frost routines in WEPP v2006.5, (B) Modular flowcharts for one-dimensional simulation of soil freeze and thaw as well as snow accumulation and snowmelt, (C) Soil water potential at freezing front, (D) Thermal conductivity of snow, residue and soil, (E) WEPP inputs for case applications, and (F) Statistical comparison of WEPP-predicted and field-observed winter hydrological data.

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CHAPTER TWO

WINTER HYDROLOGICAL AND EROSION PROCESSES IN THE U.S. PALOUSE REGION: FIELD EXPERIMENTATION AND WEPP SIMULATION

This chapter has been submitted to *Vadose Zone Journal* and is accepted for publication. Full citation: Singh, P., J.Q. Wu, D.K. McCool, S. Dun, C-H Lin, and J.R. Morse. 2008. Winter hydrological and erosion processes in the US Palouse region: Field experimentation and WEPP simulation. *Vadose Zone J.* (in press). My contribution to the manuscript is summarized in the following. Data collection: two field trips and subsequent laboratory data analysis for soil water content profiling during spring snowmelt season. WEPP modeling: incorporated and improved the alternative winter routine by Lin and McCool (2006) into WEPP v2004.7, which was used in this study; and contributed to the analysis and interpretation of WEPP simulation results. Development of manuscript: provided comments and suggestions on the original and twice revised manuscript to improve the technical rigor as well as the structure and clarity of the manuscript.

2.1. Abstract

Soil erosion by water is detrimental to soil fertility and crop yield as well as the environment. For cold areas, knowledge of winter hydrological processes is critical to determining alternative land-use and management practices for reducing soil loss and protecting land and water resources. Adequate understanding of these processes is also essential to developing models that can serve as cost effective predictive tools. The objectives of this study were to: (i) evaluate winter hydrological and erosion processes as affected by two contrasting tillage treatments; and (ii) assess the suitability of WEPP (Water Erosion Prediction Project), a physically-based erosion model with a newly implemented energy-budget-based winter routine, for quantifying the field-observed winter processes. Long-term erosion research plots subject to two tillage treatments: a worst-treatment

control, continuous tilled bare fallow (CTBF), and continuous no-tillage seeding of winter wheat after spring cereal (NT), were established at the USDA-ARS Palouse Conservation Field Station near Pullman, WA. The plots were continually monitored for runoff, erosion, soil temperature and water content, and depths of snow and freeze-thaw during October to May 2003–04 through 2006–07. Field data showed that NT plots generated negligible runoff and erosion compared to CTBF that produced substantially greater runoff and erosion. Further, frost occurred more frequently and frost depth was deeper in the CTBF treatment, likely due to its lack of residue and smaller snow depth, compared to the NT treatment. The modified WEPP model could reasonably reproduce major winter processes (e.g., snow and frost depths, runoff and erosion), but it could not represent all the complicated winter phenomena observed in the field. Continued efforts are needed to further improve the ability of WEPP to properly account for soil freeze-thaw and thus the transient soil hydraulic properties and hydrologic and erosion processes.

2.2. Objectives

The objectives of this study were to (i) evaluate winter hydrological and erosion processes as affected by CTBF and NT in the U.S. Pacific Northwest; and (ii) assess the suitability of WEPP v2004.7 with a newly implemented energy-budget approach (Lin and McCool, 2006) for quantifying the field-observed winter processes.

2.3. Materials and Methods

- Experimental site and field monitoring
- WEPP application
    - ‣ WEPP overview

    - WEPP inputs and simulation
- Statistical analysis

2.4. Results

Table 2.1.
Soil inputs for the WEPP simulation.

Parameter	Value
Texture	Silt loam
Number of soil layers	6
Albedo	0.23
Initial saturation of soil porosity, $m^3\ m^{-3}$	0.9
Baseline interrill erodibility, $kg\ s\ m^{-4}$	4.95×10^{6}†
Baseline rill erodibility, $s\ m^{-1}$	8.0×10^{-3}
Baseline critical shear, $N\ m^{-2}$	0.74

† Soil erodibility parameters, including interrill and rill erodibility and critical shear, are from Elliot et al. (1989).

Table 2.2.
Management inputs used in the WEPP simulations for the continuous till bare fallow (CTBF) and no-tillage (NT) treatments.

Parameter	CTBF	NT
Ridge height value after tillage, m	0.02	--
Ridge interval, m	0.2	--
Random roughness value after tillage, m	0.012	--
Fraction of surface area disturbed	1.0	0
Bulk density after last tillage, Mg m^{-3}	1.1	1.1
Initial frost depth, m	0	0
Cumulative rainfall since last tillage, m	0.375	0.375
Initial ridge height after last tillage, m	0.01	0.01
Initial ridge roughness after last tillage, m	0.01	0.01
Initial snow depth, m	0	0
Depth of tillage layer, m	0.2	0
Initial total submerged residue mass, kg m^{-2}	--	0.17
Initial total dead root mass, kg m^{-2}	--	0.33
Stubble height, m	--	0.15

Table 2.3.
Observed runoff and erosion and WEPP-simulated surface runoff (*R*), soil evaporation (*Es*), plant transpiration (*Ep*), deep percolation (*Dp*), subsurface lateral flow (*Q*), change in soil water (Δθ) and erosion for each monitored period under the continuous tilled bare fallow (CTBF) and no-tillage (NT) treatments.

		Observed[‡]		Simulated						
	$P^{\dagger}$	*R*	Erosion	*R*	*Es*	*Ep*	*Dp*	*Q*	Δθ	Erosion
	mm	mm	t ha^{-1}	mm	mm	mm	mm		mm	t ha^{-1}
		CTBF								
2003–04	417	67 (52, 62)	77 (35, 21)	108	233	0	42	0	34	53
2004–05	214	22 (2, 0)	3 (0.2, 0)	57	153	0	6	0	−2	48
2005–06	360	137 (102, 118)	150 (95, 92)	75	231	0	28	0	26	85
2006–07	336	97 (74, 89)	317 (214, 175)	76	211	0	27	0	22	90
		NT								
2003–04	417	0.3 (0, 0.5)	0.2 (0, 0.001)	36	108	160	30	22	61	0.03
2004–05	214	0 (0, 0)	0 (0, 0)	0	42	177	0	0	−5	0
2005–06	360	0.1 (0, 0.1)	0 (0, 0)	0	103	158	43	0	56	0
2006–07	336	0.1 (0, 0)	0 (0, 0)	0	91	149	45	1	50	0

[†] Precipitation values were for the monitored period of October to May.

[‡] For each period, the first value is for the plot on the 23% slope; the second and third values (in parentheses) are for plots on the 24% and 17% slopes, respectively.

Table 2.4.

Observed and simulated maximum snow and frost depths and total frozen-soil days for each monitored period under the continuous tilled bare fallow (CTBF) and no-tillage (NT) treatments.

	Observed[†]			Simulated		
	Max. snow depth mm	Max. frost depth mm	Frozen-soil days	Max. snow depth mm	Max. frost depth mm	Frozen-soil days
			CTBF			
2003–04	177	124	24	338	340	86
2004–05	80	187	26	81	366	44
2005–06	72	234	36	65	214	39
2006–07	78	167	57	89	106	72
			NT			
2003–04	225	36	14	409	130	128
2004–05	114	75	32	192	21	29
2005–06	123	132	29	127	8	40
2006–07	131	86	54	140	113	105

[†] Values are for individual plots on the 23% slope.

Table 2.5.

Runoff and erosion events for each monitored period under the continuous tilled bare fallow (CTBF) plot on the 23% slope separated into those with non-frozen, frozen, and thawed soil conditions.

	2003–04	2004–05	2005–06	2006–07	Total
			Non-frozen		
No. of events	3	5	25	10	43 (57)[†]
Runoff, mm	6	11	111	20	148 (44)
Erosion, t ha^{-1}	17	1	106	31	155 (28)
			Frozen		
No. of events	6	0	1	2	9 (12)
Runoff, mm	21	0	1	10	32 (9)
Erosion, t ha^{-1}	29	0	2	7	38 (7)
			Thawed		
No. of events	5	2	7	9	23 (31)
Runoff, mm	40	11	39	68	158 (47)
Erosion, t ha^{-1}	32	2	56	279	369 (65)

[†] Shown in parentheses are percentages of the total.

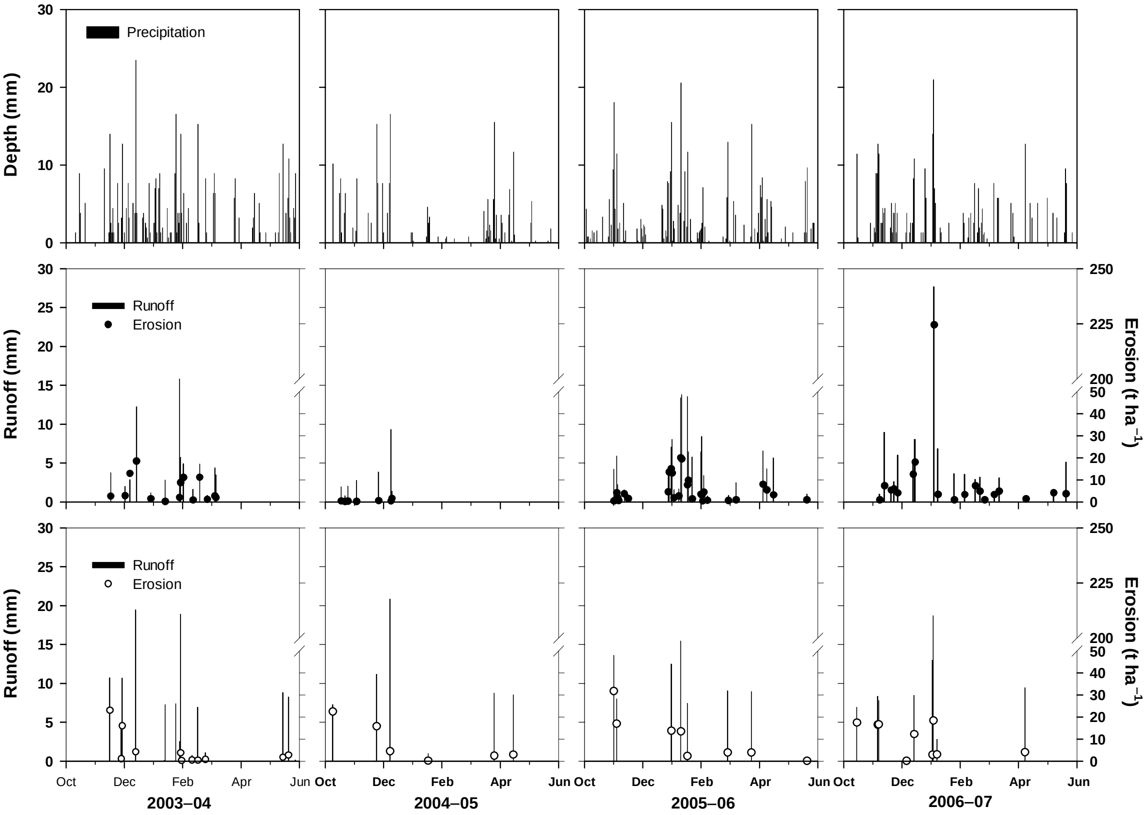

Figure 2.1. Observed daily precipitation (top panel), observed runoff and erosion (middle panel), and simulated runoff and erosion (bottom panel) in the continuous tilled bare fallow (CTBF) plot for each monitored period.

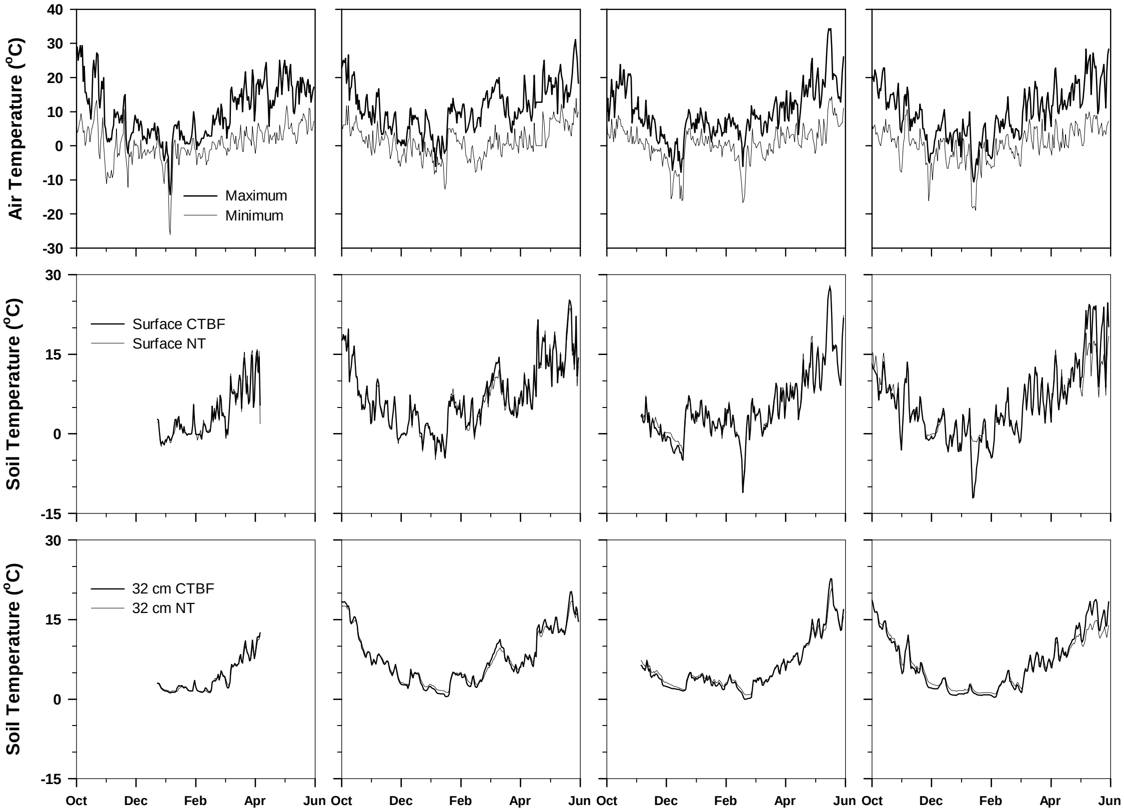

Figure 2.2. Observed air temperature (top panel), observed soil temperature at the 4-cm (middle panel) and 32-cm (bottom panel) depths for the continuous tilled bare fallow (CTBF) and the no-tillage (NT) for each monitored period.

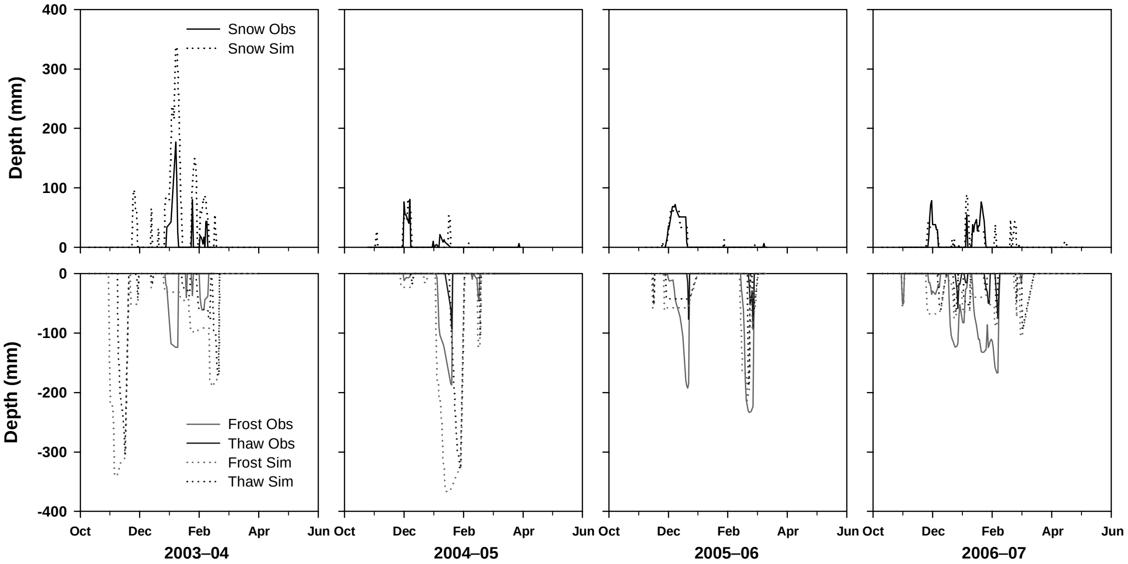

Figure 2.3. Observed and simulated snow depths (top panel), and frost and thaw depths (bottom panel) in the continuous tilled bare fallow (CTBF) plot for each monitored period. The observed frost and thaw depths were based on frost-tube readings. All events were captured during each monitored period, except those before December 23, 2003.

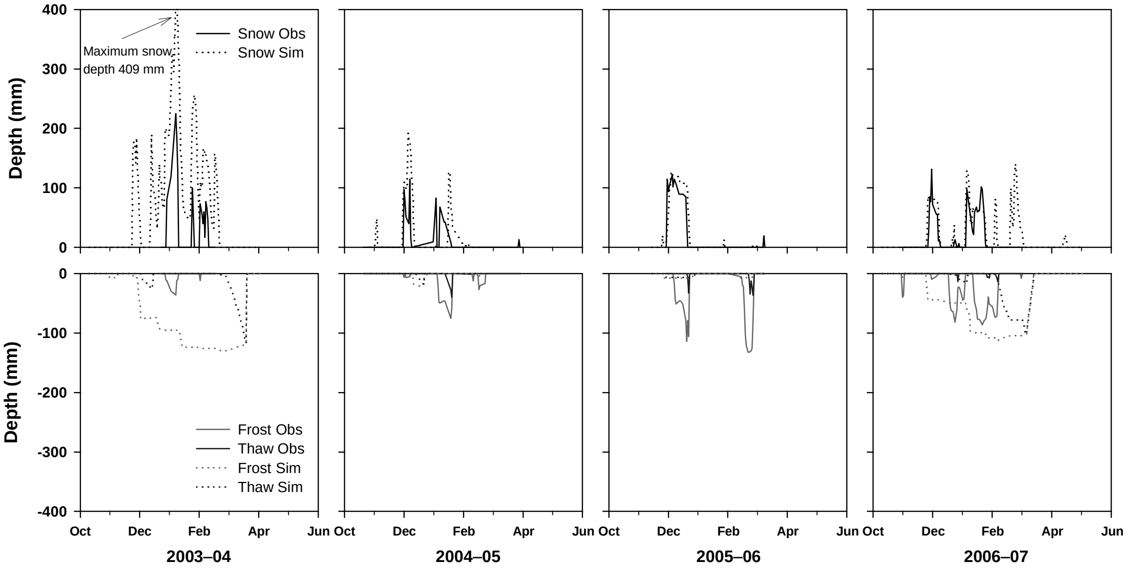

Figure 2.4. Observed and simulated snow depths (top panel), and frost and thaw depths (bottom panel) in the no-tillage (NT) plot for each monitored period. The observed frost and thaw depths were based on frost-tube readings. All events were captured during each monitored period, except those before December 23, 2003.

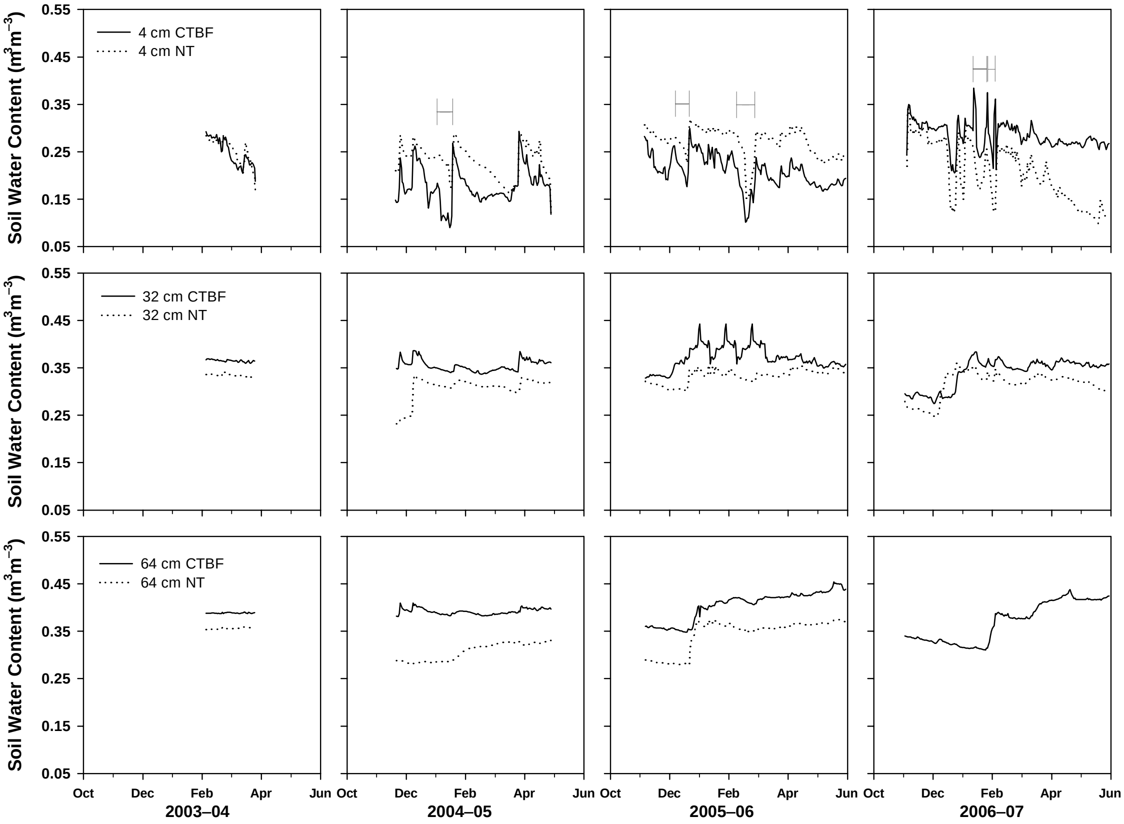

Figure 2.5. Observed soil liquid-water content at the 4-, 32-, and 64-cm depths (top, middle, and bottom panels, respectively) for the continuous tilled bare fallow (CTBF) and the no-tillage (NT) treatments for each monitored period. NOTE missing data at the 64-cm depth in the NT for 2006-07. The marks in the top panel indicate frost periods where soil liquid-water content measurements were affected by ice formation.

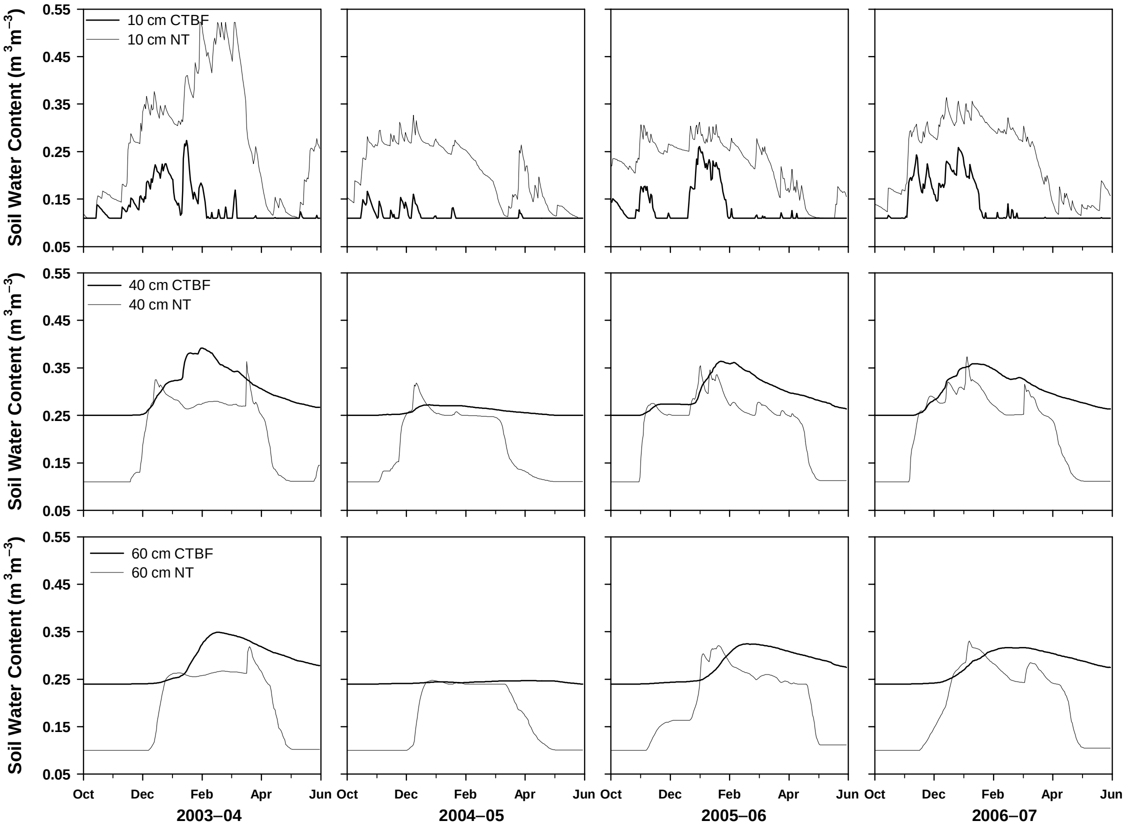

Figure 2.6. Simulated total soil water content at the 10-, 40-, and 60-cm depths (top, middle, and bottom panels, respectively) for the continuous tilled bare fallow (CTBF) and the no-tillage (NT) treatments for the monitored period.

2.5. Summary and Conclusion

This study aimed to evaluate winter hydrological and erosion processes as affected by two contrasting tillage practices; and to assess the suitability of the USDA's WEPP model for quantifying the field-observed winter processes. Field measurements of runoff and erosion as well as the depths of snow, soil frost, and thaw suggested that the effects of tillage practices on winter hydrologic and erosion processes were evident and prominent.

The CTBF treatment produced shallower snow depth and deeper frost depth, compared to the NT treatment. The CTBF generated significant amount of runoff and erosion whereas the NT produced negligible runoff and erosion. For the study period, the majority of the runoff events occurred under non-frozen conditions, yet the thawed events resulted in most of the soil erosion under the CTBF.

The WEPP model, with an alternative energy-budget-based winter routine, could well reproduce certain winter processes, including snow depth, runoff and erosion, for some monitored periods (October to May) for both the CTBF and NT. WEPP-simulated frost and thaw depths as well as the number of frozen-soil days were in reasonable agreement with field observations in certain monitor periods.

WEPP showed the potential as a modeling tool for assessing the effect of management practices on winter hydrologic and erosion processes. Yet it is not able to represent all the complicated winter phenomena observed in the field. Snow accumulation and melt, and soil freeze-thaw are complex processes that are affected by many factors. Dramatic changes in soil resistance to erosion of frozen, non-frozen and thawed soil surfaces at the time of rainfall or snowmelt or both could complicate the erosion processes, posing great challenges to modeling. Continued efforts are needed to further improve the ability of WEPP to properly account for soil freeze and thaw and thus the transient soil hydraulic properties and hydrologic and erosion processes.

CHAPTER THREE

DEVELOPMENT AND IMPLEMENTATION OF FROST SIMULATION ROUTINES FOR HYDROLOGICAL MODELING BASED ON MASS- AND ENERGY CONSERVATION[*]

3.1. 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, a physically-based erosion prediction software program developed by the US Department of Agriculture (USDA), has a major component to simulate winter processes, including 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 US and in a number of other countries. However, a preliminary study 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 so that it can be applied to adequately simulate soil freeze and thaw as well as winter runoff and erosion in cold regions. The specific objectives were: (1) to modify the related algorithms and subroutines in WEPP v2006.5 that improperly represent soil freezing and thawing processes; and (2) to assess the performance of the modified model by applying it to two research plots under different climatic conditions.

Changes in soil profile discretization and computation of key thermal ans hydraulic parameters

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were made in the frost simulation routines of WEPP (v2006.5), and the modified WEPP (v2008.9) was applied to the research experimental plots located in Pullman, WA, and Morris, MN. Simulation results from WEPP v2008.9 were compared with those from WEPP v2006.5 as well as field observations. The results from WEPP v2008.9 showed substantially improved agreement with field data compared to those from WEPP v 2006.5.

3.2. Introduction

In cold regions frozen soil has a significant influence on runoff and soil erosion (Horner et al., 1944; McCool and Molnau, 1974; 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 may occur due to the presence of frozen soil and subsequent thawing (Oygarden, 2001; Singh et al., 2008). Long-term field studies in the Palouse Region of the US Pacific Northwest showed that more than 70% of water erosion was produced due to soil freezing and thawing, and the largest erosion events occurred on thawed soil (McCool et al., 2006; Singh et al., 2008). Widespread severe soil erosion due to rapid snowmelt on thawing soils in the hilly undulating lowlands of eastern Scotland was also reported (Wade and Kirkbride, 1998).

Freeze-thaw degrades soil cohesive strength (Formanek et al., 1984; Kok and McCool, 1990) and increases soil erodibility (Van Klaveren and McCool, 1998). Frozen soil not only can substantially reduce infiltration (Boll, 1998; McCauley et al., 2002) thus increasing surface runoff but also can move significant amount of water in wet silt or corse clay from deeper soil to the freezing front (Miller, 1980) causing runoff to occur 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 perching above the frozen layer, and lead to extreme erosion vulnerability (Froese and Cruse, 1997).

Knowledge of frost formation is important for developing sound management practices for reducing winter runoff and erosion. Adequate 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 US Department of Agriculture (USDA) (Laflen et al., 1991; 1997). The WEPP model includes a major component to simulate winter processes, including soil freeze and thaw (Flanagan et al., 2001). WEPP has seen numerous applications within and outside the US (Flanagan et al., 2007). The model was used for evaluating the impacts of various management practices and natural disturbances in a forest setting (Elliot et al., 1995; Elliot and Hull, 1997; Elliot et al., 1999; Elliot, 2004; Robichaud et al., 2007; Dun et al., 2008). 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, assessment of the performance of winter routines of WEPP (Kennedy and Sharratt, 1998; McCool et al., 1998; Pannkuk et al., 2000; Greer et al., 2006) has found that the winter component of WEPP was inadequate in (i) simulation of frost depth and duration, and (ii) representing 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 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. The specific objectives were:

1. To modify the algorithms and subroutines of WEPP (v2006.5) that improperly describe soil freezing and thawing processes; and
2. To assess the performance of the modified model by applying it to two experimental research

sites under different climatic conditions.

3.3. Materials and Methods

3.3.1. 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 ability to account for the hydrology and erosion processes under different climate, vegetation and residue management, soil, and topographic conditions.

WEPP discretizes a soil profile into two 10-cm layers for the top 20-cm tillage zone, and 20-cm layers for the remainder in computing daily water balance. The winter routines of the WEPP model simulate snow accumulation and melt and soil freeze and thaw on an hourly basis. The winter processes are evaluated when a snowpack or a soil frost layer exists, or 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 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 energy balance at the surface of a snow-residue-soil system (Figure 3.1). The estimated surface temperature is used to determine heat flow to or from a freezing front (0 °C isothermal) due to a temperature gradient. WEPP accounts for thermal resistence of snow, residue, frozen soil, and unfrozen soil in heat transfer. At a freezing front, heat conducted from the surface of the system is first balanced by

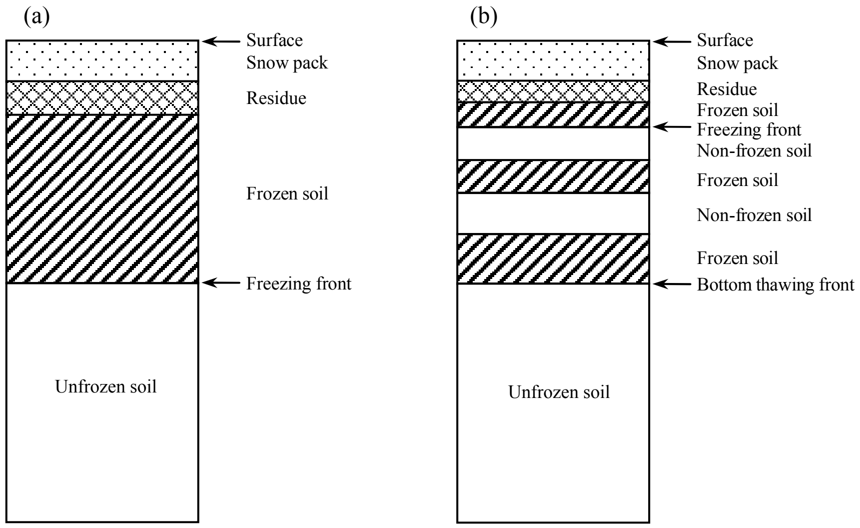

Figure 3.1. Snow-residue-soil system. Soil frost (a) without and (b) with "sandwich" layers.

the heat flow from the unfrozen soil beneath the freezing front and then the latent heat released or absorbed by freezing water or thawing ice in the soil. The thickness of soil frozen or thawed is then determined based on soil water content at the freezing 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 to be converted to ice. Soil temperature one meter below the freezing front is assumed to be 7 °C.

3.3.1.1. Estimation of surface temperature

Hourly temperature at the surface of the residue-snow-soil system, T_{hrs} (°C), was estimated based on energy balance at this position following Eq.1 (Flerchinger, 1987), with the individual terms expanded as Eq. 2–7, and the resultant T_{hrs} given by Eq. 8 (Flerchinger, 1987)

$$\frac{R_s(1-\alpha)}{t} + \varepsilon_a \sigma T_{hraK}^4 - \varepsilon_s \sigma T_{hrsK}^4 + \rho_a c_a \frac{(T_{hra} - T_{hrs})}{r_H} - K_{srf} \frac{(T_{hrs} - 0)}{d_{srf}} = 0 \tag{1}$$

$$\begin{aligned} \varepsilon_s \sigma T_{hrsK}^4 &= \varepsilon_s \sigma T_{hrsK}^4 - \varepsilon_s \sigma T_{hraK}^4 + \varepsilon_s \sigma T_{hraK}^4 \\ &\approx \varepsilon_s \sigma T_{hraK}^4 - 4\,\varepsilon_s \sigma T_{hraK}^3 (T_{hraK} - T_{hrsK}) \\ &= \varepsilon_s \sigma T_{hraK}^4 - 4\,\varepsilon_s \sigma T_{hraK}^3 (T_{hra} - T_{hrs}) \end{aligned} \tag{2}$$

$$R_{net} = \frac{R_s(1-\alpha)}{t} + (\varepsilon_a - \varepsilon_s)\, \sigma T_{hraK}^4 \tag{3}$$

$$R_{cof} = \varepsilon_s \sigma T_{hraK}^3 \tag{4}$$

$$\frac{1}{r_H} = \frac{\kappa^2 v(z)}{\ln\left[\frac{z_v - z_d + z_m}{z_m}\right] \ln\left[\frac{z_v - z_d + z_H}{z_H}\right]} \quad (5)$$

$$K_{conH} = \frac{\kappa^2 \rho_a c_a}{\ln\left[\frac{z_v - z_d + z_m}{z_m}\right] \ln\left[\frac{z_v - z_d + z_H}{z_H}\right]} \quad (6)$$

$$R_{net} + R_{cof}(T_{hra} - T_{hrs}) + K_{conH}\, v(z)\, (T_{hra} - T_{hrs}) - \frac{K_{srf}}{d_{srf}} T_{hrs} = 0 \quad (7)$$

$$T_{hrs} = \frac{R_{net} + [R_{cof} + K_{conH}\, v(z)]\, T_{hra}}{R_{cof} + K_{conH}\, v(z) + \frac{K_{srf}}{d_{srf}}} \quad (8)$$

where energy flux terms [W m^{-2}] in Eq. 1 from left to right are incoming solar radiation, long-wave radiation from air, long-wave radiation from the surface of the residue-snow-soil system, convective heat from air, conductive heat from the residue-snow-soil system, respectively. R_s [J m^{-2}] is solar radiation on a sloping surface, α [-] is albedo of the surface, t [s] is the duration for receiving the solar radiation, and σ [W m^{-2} K^{-4}] is the Stefan-Boltzman constant (5.6697×10^{-8}). ε_s and ε_a [-] are emissivities of the surface and air, respectively. T_{hrsK} and T_{hraK} [°K] are hourly temperatures of the surface and air in Kelvin, respectively. T_{hrs} and T_{hra} [°C] are hourly temperatures of the surface and air in Celsius, respectively. ρ_a [kg m^{-3}], c_a [J kg^{-1} °C^{-1}], and r_H [s m^{-1}] are air density, specific heat and the resistance to heat transfer, respectively. K_{srf} [W m^{-1} °C^{-1}] and d_{srf} [m] are effective thermal conductivity and depth of the residue-snow-frozen-soil system, respectively. R_{net} [W m^{-2}] is net radiation flux, R_{cof} [W m^{-2} °C^{-1}] is radiation coefficient, κ [-] is von Karman's constant, $v(z)$ [m s^{-1}] is wind velocity, z_v, z_d, z_m, and z_H [m] are respectively the height of wind measured, the height of zero-plane displacement of the wind profile, the momentum roughness of the surface, and the surface roughness of the temperature profile, and K_{conH} [J m^{-3} °C^{-1}] is the convective heat transfer coefficient.

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 temperature of the day are assumed to occur at the sunrise and 2:00 pm, respectively. The temperature between the maximum and minimum changes 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.

3.3.1.2. Simulation of frost thickness

Frost simulation in WEPP is a combination of mass- and energy balance at the freezing 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 Eq. 9–11.

$$\frac{L \Delta d_{fz} \theta}{\Delta t} = Q_{srf} - Q_{uf} \tag{9}$$

$$Q_{srf} = \frac{K_{srf}\Delta T_{srf}}{Z_{srf}} \tag{10}$$

$$Q_{uf} = K_{uf}\frac{\Delta T_{uf}}{Z_{uf}} + LK_w\frac{\Delta P}{Z} + \frac{C_{uf}dT_{uf}Z_{uf}}{\Delta t} \tag{11}$$

where L [J m^{-3}] is the latent heat of fusion, Δt [s] is time interval, Δd_{fz} [m] is the thickness of soil frozen or thawed within Δt, and θ (m m^{-3}) is volumetric soil water content. Q_{srf} and Q_{uf} [W m^{-2}] are the heat fluxes through the snow-residue-frozen soil zone and from the unfrozen soil beneath the frozen zone, respectively. Z_{srf} [m] and ΔT_{srf} [°C] are respectively the thickness of the snow-residue-frozen-soil zone and the temperature difference between the top of the snow-residue-frozen-soil zone and the freezing front (0 °C isotherm). Z_{uf} [m] and ΔT_{uf} [°C] are respectively the distance and 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. K_{srf} and K_{uf} [W m^{-1} °C^{-1}] are the average thermal conductivities for the snow-residue-frozen-soil zone and for the unfrozen soil, respectively. K_w [m s^{-1}] is the unsaturated hydraulic conductivity of unfrozen soil, Z [m] and ΔP_{uf} [m] are respectively the soil thickness and the difference of water potential between the freezing front and the center of the underlying unfrozen soil layer, C_{uf} [J m^{-3} °C^{-1}] is the heat capacity of the unfrozen soil, dT_{uf} [°C] is the change in temperature of a unit volume of unfrozen soil within Δt.

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 (i) heat conducted from the unfrozen soil beneath the freezing front, (ii) latent heat released from freezing the water migrated to the freezing front from the underlying unfrozen soil, and (iii) heat released from freezing the water held in place at the freezing front, and thus increasing 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.

3.3.2. Limitations of the frost simulation routines in WEPP v2006.5

Major limitations in the frost simulation routines of WEPP v2006.5 included: (i) 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; (ii) incorrect use of energy flux for the amount of energy; (iii) inadequate assumption of a constant temperature (7 °C) for the unfrozen soil 1m below the freezing front; (iv) no simulation of movement of unsaturated water; (v) accounting for only one frost "sandwich" layer; (vi) insufficient adjustment of saturated hydraulic conductivity of frozen soil (Greer et al., 2006); and (vii) programming errors in computing unsaturated hydraulic conductivity, soil water potential, and upward water movement to a freezing front. A detailed description of these limitations is included in Appendix A.

3.3.3. Development and implementation of frost-simulation routines based on mass- and energy conservation

Frost simulation routines were developed following the same equations in WEPP v2006.5 Eq. 9–11. A main program was developed, which calls nine subroutines that respectively simulate: (i) surface temperature of the snow-residue-soil system, (ii) soil temperature below the bottom-most frozen zone, (iii) freezing of soil water at the freezing front following energy balance, (iv) thawing of top-most frozen soil due to heat from the surface, (v) thawing of bottom-most frozen soil due to heat from underlying unfrozen soil, (vi) unsaturated hydraulic conductivity and matric potential of unfrozen soil based on soil texture and transient volumetric soil water content, (vii) movement of unsaturated soil water within unfrozen soil based on Darcy's law, (viii) saturated hydraulic conductivity of frozen soil, and (ix) updated soil water balance at the end of a simulation step. The surface-temperature subroutine was improved from WEPP v2006.5, while the other subroutines were newly developed. These routines were incorporated into WEPP v2008.9, with the (i) discretization of a snow-residue-soil system, (ii) computation of soil temperature, soil water movement in unsaturated soil, saturated hydraulic conductivity of frozen soil, and thermal conductivity of snow, and (iii) integration of the frost-simulation routines and other water balance routines of WEPP detailed below.

3.3.3.1. 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. The amount of ice, the thickness of frozen soil, and soil water content of unfrozen soil in each layer were explicitly tracked. The fine discretization allowed more accurate simulation of liquid soil water and ice as well as the occurrence of frost "sandwich".

3.3.3.2. Temperature of soil below the bottom-most frozen zone

The temperature of unfrozen soil was estimated following Campbell and Norman (1998), an analytical solution of 1-*d* heat transfer for uniform soil (Eq. 12). 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).

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

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

where T_{avg} and A_0 [°C] are respectively the annual average and amplitude of fluctuation of the temperature at soil surface, $\omega = 2\pi/365$ [rad d^{-1}], D [m] is damping depth, z [m] is soil depth, t [d] is time in Julian day, and t_0 [d] is temporal phase shift.

Eq. 12 and 13 suggest that, for a given time, temperature of the soil underneath 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.

The damping depth in Eq. 12 was assumed to be 2 m for temperature changes on a yearly time scale. Other parameters in Eq. 12, i.e., T_{avg}, A_0, and t_0, were estimated from monthly average temperature approximated by a sine curve. No heat transfer from the unfrozen soil would take place if the estimated temperature for the soil 1 m below the bottom-most frozen zone is below 0 °C.

3.3.3.3. Unsaturated hydraulic conductivity, water characteristic, and soil water movement

Unsaturated hydraulic conductivity and matric potential of unfrozen soil were determined from volumetric soil water content and soil texture of individual computational layers following Saxton and Rawls (2006). Unsaturated soil water movement between computational layers was subsequently calculated on an hourly basis using Darcy's law.

Soil water potential of frozen soil was estimated from soil temperature using the generalized form of the Clausius–Clapeyron equation (Watanabe and Wake, 2008). In calculating soil water potential at a freezing front, soil temperature at this point was assumed the same as the freezing depression temperature, typically ranging 0.01–2.5 °C as a function of volumetric soil water content and soil texture (Kozlowski, 2004). Such a temperature range of a freezing front would lead to a water potential range of −15 m to −3,500 m (see Appendix C for detailed calculation).

3.3.3.4. Saturated hydraulic conductivity of frozen soil

It was assumed that ice in soil occupies pore spaces in the same manner as does air in 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. The estimated unsaturated hydraulic conductivity for the soil water content equal to porosity minus ice content is used as the saturated hydraulic conductivity for frozen soil.

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. Vertical and horizontal hydraulic conductivity 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. Saturated hydraulic conductivity of the lager 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).

3.3.3.5. Thermal conductivity of snow

Snow thermal conductivity was estimated following Sturm et al. (1997) based on snow density

$$K_{snow} = 0.023 + 0.234\,(\rho_{snow}/1000) \qquad \rho_{snow} \le 156 \tag{14}$$

$$K_{snow} = 0.138 - 1.01\,(\rho_{snow}/1000) + 3.233\,(\rho_{snow}/1000)^2 \qquad \rho_{snow} > 156 \tag{15}$$

where K_{snow} [W m^{-1} °C^{-1}] is snow thermal conductivity, and ρ_{snow} [kg m^{-3}] is snow density.

A proportionality coefficient Kf_{snow} was used to adjust for site-specific relationship between thermal conductivity and snow density. In WEPP v2008.9, Kf_{snow} is a user-input parameter with a default value of 1.0.

3.3.3.6. 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 other 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.

3.3.4. Site Description

Two study sites under different climatic conditions were chosen to assess the performance of the winter routines in WEPP v2008.9. One site was the Palouse Conservation Field Station (PCFS, 46°44′N, 117°8′W), located 3 km northwest of Pullman, Washington. Long-term experimental runoff plots have been installed at the PCFS since the 1970's (McCool et al., 2002). Data from these experimental plots included break-point and daily rainfall, snow and frost depths as well as runoff and sediment yield recorded from fall 1983 to spring 1990. A rain gage near the runoff plots and a NOAA weather station (Pullman 2 NW) 0.5 km to the north of the runoff plots (Lin and McCool, 2006) recorded climate data during this study period.

The other study site (45°41′N, 95°48′W) was located near Morris, Minnesota in the northern US Corn Belt. 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).

The PCFS is in the semiarid steppe climate zone of Eastern Washington with an average annul temperature of 8.5 °C and a yearly precipitation of 530 mm. Rapid rise in temperature can occur multiple times during winter. Snow cover is transient, with accumulated snow subject to rapid melt by the warm fronts. Frost in the soil often reaches 0.2 to 0.5 m (WRCC, 2008), and numerous freeze-thaw cycles may occur (McCool, 1990). In contrast, the Morris research site is typified by a continental climate with a mean annual temperature of 5.5 °C and a yearly precipitation of 600 mm. Snow cover persists from early December to late March and soil frost may start to form from mid-November and last to next spring. Soil frost penetrated up to 1.2 m as observed in a field study during 1993–1996 (Sharratt, 2002).

3.3.5. 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 dew-point temperature. Daily precipitation and temperature during the study periods are shown in Figures 3.2 and 3.3. Monthly precipitation and monthly average temperature are shown in Tables 3.1 and 3.2. Annual mean temperature of the two study sites did not differ substantially; however, Morris had much greater temperature fluctuation

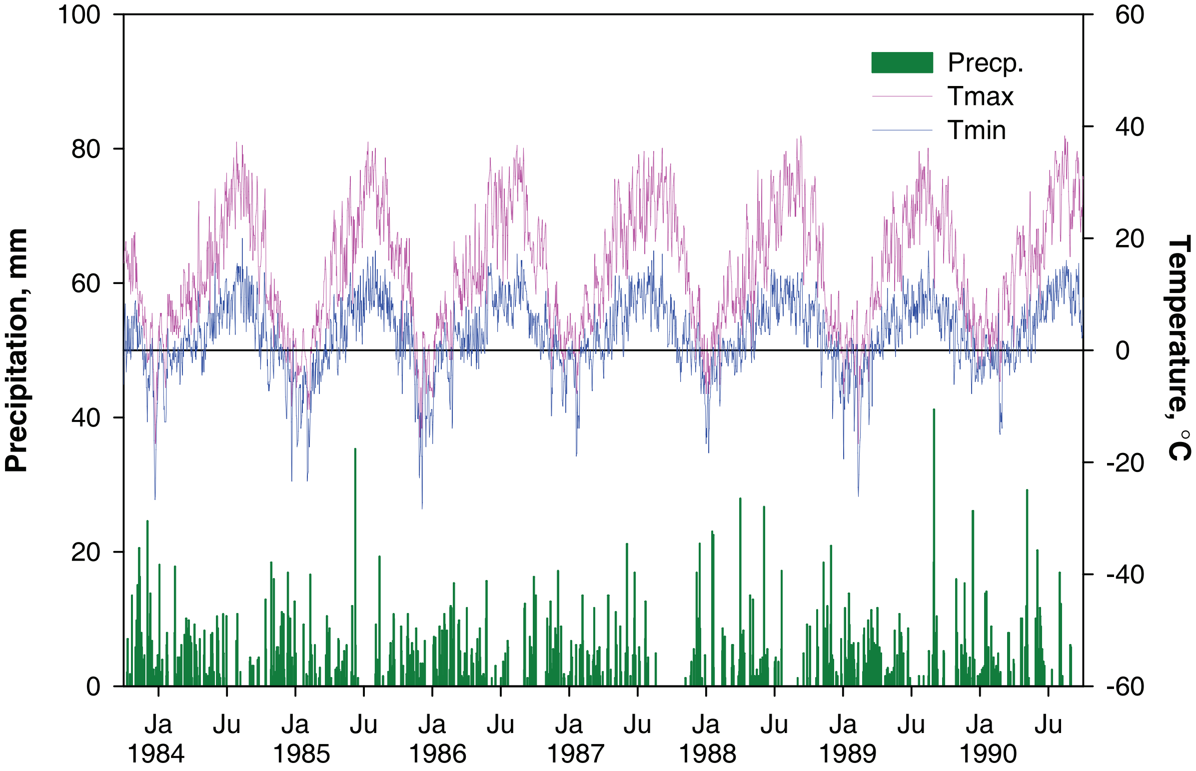

Figure 3.2. Observed daily preciptation and maximum and minimum air temperature, Pullman, WA

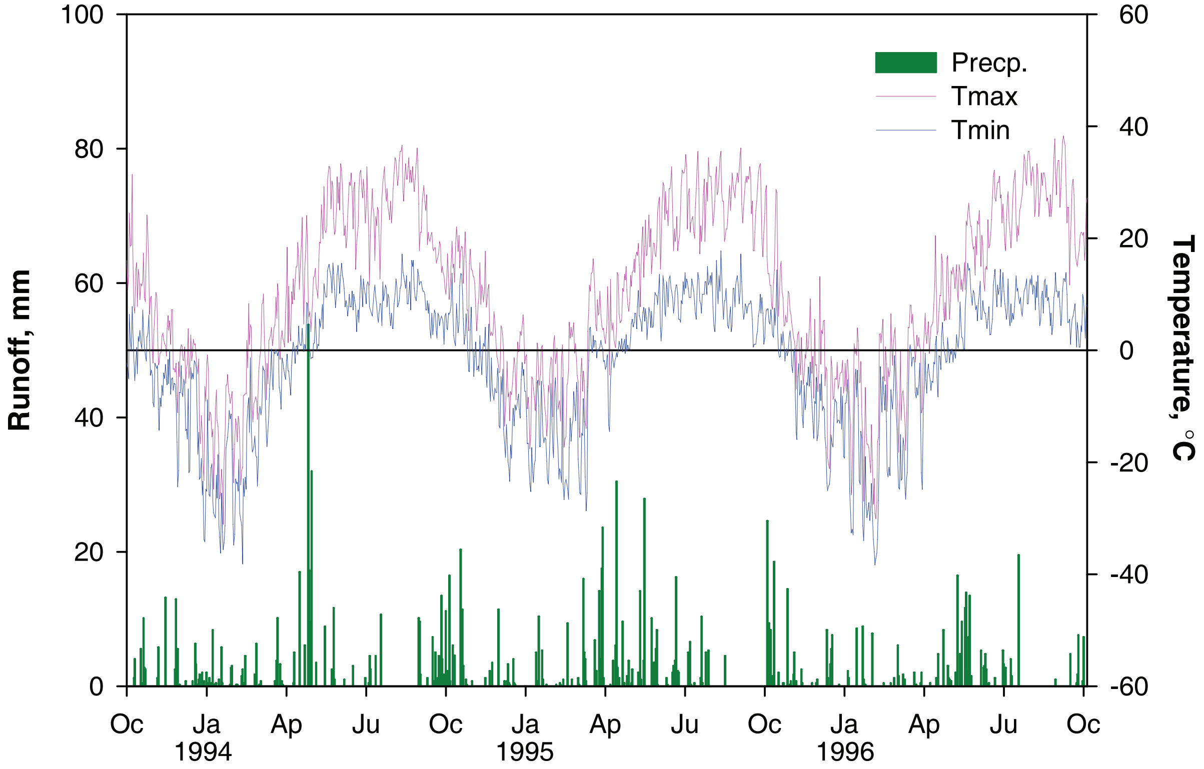

Figure 3.3. Observed daily preciptation and maximum and minimum air temperature, Morris, MN

Table 3.1. Monthly average of observed climate data during study, Pullman, WA

Month	Precipitation mm	Maximum temperature °C	Minimum temperature °C	Solar radiation langley d^{-1}	Wind velocity m s^{-1}	Dewpoint temperature °C
10	27	17.1	2.6	234	2.7	2.8
11	75	5.6	−1.1	142	3.6	−1.1
12	53	−0.1	−6.5	87	3.3	−6.5
1	56	1.7	−4.7	120	3.7	−4.7
2	42	4.4	−3.5	206	4.0	−3.5
3	57	9.5	0.2	308	4.2	0.2
4	40	15.0	2.8	438	3.9	−0.4
5	50	18.8	5.3	539	3.4	3.6
6	34	23.6	8.4	603	3.3	6.5
7	21	27.9	9.6	636	3.1	6.2
8	25	28.0	9.8	526	3.1	6.2
9	25	22.2	6.0	388	2.8	4.1
Yearly	505	14.5	2.4	352	3.4	1.1

Table 3.2. Monthly average of observed climate data during study, Morris, NN.

Month	Precipitation mm	Maximum temperature °C	Minimum temperature °C	Solar radiation langley d^{-1}	Wind velocity m s^{-1}	Dewpoint temperature °C
10	64	13.0	2.5	191	4.1	2.5
11	24	2.3	−6.6	123	4.6	−6.6
12	19	−4.2	−13.1	108	4.3	−13.1
1	26	−10.9	−21.1	147	4.7	−21.1
2	14	6.2	−17.7	231	5.0	−17.7
3	41	1.5	−7.5	306	4.6	−7.5
4	75	9.6	−0.8	378	4.6	−0.8
5	64	19.4	7.4	364	4.4	7.4
6	23	24.7	8.9	575	3.2	8.9
7	28	26.3	9.4	630	3.2	9.4
8	9	29.5	9.9	537	3.1	9.9
9	26	23.4	6.4	387	2.7	6.4
Yearly	413	10.7	−1.9	340	4.0	−1.9

within a year and much colder winters than Pullman.

The study plot at the PCFS was under continuous bare fallow on Palouse silt loam. The plot was 22.3 m long and 3.7 m wide on a 21% south-facing slope (McCool et al., 1995). The study plot at the Morris research site was 12 m long and 18 m wide on a 2% east-facing slope in a no-tillage corn field. The soil was Barnes loam. Standing stubble and flat residue were removed from the plot after each harvest (Sharratt, 2002). Topographic inputs for both study plots included a uniform slope configuration with respective slope gradients, slope aspects, and plot dimensions. Management was continuous fallow for the PCFS plot (Lin and McCool., 2006) and was no-tillage corn with a 100% residue removal for the Morris plot (Kennedy and Sharratt, 1998).

The soil inputs (Tables 3.3 and 3.4) were primarily from field measurements as reported in Lin and McCool (2006) and Kennedy and Sharratt (1998). Parameters, including effective hydraulic conductivity, 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. Previous studies have shown that both parameters are strongly impacted by crop and tillage management, and therefore should be calibrated to site-specific surface conditions in WEPP applications to the Palouse region (McCool et al., 1998; Pannkuk et al., 2000; Greer et al., 2006; Singh et al., 2008). Calibrated effective hydraulic conductivity (0.5 mm hr^{-1}) was lower than the default value (1.5 mm hr^{-1}) for Palouse silt loam in the WEPP database (Table 3.3). Calibrated critical shear stress (0.08 N m^{-2}) was at the lower end of the range (0–2.1 N m^{-2}) of field-measured values (Elliot et al., 1989). 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 erosion parameters differed from the field-measured values likely because those were obtained from field experiments conducted during summer (Elliot et al., 1989) without the impact of soil freeze and thaw.

Table 3.3. Soil properties of Palouse silt loam

Albedo	0.23					
Initial soil saturation, %	75					
Interrill erodibility, kg s m^{-4}	4.9×10^{6}					
Rill erodibility, s m^{-1}	9.0×10^{-3}					
Rill erodibility, s m$^{-1\,*}$	1.2×10^{-2}					
Critical shear, N m$^{-2\,*}$	0.08					
Effective hydraulic conductivity, mm hr^{-1}	1.5					
Effective hydraulic conductivity, mm hr$^{-1\,*}$	0.5					
	Soil depth, m					
	0–0.2	0.2–0.4	0.4–0.6	0.6–0.9	0.9–1.2	1.2–1.6
Sand, % weight	9.8	8.3	8.3	8.5	9.5	8.9
Clay, % weight	20.1	22.3	21.5	18.8	17.8	15.0
Organic matter, % weight	2.6	1.1	0.8	0.6	0.4	0.2
CEC, cmol kg^{-1}	19.6	20.5	21.2	21.0	21.0	21.1

[*] Adjusted value

Table 3.4. Soil properties of Barnes loam

Albedo	0.23				
Initial soil saturation, %	50				
Interrill erodibility, kg s m^{-4}	4.9×10^{6}				
Rill erodibility, s m^{-1}	5.5×10^{-3}				
Critical shear, N m^{-2}	3.1				
Effective hydraulic conductivity, mm hr^{-1}	5.5				

	Soil depth, m				
	0–0.05	0.05–0.15	0.15–0.45	0.45–0.75	0.75–1.05
Sand, % weight	39.8	39.3	36.8	44.6	55.5
Clay, % weight	25.4	23.8	23.8	22.5	17.5
Organic mater, % weight	5.8	4.0	3.5	2.0	1.0
CEC, cmol kg^{-1}	19.5	10.5	8.7	9.8	9.4
Rock fragments, % weight	6	16	14	13	10

In addition, Kf_{snow} was changed from the default value of 1.0 to 3.6 for the Pullman site in estimating snow thermal conductivity following Eq. 14 and 15 to better reproduce the field-observed frost depths. The increase in thermal conductivity may be attributed to two reasons. First, rapid and frequent freeze and thaw of snow at the Pullman site can cause rapid increase in snow density as well as thermal conductivity. Eq. 14 and 15 relate thermal conductivity to snow density yet these relationships may not fully describe the field snow conditions in Pullman. Second, non-uniformity of snow cover at this site where snow depth rarely exceeded 200 mm during the study period could lead to large spatial variation in snow thermal conductivity.

WEPP simulations for the Pullman and Morris sites were conducted using v2008.9 and the previous v2006.5 in order to assess the performance of the new frost routines. The simulated snow and frost depths were compared with field observations using graphical plots and statistical indices. Additionally, field-observed runoff and sediment yield from the PCFS experimental plot were also used to assess the ability of the WEPP model in representing winter hydrologic and erosion processes.

The following statistical indices were used to assess the performance of WEPP: standard error of estimate (*SEE*), percent bias (*PBIAS*), and standard deviation of observations (*RMS*)

$$SEE = \sqrt{\frac{\sum_{i=1}^{n} (x_{s,i} - x_{o,i})^2}{n - 2}} \tag{16}$$

$$PBIAS = \frac{\sum_{i=1}^{n} (x_{s,i} - x_{o,i})}{\sum_{i=1}^{n} x_{o,i}} \times 100\,\% \tag{17}$$

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} \left(x_{o,i} - \sum_{i=1}^{n} x_{o,i} / n \right)^2}{n - 2}} \tag{18}$$

where $x_{s,i}$, and $x_{o,i}$ are simulated and observed values for a sampling day, i.e., a snow cover, a frost depth, or a runoff and erosion event, was observed, and n is the sample size.

In addition, non-parametric Wilcoxon two-sample tests were conducted using SAS (SAS Institute Inc., 2004) to compare WEPP-simulated and field-observed snow and frost depth as well as runoff and erosion events. The non-parametric two-sample test instead of paired *t*-test was chosen due to the non-normality and lack of independence associated with our snow and frost depth and runoff and sediment yield data.

3.4. Results and Discussion

Considerably different snow and frost characteristics were observed from the two study plots at the PCFS and the Morris research site (Figure 3.4). Simulation results using WEPP v2008.9 and v2006.5, in comparison with field observation for the two study sites, are presented below sequentially.

3.4.1. WEPP v2008.9 simulation

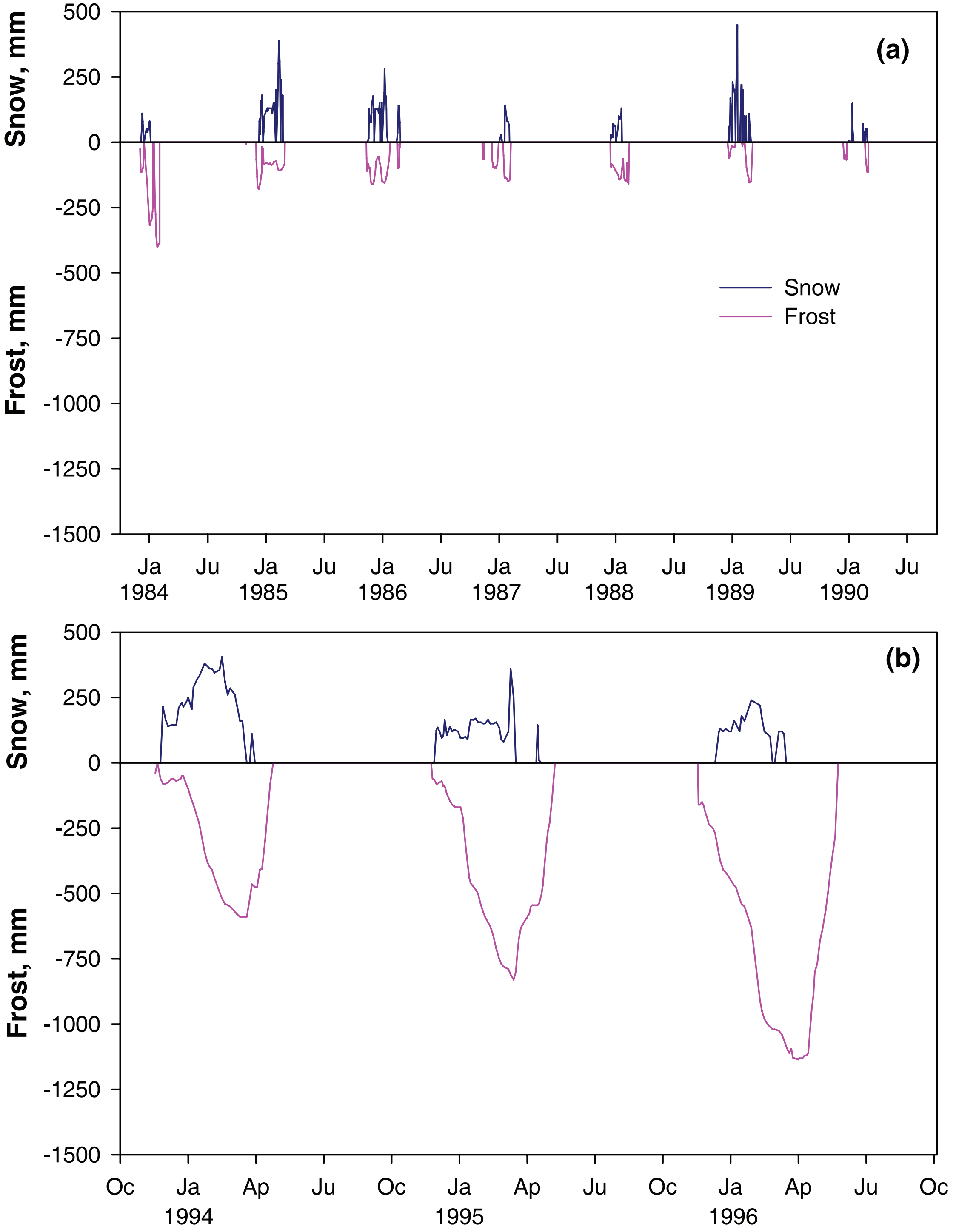

Figure 3.4. Observed snow and frost depths in (a) Pullman, WA, and (b) Morris, MN

3.4.1.1. Continuous fallow plot at the PCFS

There was a good agreement between WEPP v2008.9-predicted and field-observed snow and frost depths at the continuous fallow plot at the PCFS (Figure 3.5). Generally, WEPP v2008.9 adequately simulated the magnitude of snow and frost depths as well as the occurrence and duration of the major snow cover and frost presence for the study plot. Wilcoxon two-sample test showed that WEPP-simulated and field-observed snow depths did not differ significantly, but WEPP-simulated frost depth differed from field observations. The *PBIAS* of −8% for snow depth and −26% for frost depth (Table 3.5) suggest under-estimates of both quantifies by WEPP 2008.9. Adequate prediction of frost penetration depends on proper prediction of snow depth. A negative *PBIAS* indicated that WEPP v2008.9 may have not fully depicted the temporal change of the snow pack and soil frost. Average daily maximum temperature at the PCFS fluctuated around 0 °C in December during the study period (Table 3.1), posing a challenge for simulating the dynamics of snowmelt and soil freeze-thaw.

There were no significant differences between WEPP v2008.9-simulated and field-observed annual runoff and sediment yields with the standard error of estimate slightly larger than the standard deviation of field observations (Tables 3.5 and 3.6). However, the simulated event-by-event runoff and sediment yields were significantly different from the field observations, with *PBIAS* of −57% and −30%, respectively, suggesting under-estimates by WEPP.

WEPP v2008.9 reproduced the large runoff events typically observed in winter (Figure 3.6). However, WEPP did not predict some of the small runoff events observed during winter, and predicted events that were not observed, especially during summer (Figure 3.6). The incorrect simulated timing of the small runoff events in winter was likely due to the inadequate simulation of the rapid snowmelt and soil freeze-thaw processes in the Palouse region. The incorrect simulated

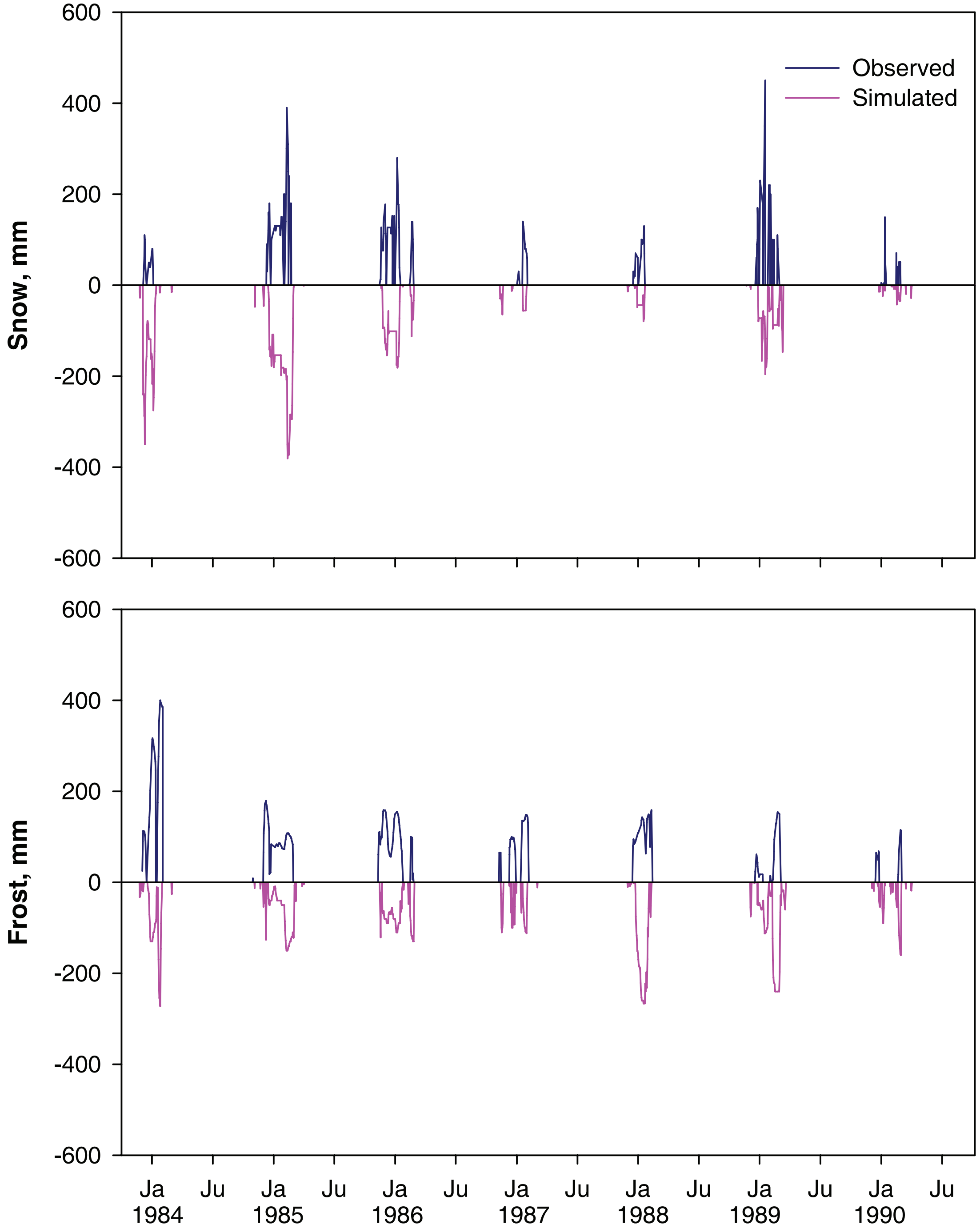

Figure 3.5. Comparison of WEPP v2008.9-simulated and field-observed snow (upper panel) and frost (lower panel) depths for the PCFS continuous fallow plot near Pullman, WA

Table 3.5. Statistical tests comparing WEPP simulation results and field observations, Pullman, WA

WEPP version		Simulated		*SEE*	*PBIAS* %	Wilcoxon test*	
		Mean	*RMS*			*Z*-score	*P*-value
v2008.9	Snow depth, mm (145) †	109 (118) ‡	86 (72) ‡	76	−8	1.6	0.1
	Frost depth, mm (254)	88 (118)	79 (77)	96	−26	6.1	<0.0001
	Event runoff, mm (148)	4.5 (6.5)	5.1 (7.5)	7.9	−57	7.0	<0.0001
	Event sediment yield, t ha^{-1} (148)	5.9 (5.2)	9.8 (9.9)	13.3	−30	7.0	<0.0001
	Annual runoff, mm (7)	134 (133)	49 (48)	67	0	0.06	0.9
	Annual sediment yield, t ha^{-1} (7)	103 (104)	57 (59)	73	−1	0.00	1.0
v2006.5	Snow depth, mm	40	66	120	−67	10.7	<0.0001
	Frost depth, mm	90	29	89	−25	3.6	0.0003
	Event runoff, mm	2.6	3.1	9.7	−86	12.1	<0.0001
	Event sediment yield, t ha^{-1}	7.7	11.4	14.3	−47	9.0	<0.0001
	Annual runoff, mm	46	15	110	−188	−2.9	0.003
	Annual sediment yield, t ha^{-1}	91	79	75	−14	−0.4	0.7

RMS = standard deviation (root mean square), *SEE* = standard error of the estimate, *PBIAS* = percent bias.

* Significance level $\alpha = 0.05$.

† Value in parentheses is sample size.

‡ Value in parentheses is for field observed values.

Table 3.6. WEPP-simulated and field-observed annual runoff and sediment yield, Pullman, WA

Water year	Precipitation mm	Runoff, mm			Sediment yield, t ha $^{-1}$		
		Observed	Simulated		Observed	Simulated	
			v2008.9	v2006.5		v2008.9	v2006.5
1984	596	228	134	77	181	187	260
1985	515	119	187	43	31	61	29
1986	536	147	162	45	167	35	39
1987	415	71	76	38	71	74	43
1988	424	108	118	33	69	69	88
1989	559	125	189	52	66	158	92
1990	492	134	69	36	144	138	84
Average	505	133	134	46	104	103	91

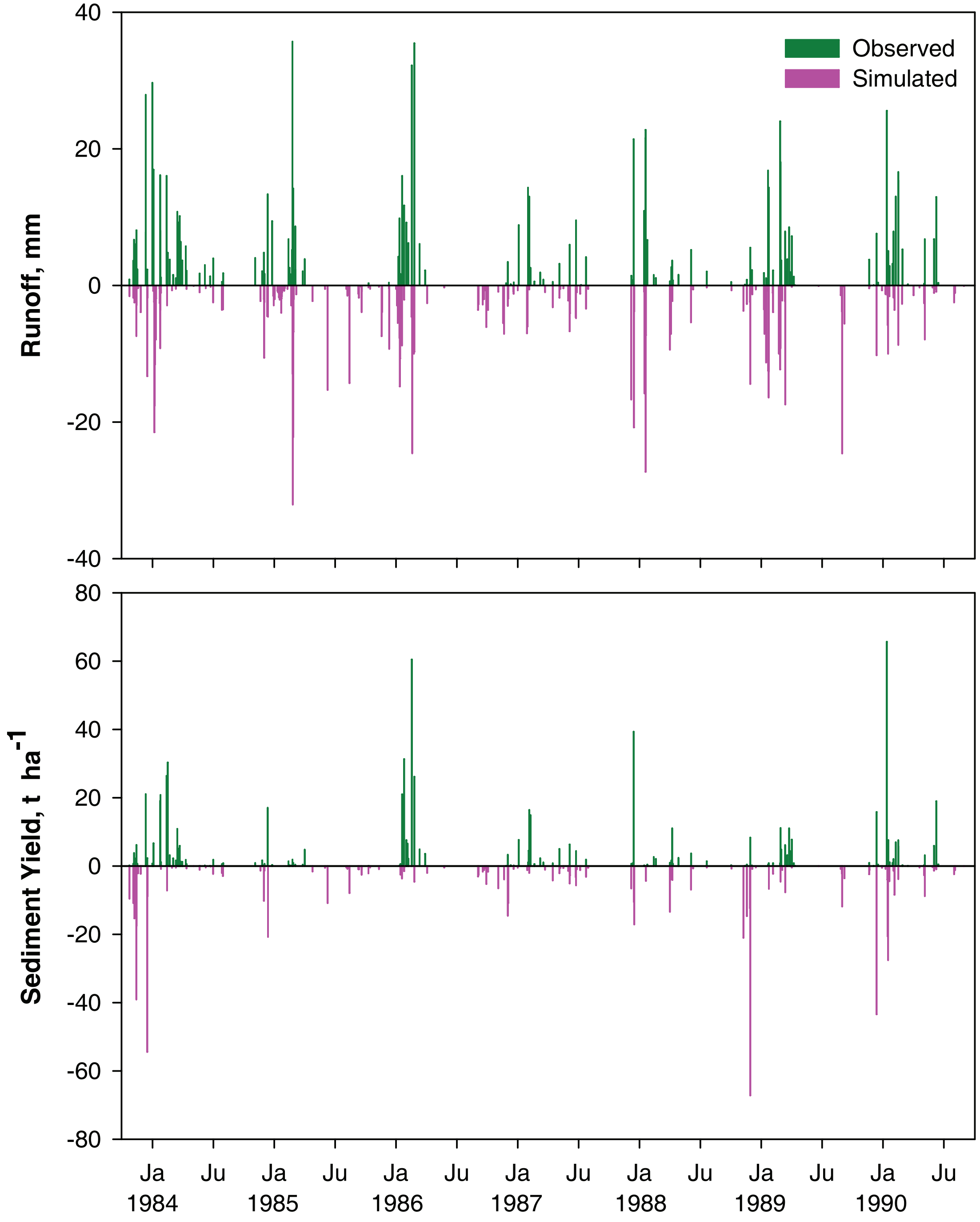

Figure 3.6. Comparison of WEPP v2008.9-simulated and field-observed runoff (upper panel) and sediment yield (lower panel) for the continuous fallow plot near Pullman, WA

summer runoff may be due to the improper characterization of seasonal changes in soil hydraulic properties. The calibrated effective hydraulic conductivity (0.5 mm hr^{-1}) was lower than either lab- or field-measured values (3.2–212.4 mm hr^{-1}, Greer et al., 2006).

WEPP v2008.9 reproduced the occurrence of the major observed erosion events. However, the amount of sediment yield was either under- or over-predicted, further suggests the complexity of the dynamic changes in soil properties and the need for improving the representation of such dynamics.

3.4.1.2. Residue removal plot at the Morris research site

For the study site in Morris, WEPP v2008.9 satisfactorily simulated snow depth and snow cover (Figure 3.7). No significant difference between WEPP v2008.9-simulated and field observed snow depth were detected by Wilcoxon two-sample test (Table 3.7).

Simulated frost depth differed from field observations with a P-value of 0.03 using Wilcoxon test at significant level of 0.05. WEPP v2008.9 underestimated frost depth with $PBIAS$ of -15% (Table 3.7). WEPP v2008.9 simulated well the frost penetration process including frost penetration rate and maximum frost depth (Figure 3.7). However the simulated thawing rates were much faster than the field observations suggesting either an under estimation of thermal conductivity (see Appendix D for estimation method) of the thawing soil or a problem of neglecting the energy spent on raising the temperature of the non-frozen soil above a thawing front. Consequently, the simulated frost periods were shorter than field-observed.

3.4.2. Comparison of the simulations from WEPP v2008.9 and WEPP v2006.5

3.4.2.1. Continuous fallow plot at the PCFS

Compared with WEPP v2006.5, WEPP v2008.9 was substantially improved in simulating snow and frost depth for the PCFS continuous fallow plot. Snow depth simulated from WEPP v2008.9 was not significantly different from the observations. Whereas simulation results from WEPP v2006.5

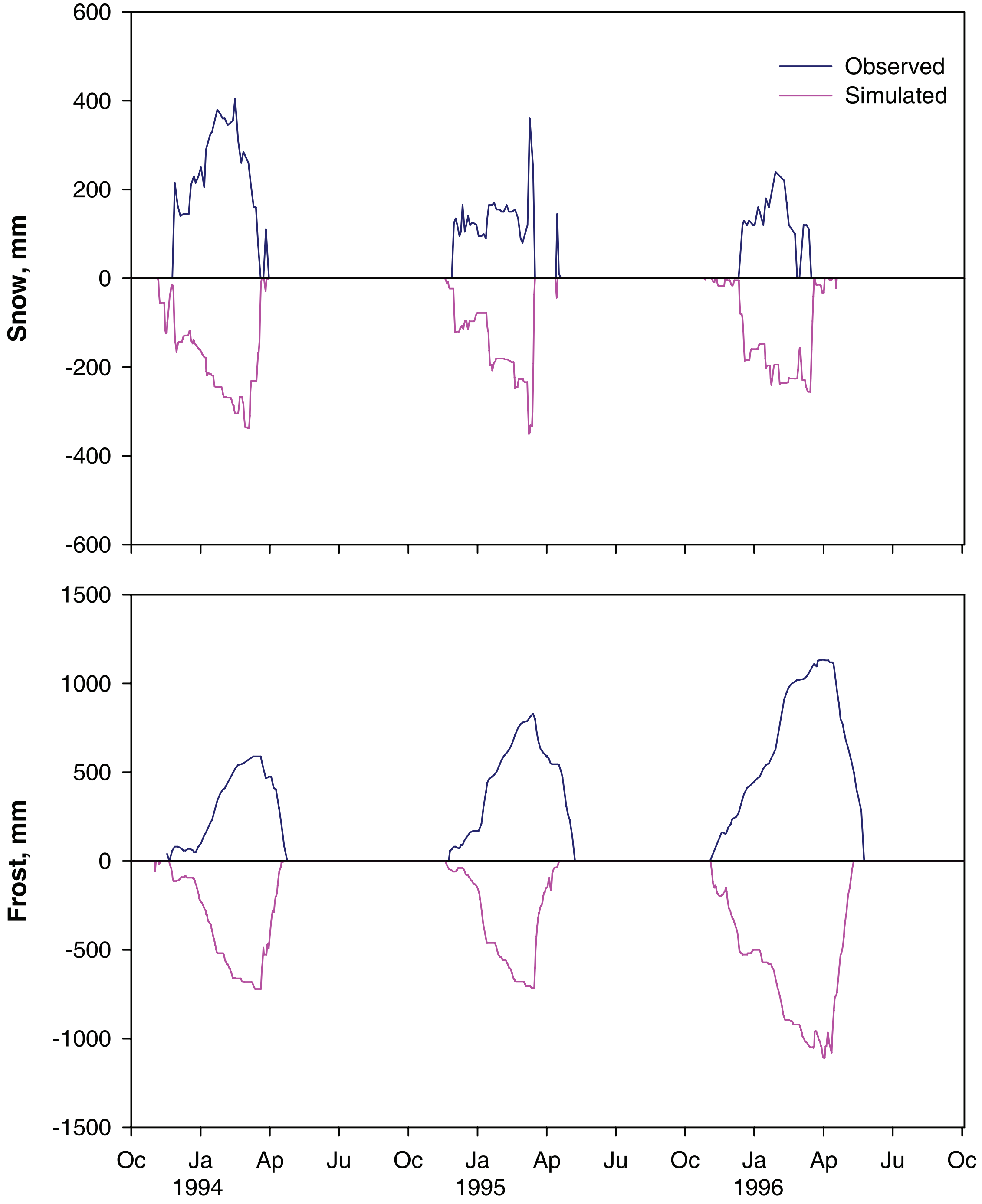

Figure 3.7. Comparison of WEPP v2008.9-simulated and field-observed snow (upper panel) and frost (lower panel) depths for the residue removal plot in no-tillage corn field at Morris, MN

Table 3.7. Statistical tests comparing WEPP simulation results and field observations, Morris, MN

WEPP version		Simulated		*SEE*	*PBIAS* %	Wilcoxon test[*]	
		Mean	*RMS*			*Z*-score	*P*-value
v2008.9	Snow depth, mm (87) [†]	180 (178) [‡]	73 (84) [‡]	69	1	−0.9	0.4
	Frost depth, mm (157)	448 (496)	327 (321)	200	−15	2.1	0.03
v2006.5	Snow depth, mm	178	120	75	0	0.4	0.7
	Frost depth, mm	115	98	527	−79	11.7	<0.0001

RMS = standard deviation (root mean square), *SEE* = standard error of the estimate, *PBIAS* = percent bias.

[*] Significance level $\alpha = 0.05$.

[†] Value in parentheses is sample size.

[‡] Value in parentheses is for field observed values.

were significantly different from the field observations (Table 3.5). WEPP v2006.5 underestimated snow depth with a much larger *PBIAS* value (−67% for v2006.5 vs. −8% for v2008.9, Table 3.5). Snow cover period simulated from WEPP v2006.5 was much smaller than that of the observations (Figure 3.8). WEPP v2008.9 had largely improved simulated snow cover period for Pullman (Figure 3.5).

Simulated frost depth from both WEPP versions differed significantly from the field observations indicated by the Wilcoxon tests (Table 3.5). Simulation results from WEPP v2006.5 had similar *PBIAS* and *SEE* values as those for WEPP v2008.9. However, standard deviation of WEPP v2008.9 simulation results was much closer to the standard deviation of the observations than that for WEPP v2006.5. WEPP v2006.5 simulated much longer frost period than the field observations and maximum simulated frost penetration was around 100 mm which was not consistent with the field observations (Figure 3.8). In contrast, WEPP v2008.9 simulated more realistic frost duration and more variation in frost penetration depth (Figure 3.5).

Using the same WEPP inputs as WEPP v2008.9, WEPP v2006.5 underestimated annual runoff and sediment yield with *PBIAS* of −188% and −14% (Table 3.5). Simulated annual sediment yield was not significantly different than the observations whereas annual runoff differed significantly from the field observations.

WEPP v2006.5 simulated fewer erosion events and less event by event sediment yield than the simulation results from WEPP v2008.9 except one extreme event simulated in December, 1983 with 22.3 mm runoff and 100 t ha^{-1} sediment yield (Figures 3.6 and 3.9). This extreme event was due to a simulated rain on snow on thawing soil event. The runoff amount of this simulated extreme event was similar with the field observation. However the simulated sediment yield is larger than the maximum event by event sediment yield (66 t ha^{-1}) observed during the entire monitoring period.

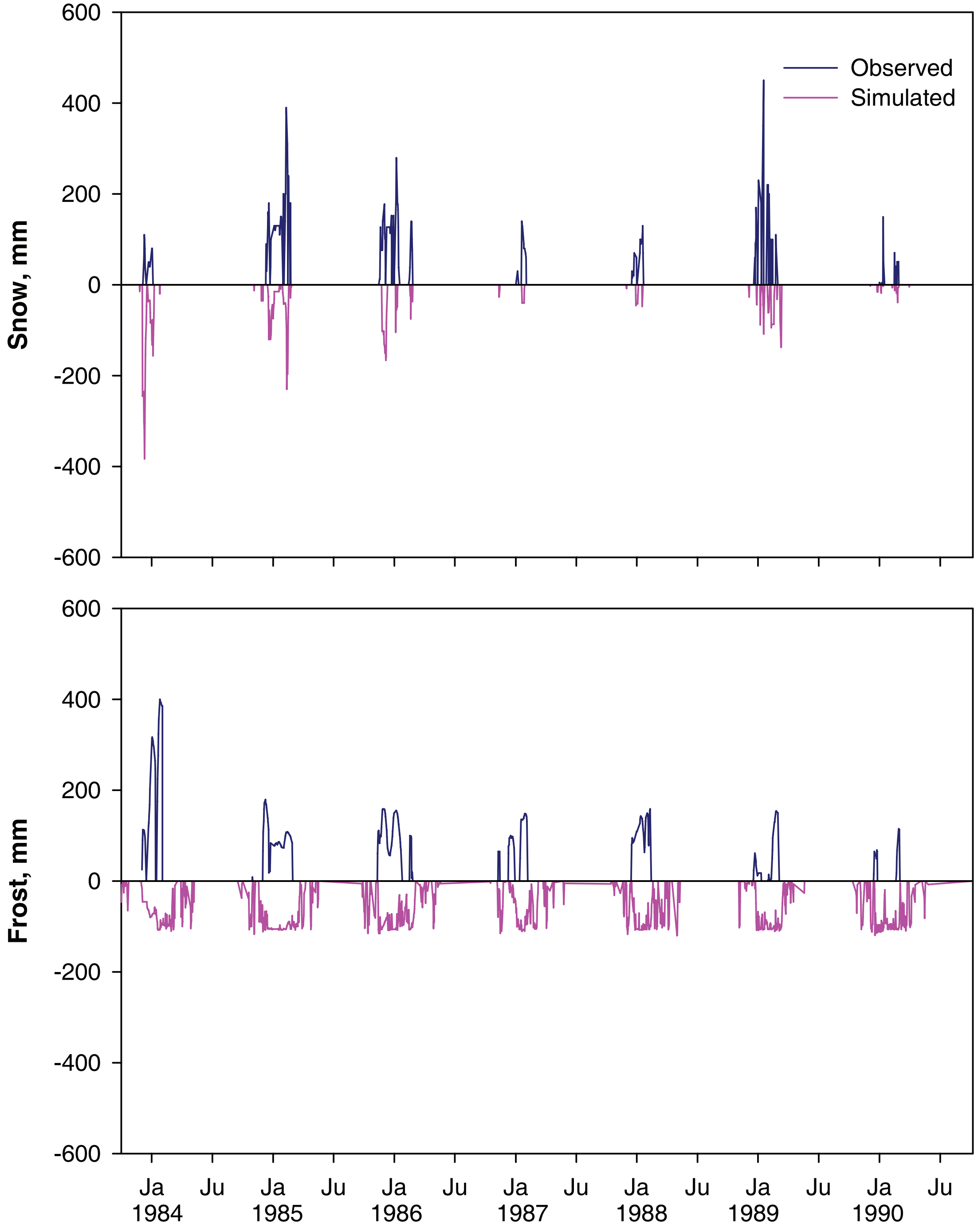

Figure 3.8. Comparison of WEPP v2006.5-simulated and field-observed snow (upper panel) and frost (lower panel) depths for the PCFS continuous fallow plot near Pullman, WA

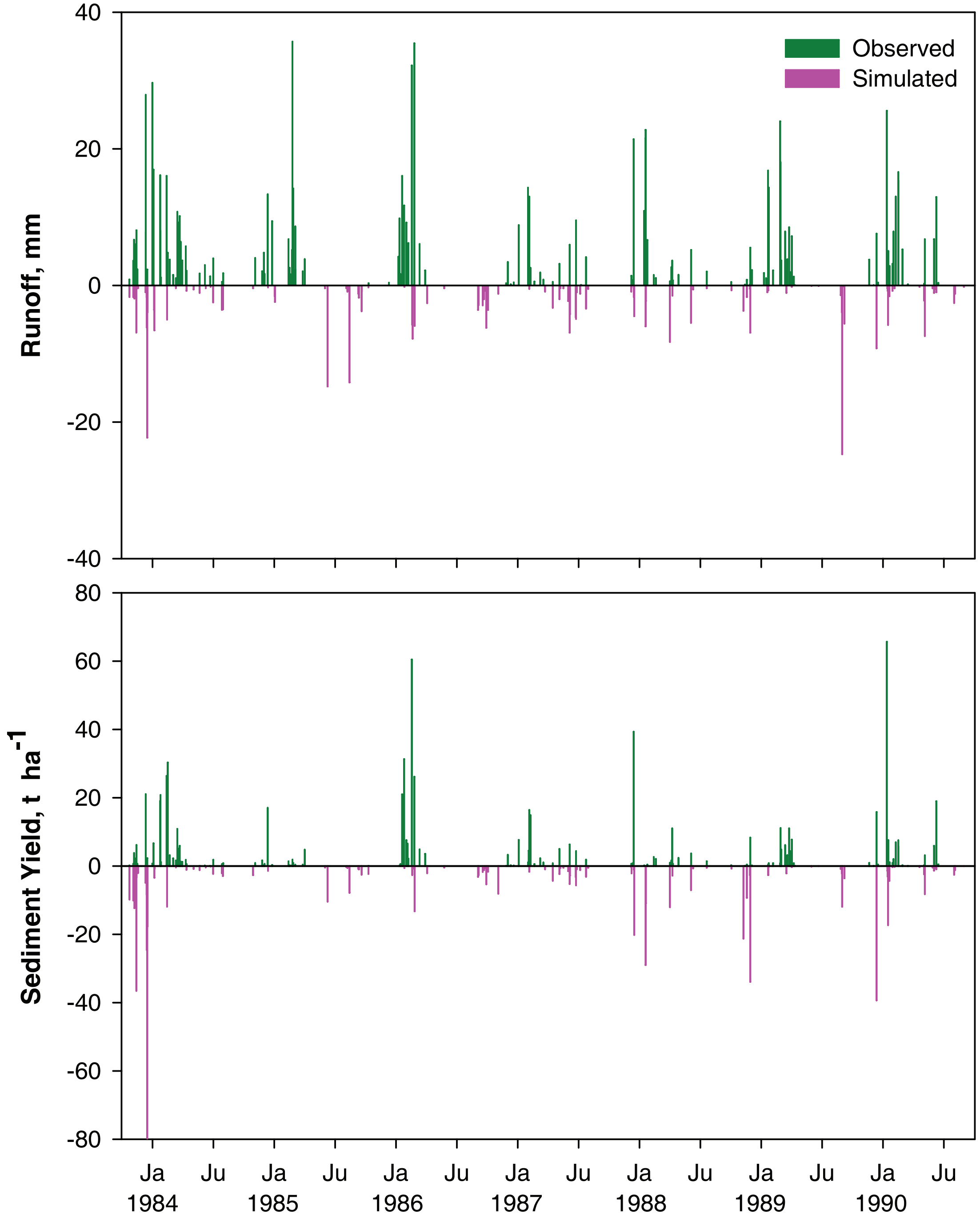

Figure 3.9. Comparison of WEPP v2006.5-simulated and field-observed runoff (upper panel) and sediment yield (lower panel) for the PCFS continuous fallow plot near Pullman, WA

Similar to WEPP v2008.9, WEPP v2006.5 generated runoff and erosion events during summer which were not observed in the field. Whereas, WEPP v2008.9 reproduced much more winter runoff and erosion events than WEPP v2006.5.

3.4.2.2. Residue removal plot at the Morris research site

Statistical indices indicated no significant differences between WEPP v2006.5-simulated and field observed snow depth for Morris study site (Table 3.7), whereas Figure 3.10 showed slight overestimation of snow depth in year 1994 and 1996 and underestimation in year 1995. WEPP v2006.5 significantly underestimated frost duration and penetration (Figures 3.10, Table 3.7).

WEPP v2006.5 simulated slightly better snow pack dynamics than WEPP v2008.9 with similar curve shape in snow depth graph (Figures 3.7 and 3.10), whereas WEPP v2008.9 simulated much more reasonable frost penetration and frost duration.

3.5. Summary and Conclusion

This study aimed to modify the algorithms and subroutines of WEPP v2006.5 that improperly 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 v2008.9. Specifically, improvement was made in (i) discretization of a snow-residue-soil system, (ii) computation of soil temperature, soil water movement in unsaturated soil, and saturated hydraulic conductivity of frozen soil, and (iii) integration of the frost-simulation routines and other water balance routines of WEPP. The refined

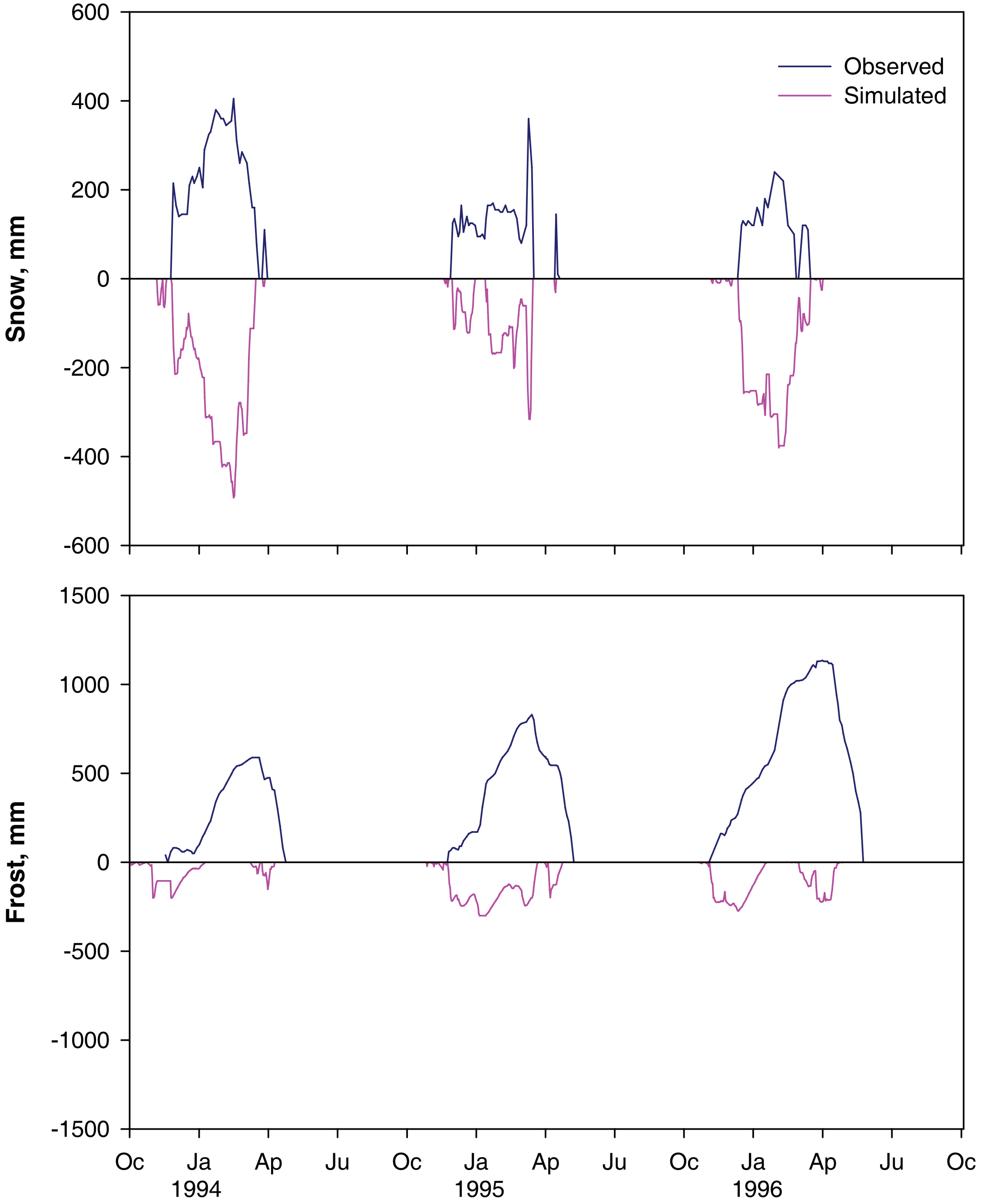

Figure 3.10. Comparison of WEPP v2006.5-simulated and field-observed snow (upper panel) and frost (lower panel) depths for the residue removal plot in no-tillage corn field at Morris, MN

WEPP model has the ability to account for multiple sandwiched frost layers, soil water migration to freezing front, and change of soil water due to unsaturated soil water movement. Further, the model allows for interaction between hourly frost simulation and other daily water balance computation. Compared to WEPP v2006.5, WEPP v2008.9 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 the experimental research sites at Pullman, WA and Morris, MN, respectively. Pullman is typified by rapid snow melt and numerous freeze-thaw cycles under semiarid steppe 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 v2008.9 showed WEPP v2008.9 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 PCFS experimental plot.

WEPP v2008.9 simulated contrasting snow and frost characteristics for the two study sites, consistent with field observations. With the new frost routines, WEPP v2008.9 could well represent the major winter processes at the study sites. WEPP-simulated snow and frost depths, snow cover period and frost duration, as well as runoff and erosion were in reasonable agreement with field observations for both study sites.

WEPP v2008.9 appears to be a promising tool for evaluating winter hydrologic and erosion processes in cold regions. However, it was not able to fully describe the dynamic winter processes in the field at the time scale of a day. Snow accumulation and melt, and soil freeze-thaw are complex processes that are impacted by numerous factors, including weather characteristic, surface conditions, and soil type. Future efforts should be devoted to further improving the ability of WEPP in simulating snow pack dynamics, frost thawing process, and the transient change of soil hydraulic and erosion properties.

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CHAPTER FOUR

WEPP SIMULATIONS OF DRYLAND CROPPING SYSTEMS IN SMALL DRAINAGES OF NORTHEASTERN OREGON

This chapter has been submitted to *Journal of Soil and Water Conservation* and is currently in review. Full citation: Williams, J.D., S. Dun, D.S. Robertson, J.Q. Wu, E.S. Brooks, D.C. Flanagan, and D.K. McCool. 2008. WEPP simulations of dryland cropping systems in small drainages of Northeastern Oregon. *J. Soil Water Conserv.* (in review). My contribution to the manuscript is summarized in the following. Data collection: no contribution. WEPP modeling: carried out all model runs with Dr. John Williams; major technical contributor (together with Dr. Joan Wu) to WEPP v2008.9, which was used in this study; worked with Drs. John Williams, Joan Wu, and Erin Brooks in analyzing and interpreting WEPP simulation results. Development of manuscript: worked with Dr. Joan Wu in revising the manuscript first developed by Dr. John Williams to improve the technical rigor as well as the structure and clarity of the manuscript.

4.1. Abstract

Computer simulation models are essential tools for evaluating soil erosion potential over large areas of cropland. Small-plot and field-scale evaluations are commonly conducted for federal farm program compliance, but producers are now faced with off-farm water quality concerns. Predicting the potential contribution of upland sediment is of interest to producers and state and federal agencies. The purpose of this study was to evaluate the applicability of the Water Erosion Prediction Project (WEPP) model for quantifying hydrological and erosion processes in the semiarid croplands of the Columbia Plateau. Two headwater drainages managed using conventional inversion tillage (CT) or no-tillage (NT) technologies were monitored from 2001 through 2007 in the dryland cropping region of northeastern Oregon. WEPP was parameterized primarily from field data,

including management and weather data. Crop parameters (above-ground biomass, crop yield), water balance components (volumetric soil water, evapotranspiration (ET), and surface runoff), and soil loss were observed and subsequently used to evaluate WEPP simulations. This detailed dataset allowed for a unique opportunity to evaluate not only the WEPP routines for runoff and erosion but also the routines for crop growth and residue decomposition, which greatly influence the erodibility and hydraulic conductivity of top soil layers. Graphical and goodness-of-fit analyses indicate that WEPP generated satisfactory estimates for volumetric soil water and crop yields in NT and CT, and above-ground biomass production in NT. Gross patterns of ET simulated by WEPP and deduced from precipitation and changes in soil water were commensurate. Observed annual runoff and erosion values from both drainages were low (NT: 0.1 mm, 2.5 kg ha^{-1}; CT: 0.9 mm, 118.7 kg ha^{-1}). On average only 0.3% and 0.03% of total precipitation left the catchment as runoff during the six-year study period for CT and NT, respectively. No runoff was predicted by WEPP when default input values for a Walla Walla silt loam soil were used in the model. Simulated and observed runoff agreed well after the effective surface hydraulic conductivity K_{eff} was reduced by 90% and 70% for CT an NT, respectively. With minimal calibration the WEPP model was able to successfully represent the hydrology, sediment transport, and crop growth for CT and NT cropping systems in northeastern Oregon.

4.2. Objectives

The objective of this study was to evaluate the ability of WEPP to simulate (i) the spatial variability in soil water content and evapotranspiration throughout two headwater catchments, (ii) surface runoff and sediment yield at the outlet of the catchments, and (iii) crop yield and biomass production in two- and four-year winter wheat cropping rotations.

4.3. Materials and Methods

- Site description
- Tillage management
- Soil water, runoff, and erosion measurement
- WEPP model description, input, and assessment

4.4. Results

Table 4.1.
Soil properties of the Walla Walla silt loam

Albedo	0.23
Initial soil saturation, %	75
Interrill erodibility, kg s m^{-4}	5.4×10^{6}
Rill erodibility, s m^{-1}	2.0×10^{-2}
Rill erodibility, s m^{-1} *	5.0×10^{-3}
Critical shear, N m^{-2}	3.5
K_{eff} of surface soil, mm h^{-1}	4.5
K_{eff} of surface soil, mm h^{-1} †	0.5
K_{eff} of surface soil, mm h^{-1} ‡	1.2

	Soil depth, m			
	0–0.3	0.3–0.6	0.6–0.9	0.9–1.2
Sand, % weight	27.4	35.3	35.3	35.3
Clay, % weight	11.5	14.0	14.0	14.0
Organic matter, % weight	2.5	0.83	0.28	0.18
CEC, cmol kg^{-1}	11.3	8.4	8.4	8.4

* Calibrated value.
† Calibrated value for conventional tillage.
‡ Calibrated value for no-tillage.

Table 4.2.
Crop rotations for crop years 2001–2006

Crop year	No-tillage				Conventional tillage	
	NT1	NT2, NT3	NT4, NT5	NT6, NT7	CT1	CT2, CT3
2001	Ch[*]	CF	SW	WW	F	F
2002	WW	WW	CF	Ch	WW	WW
2003	CF	Ch	WW	WW	F	F
2004	WW	WW	Ch	CF	WW	WW
2005	DP	CF	SW	WW	F	SW
2006	WW	WW	CF	DP	WW	V[†]

[*] DP, dry peas; Ch, chickpeas; CF, chemical fallow; F, fallow (inversion tillage); SW, spring wheat; V, volunteer crop; WW, winter wheat.

[†] Producer allowed volunteer wheat to mature. The only tillage was to fertilize the field.

Table 4.3.
Tillage operations, dry biomass (DB), and crop yields (CY).

Year	Hillslope	Tillage					Planting	Harvest	Yield (kg m^{-2}) [*]	
		PT [†]	ST$_1$	ST$_2$	ST$_3$	ST$_4$			DB	CY
2001	NT1	4/2 [‡]					4/17	8/21	0.33	0.11
	NT2, NT3								0.00	0.00
	NT4, NT5						3/22	8/6	0.89	0.42
	NT6, NT7						10/20	8/6	0.91	0.39
	CT1, CT2, CT3								0.00	0.00
2002	NT1						10/15	7/30	0.65	0.23
	NT2, NT3						10/15	7/30	1.21	0.43
	NT4, NT5								0.00	0.00
	NT6, NT7						4/9	7/30	0.23	0.07
	CT1, CT2, CT3	3/15 [§]	3/25	5/10	6/15	9/10	10/10	7/30	1.20	0.44
2003	NT1	8/14							0.00	0.00
	NT2, NT3	8/14					4/4	8/27	0.40	0.01
	NT4, NT5						10/22	8/24	1.23	0.46
	NT6, NT7	9/20					10/22	8/25	1.14	0.41
	CT1, CT2, CT3								0.00	0.00
2004	NT1						10/15	7/29	1.41	0.62
	NT2, NT3						10/15	7/29	1.32	0.58
	NT4, NT5	2/4					4/1	9/7	0.46	0.17
	NT6, NT7	9/4							0.00	0.00
	CT1, CT2, CT3	3/15[§]	3/25	5/10	6/15	9/10	10/10	7/30	0.99	0.46
2005	NT1	10/6	4/6[§§]				4/3	7/28	--	0.16
	NT2, NT3	10/6							0.00	0.00
	NT4, NT5						10/2	8/5	0.95	0.38
	NT6, NT7						10/2	8/5	1.40	0.60
	CT1						7/28		0.00	0.00
	CT2, CT3	9/5	10/5				10/15	7/28	1.19	0.36
2006	NT1	10/5					10/27	7/27	1.19	0.43
	NT2, NT3	9/27					10/27	7/27	1.20	0.49
	NT4, NT5								0.00	0.00
	NT6, NT7	9/27	4/14				4/12	7/25	--	0.16
	CT1	4/15[§]	5/15	6/15	7/10	9/15	10/20	7/28	1.76	0.74
	CT2, CT3		9/20					7/28	1.13	0.48

[*] Dry biomass (residue and grain) was taken as the average of 25 bundles from each crop; grain yield was determined from combine harvest.

[†] PT, primary tillage, ST, secondary tillage.

[‡] Management in no-tillage other than planting included residue management to shake weed seeds to the ground and lay standing residue prone without disturbance to soil surface.

[§] Tillage operations in winter wheat occurred previous year.

[§§] Dry green peas were rolled after planting with a roller harrow.

--, missing data.

Table 4.4.
Tillage parameters for WEPP simulation of winter wheat, chickpeas, and dry peas

Equipment	Tillage intensity[*]		Ridge height (m)	Ridge interval (m)	Random roughness (m)	Fraction disturbed	Tillage depth (m)
	Fragile[†]	Non-fragile					
Chisel/chopper with fertilizer applicator	0.50	0.30	0.05	0.38	0.04	1.0	0.15
Disk, tandem -primary cutting >23-cm spacing	0.70	0.45	0.08	0.30	0.02	1.0	0.10
Drill (CT), hoe opener	0.50	0.35	0.10	0.20	0.01	0.8	0.03
Drill (NT), one pass, hoe opener	0.50	0.35	0.05	0.30	0.01	0.5	0.03
Harrow -springtooth (coil tine)	0.25	0.15	0.00	0.00	0.01	**0.1**	0.00
Moldboard plow, 20 cm deep	0.98	0.95	0.15	0.20	0.05	1.0	0.20
Rodweeder, rotary rod with semi-chisels (cultiweeder)	0.35	0.25	0.00	0.00	0.04	1.0	0.15
Rodweed, plain rotary rod	0.40	0.10	0.00	0.00	0.01	1.0	0.05

[*] Tillage intensity indicates the percent area disturbed due to tillage.
[†] In this study, wheat and grass were considered as non-fragile, and chickpea and dry pea as fragile.

Table 4.5.

Crop growth parameters for WEPP simulation of chickpeas and dry green peas

Canopy cover coefficient	14
Canopy height coefficient	3
Biomass energy ratio, kg MJ^{-1}	35
Base daily air temperature, °C	4.4
Parameter for flat residue cover equation, m^{2} kg^{-1}	5.2
Growing degree days to emergence, °C	30
Height of post-harvest standing residue, m	0.15
Fraction canopy remaining after senescence	0.1
Plant stem diameter at maturity, m	0.0085
Heat unit index when leaf area index starts to decline	0.9
Fraction of biomass remaining after senescence	0.1
Radiation extinction coefficient	0.3
Standing to flat residue adjustment factor	0.99
Maximum Darcy–Weisbach friction factor for living plant	0
Growing degree days for growing season	999
Harvest index	0.3
Maximum canopy height, m	0.38
Decomposition constant for above-ground biomass	0.013
Decomposition constant for root biomass	0.013
Optimal temperature for plan growth, °C	22
Plant drought tolerance factor	0.0
In-row plant spacing, m	0.025
Maximum root depth, m	1.0
Root to shoot ratio	0.25
Senescence period, d	14
Maximum leaf area index	5

Table 4.6.
Observed and simulated annual water balance in depth, mm, for each water year (Oct. 1–Sept. 30).

Year	Observed				Simulated		
	Precipitation	Runoff	Change of soil water[†]	Deduced ET	Runoff	ET	Deep percolation
				No-tillage			
2001	296	0	--	--	0	378	100
2002	245	0	--	--	0	285	10
2003	364	0.38	--	--	0.45	336	0
2004	423	0	45	402	0	411	10
2005	257	0.13	−16	281	0	291	0
2006	455	0.05	5	459	0	426	0
Average [*]	340	0.09	25	380	0.08	354	20
				Conventional tillage			
2001	296	0	--	--	0.28	173	0
2002	245	0	--	--	0	392	0
2003	364	1.17	--	--	3.55	193	0
2004	423	3.94	−29	476	4.59	546	14
2005	257	0.34	−32	274	0	232	0
2006	455	0	−31	478	0.79	493	0
Average	340	0.91	−31	410	1.54	338	2

[*] The averages were made over the observation period.
[†] Based on post-harvest soil water content measurements taken before the onset of fall rainfall.
--, no observation.

Table 4.7.
Observed and simulated runoff and erosion events during October 2000–December 2006. WEPP simulated events presented here after calibration of soil properties K_{eff} and K_r

Date[*]	Precipitation (mm)	Intensity (mm h^{-1})		Duration (hr)	Runoff (mm)		Sediment yield (kg ha^{-1})	
		Maximum	Average		Observed	Simulated	Observed	Simulated
No-tillage								
1/29/03	10.9	2.9	0.8	13.8	0.1		2.5	
1/30/03	14.6	6.5	0.7	21.2	0.2		4.1	
1/31/03	**14.9**	**8.7**	**1.8**	**8.1**	**0.2**	**0.4**	**8.2**	**1.6**
1/18/05[†]	4.4	31.0	0.7	5.9	0.1		<0.1	
12/22/05[†]	3.8	4.2	0.2	19.6	<0.1		<0.1	
12/30/05[†]	20.3	5.2	0.9	23.6	<0.1		<0.1	
Annual average					0.1	0.07	2.5	0.3
Conventional tillage								
6/12/01	*9.65*	*25.0*	*1.7*	*5.7*		*0.3*		*2.2*
1/26/03	15.5	6.5	0.7	21.7	0.3		14.2	
1/29/03	10.9	2.9	0.8	13.8	0.4		22.2	
1/30/03	14.6	6.5	0.7	21.2	0.5		73.5	
1/31/03	**14.9**	**8.7**	**1.8**	**8.1**	[‡]	**3.5**	[‡]	**381.1**
11/29/03	*16.26*	*5.2*	*2.8*	*5.8*		*0.2*		*26.3*
12/13/03	*16.5*	*5.0*	*0.9*	*18.4*		*0.2*		*11.3*
1/23/04[†]	**26.6**	**5.1**	**0.9**	**31.3**	[‡]	**2.6**	[‡]	**49.5**
1/26/04[†]	0.76	0.8	0.4	2.1	0.3		2.7	
1/28/04[†]	**19.3**	**4.3**	**0.5**	**39.4**	**0.6**	**1.7**	**43.7**	**34.0**
2/6/04	9.4	3.3	0.9	10.0	0.3		8.7	
2/16/04	12.7	2.9	1.1	11.6	0.6		138.3	
2/17/04	6.3	3.3	0.3	20.51	0.3		47.6	
2/24/04	9.2	13.0	0.9	9.9	0.3		53.5	
4/15/04	24.6	12.5	3.5	7.0	0.3		[§]	
6/8/04	21.1	6.5	3.6	5.9	1.3		[§]	
1/18/05[†]	4.4	31.0	0.7	5.9	0.3		0.3	
12/22/05[†]	*3.8*	*4.2*	*0.2*	*19.6*		*0.8*		*0.0*
Annual average					0.9	1.6	67.5	84.1

[*] Dates in bold face and normal font are those for which WEPP produced or failed to reproduce the observed events, respectively. Dates in Italic and underscored are those for which WEPP predicted an event that was not observed.

[†] Runoff and soil erosion associated with frozen or thawing soil.

[‡] Stage failure due to freezing in the stilling well and intake line of stormwater samplers.

[§] Event observed but no sediment data collected due to malfunctioning of samplers.

Table 4.8.
Statistical tests comparing WEPP simulation results and field observations. Analysis of runoff and sediment yield were conducted after calibration of K_{eff} and K_r for the Walla Walla silt loam in the WEPP data base

Treatment		Observed		$RMSD$ [*]	Wilcoxon test[†]	
		Sample size	Standard deviation		Z-score	P-value
No-tillage	Above-ground biomass, kg m^{-2}	6	0.23	0.14	−0.40	0.69
	Crop yield, kg m^{-2}	6	0.08	0.09	−0.56	0.57
	Soil water content, m^3 m^{-3}	20	0.03	0.03	1.99	0.05
	ET, mm	19	57	44	0.79	0.43
	Annual runoff, mm	6	0.2	0.06	0.53	0.60
	Annual sediment yield, kg m^{-1}	6	5.5	5.4	0.00	1.0
Conventional tillage	Above-ground biomass, kg m^{-2}	4	0.23	0.60	−1.28	0.20
	Crop yield, kg m^{-2}	4	0.13	0.07	−0.08	0.94
	Soil water content, m^3 m^{-3}	20	0.03	0.03	−0.11	0.91
	ET, mm	19	65	37	0.29	0.77
	Annual runoff, mm	6	1.7	1.1	−0.50	0.62
	Annual sediment yield, kg m^{-1}	6	130	150	−0.27	0.79

[*] *RMSD*, root mean square deviation.
[†] significance level $\alpha = 0.05$.

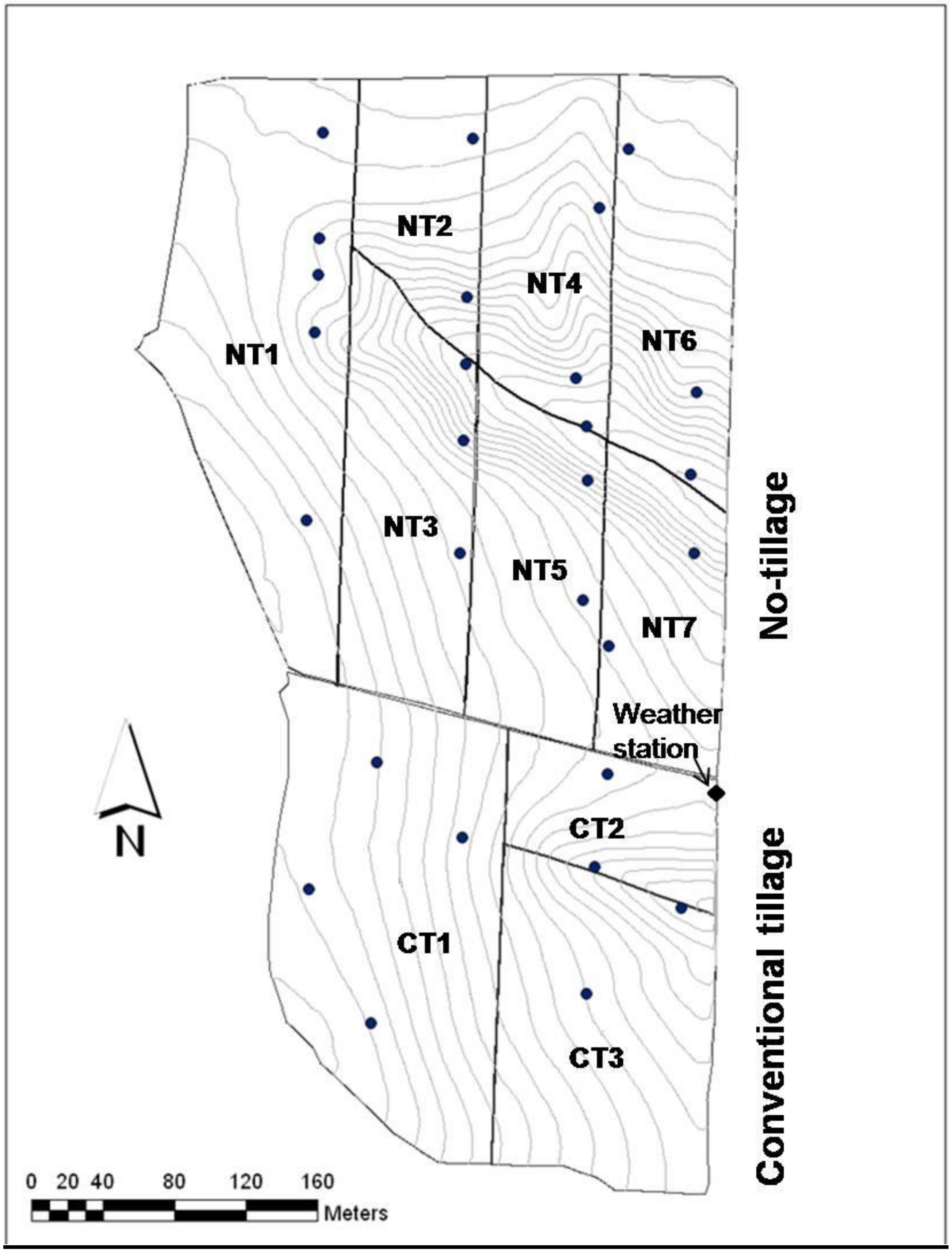

Figure 4.1. Hillslopes for WEPP simulations and locations for soil water measurement.

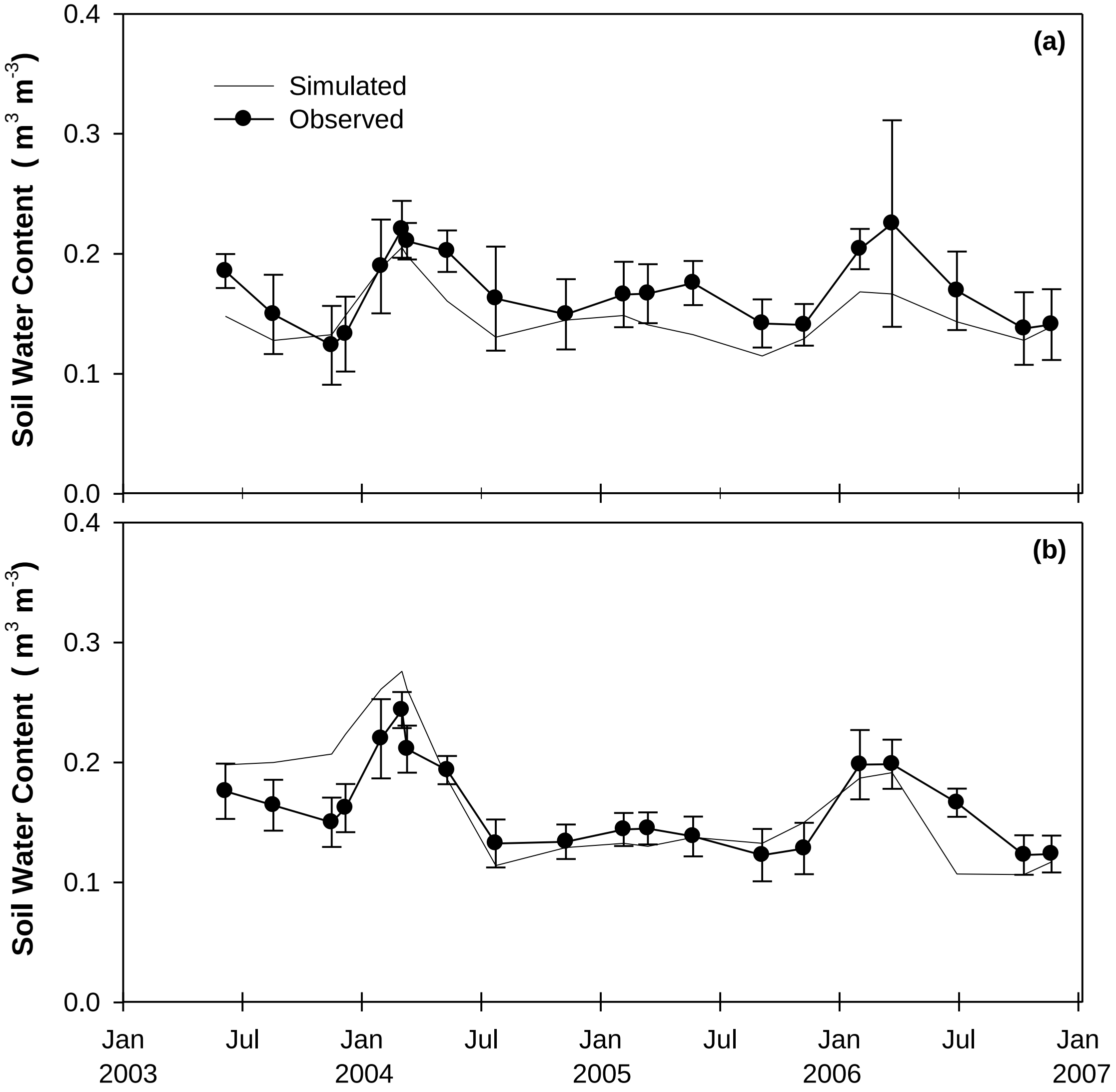

Figure 4.2. Observed and simulated soil water content for (a) NT drainage and (b) CT drainage. Error bars represent standard deviations of soil water measurements on a given day.

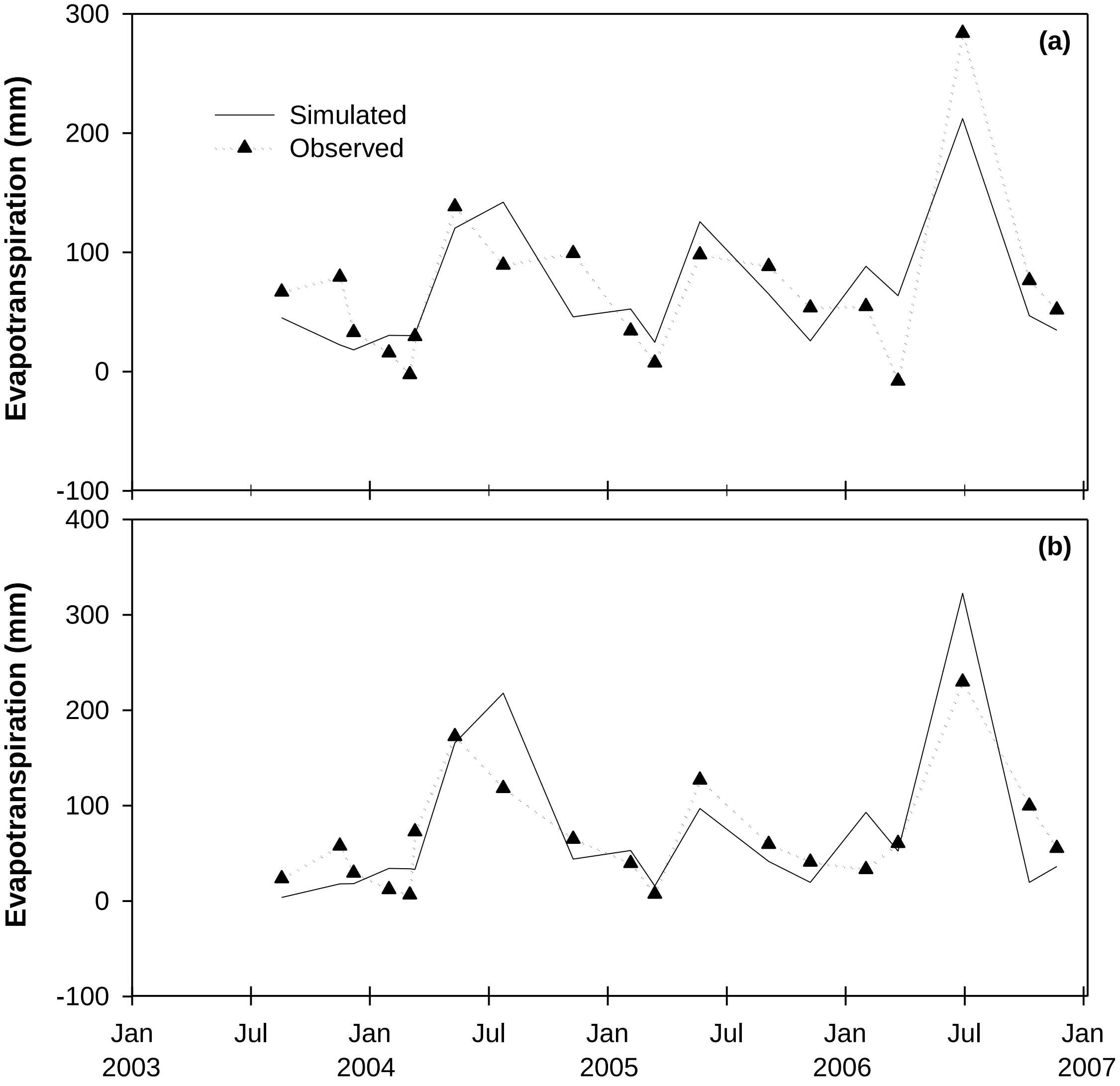

Figure 4.3. Deduced and simulated ET for (a) NT drainage and (b) CT drainage. Deduced ET was calculated as **Precipitation − Change in Soil Water – Runoff.**

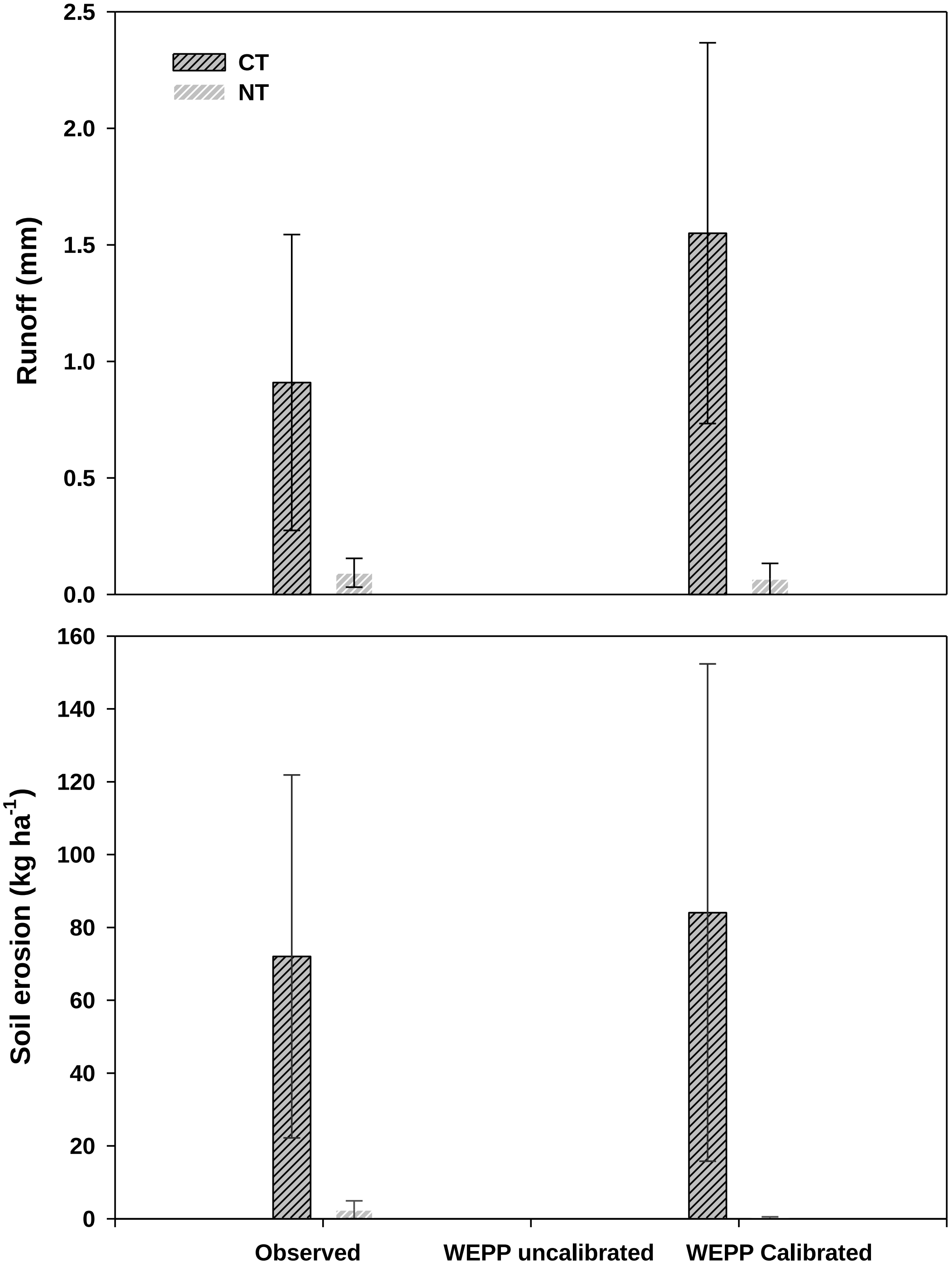

Figure 4.4. Annual averages and standard errors of annual runoff and soil erosion demonstrating improvement in WEPP performance through the calibration of effective hydraulic conductivity and rill erodbility parameters.

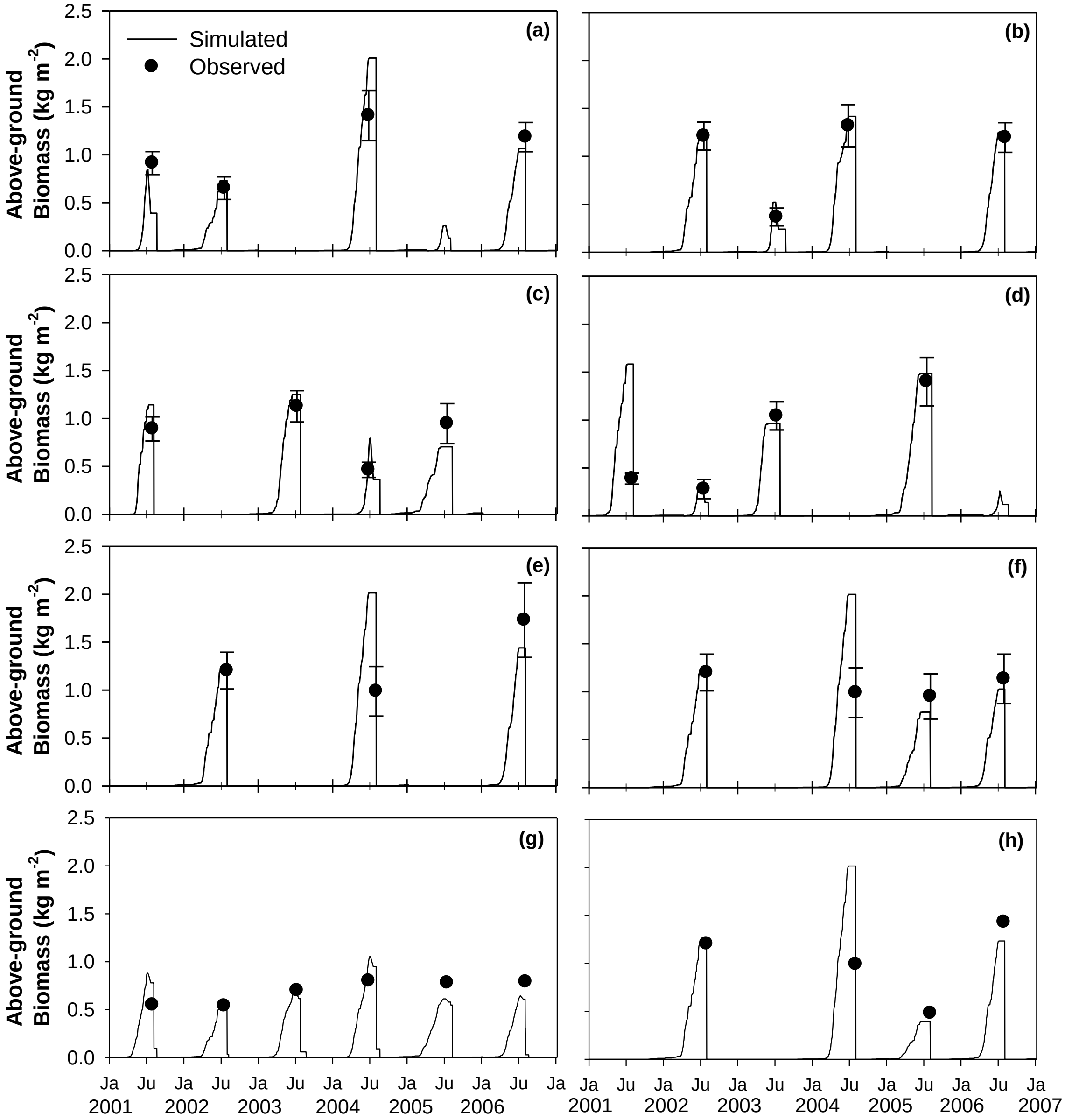

Figure 4.5. Observed and simulated above-ground biomass for (a) NT1, (b) NT2 and NT3, (c) NT4 and NT5,(d) NT6 and NT7, (e) CT1, (f) CT2 and CT3, (g) NT drainage, and (h) CT drainage. Averages and standard deviations in panels (a) through (f) were calculated from multiple-field samples. Drainage annual averages in panels (g) and (f) were calculated from component hillslope values.

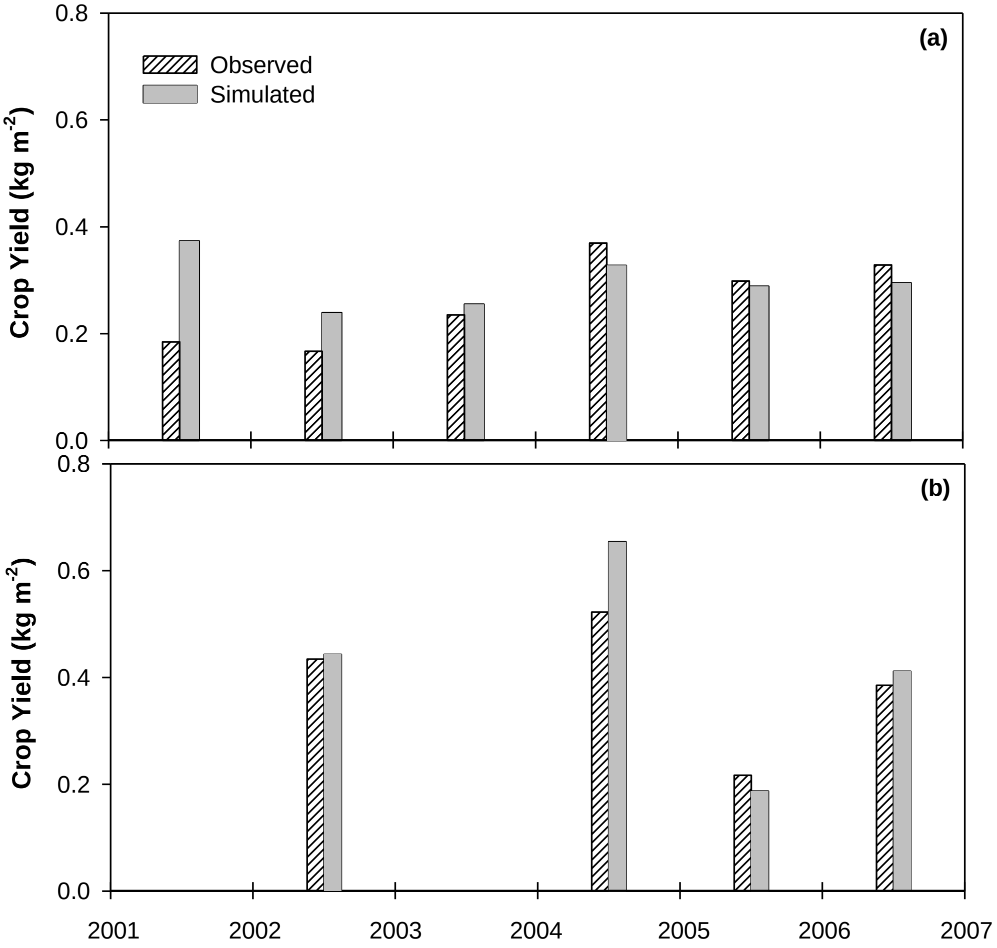

Figure 4.6. Observed and simulated crop yield for (a) NT drainage and (b) CT drainage. Note fallow years 2001 and 2003 under the CT. Observed averages were calculated from component hillslope values. Crop yields for the CT in 2002 and 2004 were single, whole-field values.

4.5. Summary and Conclusion

Intensive, long-term hydrologic and soil erosion research on croplands of the inland Pacific Northwest are largely limited to small plot experimentation (e.g., Greer et al. 2006; Singh et al. 2008). This study is among the few that evaluates drainage-scale runoff, sediment yield, and above-ground biomass and crop yield under different tillage practices.

Water balance (volumetric soil water, ET, and runoff), soil loss, above-ground biomass, and crop yield from two headwater drainages respectively under the NT and CT treatments in northeastern Oregon were simulated with WEPP, a physically-based water erosion prediction model developed by the USDA. The simulation was conducted using observed weather as well as crop and tillage management data together with measured topography and soil properties. Without calibrating any vegetation parameters in the model, WEPP was able to reproduce field-measured crop yields within 9% and 12% for the CT and NT cropping systems, respectively. Above-ground biomass, soil water content, and ET were also adequately predicted. The error in predicted soil water content and ET was in the range of measurement error.

Overall crop yield and above-ground biomass predictions agreed well with observations. Over-prediction of above-ground biomass during a wet year in the CT system suggests the need for calibration of vegetation parameters in case applications and further improvement of WEPP crop growth routines by including additional limiting factors.

Using the default soil parameters in the WEPP database without adjustment, WEPP predicted no runoff or erosion events for the two study drainages where 0.03% or 0.3% of the overall precipitation became runoff. With calibration of the effective hydraulic conductivity and rill erodibility, WEPP was able to generate observed major runoff and erosion events and to simulate the differences in the hydrologic and erosion processes under the two tillage treatments.

Nonparametric statistical tests indicated no significant difference between the simulated and observed data for un-calibrated simulations of seasonal ET, change in soil water content, above-ground biomass, and crop yield, and calibrated simulations of annual runoff and sediment yield, suggesting the adequacy of the WEPP results.

Confounding the performance of WEPP in modeling the hydrologic and erosion processes in this study were a combination of low rainfall intensities, long-duration storms, and a high frequency of soil freezes and thaws during winter. Our ability to evaluate and parameterize the WEPP model for application across the dryland farming region of the U.S. Pacific Northwest would be enhanced in the future by additional large plot- and drainage-scale cropping system research. In physically-based soil erosion models where infiltration, runoff, and erosion are tightly coupled to soil water, vegetative growth, and residue build-up and decay, model assessment should not only include comparisons of simulated and observed runoff and erosion, but also include evaluation of simulated crop growth and residue characteristics. Such analysis is a step forward in the development of physically-based models that adequately assess management impacts on runoff and sediment yield from small agricultural drainages.

CHAPTER FIVE

APPLYING THE WATER EROSION PREDICTION PROJECT (WEPP) MODEL TO SIMULATE WATER BALANCE IN A FOREST WATERSHED, US PACIFIC NORTHWEST

This chapter is to be submitted to *Hydrological Processes* for publication and is currently in submission. Full citation: Cheng, C.X., J.Q. Wu, S. Dun, W.J. Elliot, K.L. Kavanagh, T.E. Link, E. Du, and X. Li. 2008. Applying the Water Erosion Prediction Project (WEPP) model to simulate water balance in a forest watershed, US Pacific Northwest, *Hydrol. Process.* My contribution to the manuscript is summarized in the following. Data collection: no contribution in collecting field data; contributed to review and synthesize literature data. WEPP modeling: developed and incorporated the Penman-Monteith ET routine into WEPP and improved the model's snow simulation routines to increase its applicability, especially to forest settings; carried out model runs using WEPP v2008.9 with Ms. Cecilia Cheng; worked with Ms. Cecilia as well as Drs. Joan Wu and Williams Elliot in analyzing and interpreting WEPP simulation results. Development of manuscript: worked with Dr. Joan Wu on the "Results and Discussion" and "Summary and Conclusion" sections of the manuscript first developed by Ms. Cecilia Cheng and Dr. Joan Wu to improve the technical rigor and clarity of the manuscript; and worked with Dr. Joan Wu in developing the abstract of the manuscript.

5.1 Abstract

Water is a major limiting factor for forest ecosystems, especially in arid US Pacific Northwest. Knowledge of the characteristics of water balance in a forest watershed is necessary for sound forest management and long-term sustainability. Due to the complicated hydrological processes in water balance and the high cost in monitoring these processes, models are widely used as cost-effective tools in forest hydrologic studies.

The Water Erosion Prediction Project (WEPP) model is a physically-based hydrology and erosion prediction technology developed by the US Department of Agriculture. WEPP has seen

numerous applications within and outside the US. Yet studies assessing the adequacy and ability of WEPP in simulating the water balance and the individual hydrologic processes of ET, streamflow, soil water content, and deep percolation under forest conditions are still lacking, likely because of the difficulty in obtaining these field data over a sufficiently long time period.

In the last decade, a comprehensive investigation of cumulative hydrology effects of forest management activities was carried out at Mica Creek Experimental Watershed (MCEW) located in Shoshone County, northern Idaho, USA. A nested sampling design was used to collect daily streamflow at seven subwatershed outlets before road construction and timber harvesting, after road construction, and after harvesting. Sap-flux based transpiration was measured for selected species in an unharvested subwatershed, and soil water content was also monitored. Meteorology data were collected using a USDA NRCS SNOTEL station and four weather stations distributed across the watershed.

The main purpose of this study was to assess the performance of the WEPP model in simulating the major components in water balance under forest settings using field data. The specific objectives were: (i) to present field-observed water balance and major components, including streamflow, tree transpiration, transient soil water content, for MCEW; and (ii) to evaluate the suitability of WEPP in simulating these hydrologic processes under forest settings by applying the model to the MCEW

WEPP v2008.9 was applied to the sub-watershed with measured sap-flux and soil water content. WEPP-simulated annual and daily watershed discharge was agreeable with field observation. Without accounting for tree water storage, WEPP could not properly simulate temporal dynamic of plant transpiration in particular for the drying period in summer. As a consequence, WEPP simulated abrupt drop in soil water during this time period. Future efforts ahould be devoted to assessing the influence of snowmelt timing on streamflow and including tree water storage in estimation of plant transpiration and soil water dynamics .

5.2 Objectives

The main purpose of this study was to assess the performance of the WEPP model in simulating the major components in water balance under forest settings using field data. The specific objectives were: (i) to present field-observed water balance and major components, including streamflow, tree transpiration, transient soil water content, for MCEW; and (ii) to evaluate the suitability of WEPP in simulating these hydrologic processes under forest settings by applying the model to the MCEW

5.3 Materials and methods

- Study site
- Field instrumentation and measurements
- Model application
    - WEPP overview
    - WEPP inputs and simulation
- Statistical analysis

5.4 Results

Table 5.1. Soil inputs for WEPP applications to the sub-watershed 3 (SWD3) in the Mica Creek Experimental Watershed (MCEW)

	Soil Layer			
	1	**2**	**3**	**4**
Soil depth, mm	50	450	1050	1800
Sand, % weight	80	30	30	80
Clay, % weight	10	10	10	10
Organic matter, % volume	5	5	5	5
Cation exchange capacity, cmol kg^{-1}	1.5	15	15	1.5
Rock, %	0	20	40	0
Effective saturated hydraulic conductivity of surface soil, mm h^{-1}	200			
Saturated hydraulic conductivity of restricted layer, mm h^{-1}	0.06			
Soil anisotropy ratio	15			

Table 5.2. Management inputs for WEPP applications to the sub-watershed 3 (SWD3) in the Mica Creek Experimental Watershed (MCEW)

Parameter	**Forest Perennial**
Initial ground cover, %	90
Period over which senescence occurs, days	90
Fraction of canopy remaining after senescence	0.5
Fraction of biomass remaining after senescence	0.8
Decomposition constant for above-ground biomass	0.006
Biomass energy ratio, kg MJ^{-1}	15
Plant stem diameter at maturity, m	0.25
Maximum canopy height, m	6
Maximum root depth, m	0.5
Plant spacing, m	2
Plant coefficient (K_c)	1
Depletion Fraction (P)	0.7
Maximum leaf area index	6

Table 5.3. WEPP-simulated annual water balance (mm) for the sub-watershed 3 (SWD3) in the Mica Creek Experimental Watershed (MCEW)

Water Year	P	Q	E_p	E_s	D_p
1992	1367	405 (321)*	423	112	342
1993	1359	548 (531)	380	113	432
1994	925	250 (238)	402	95	297
1995	1563	615 (531)	410	104	389
1996	1761	924 (961)	347	83	536
1997	2094	1125 (997)	416	108	433
1998	1256	392 (441)	425	108	447
1999	1555	723 (661)	395	88	422
2000	1502	691 (609)	370	81	396
2001	1077	370 (308)	391	81	358
2002	1639	782 (665)	366	74	455
2003	1266	428 (427)	330	78	513
2004	1454	465 (430)	399	95	430
2005	1159	309 (514)	365	68	640
2006	1404	439 (570)	359	69	563
Average	1425	564 (547)	385	90	444

P = precipitation, Q = surface runoff, E_p = plant transpiration, E_s = soil evaporation, D_P = deep percolation

* Value in parentheses is field observed runoff.

Table 5.4. Pearson correlation coefficients between field-measured and WEPP-simulated annual discharges and observed annual precipitation (all in mm) for the SWD3.

	Precipitation		*Observed Runoff*		*Simulated Runoff*	
	r	*P*-value	*r*	*P*-value	*r*	*P*-value
Precipitation	1.000					
Observed Runoff	0.897	< 0.001	1.000			
Simulated Runoff	0.951	<0.001	0.927	<0.001	1.000	

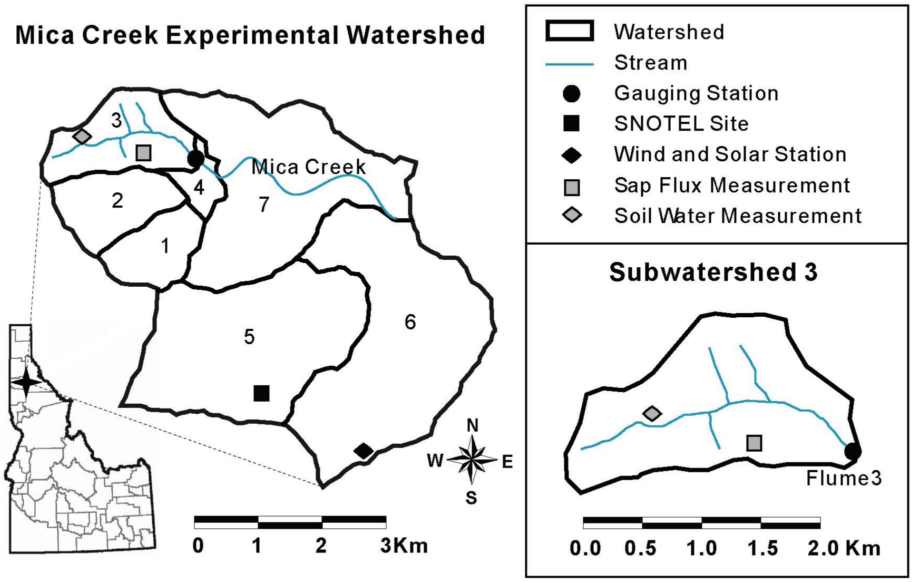

Figure 5.1. Schematic of the Mica Creek Experimental Watershed (MCEW), Shoshone County, Idaho

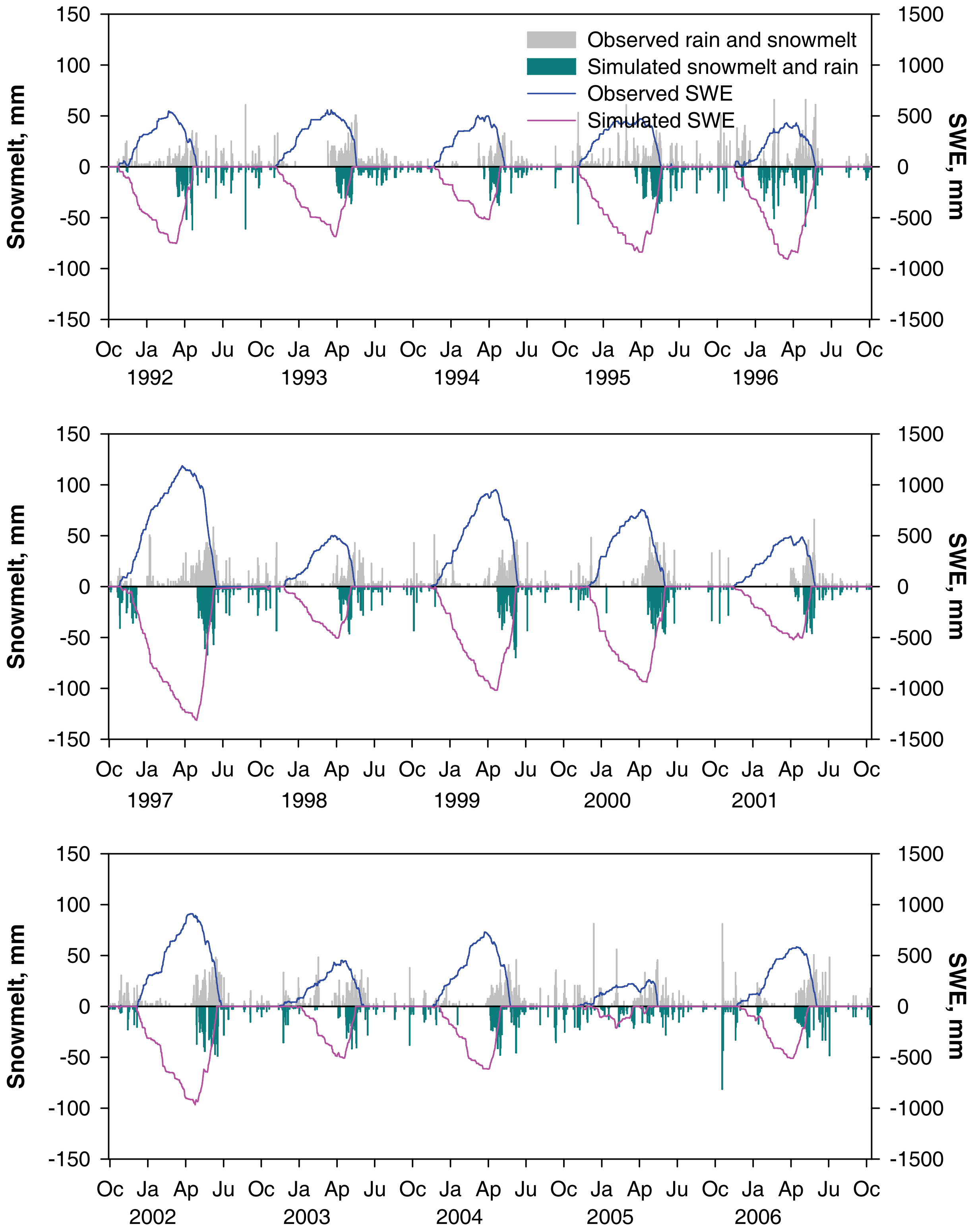

Figure 5.2. WEPP-simulated and field-observed snow water equivalent (SWE) and snowmelt for the SNOTEL station in MCEW (1991–2006). Note that the entire simulation was presented in three panels for clarity

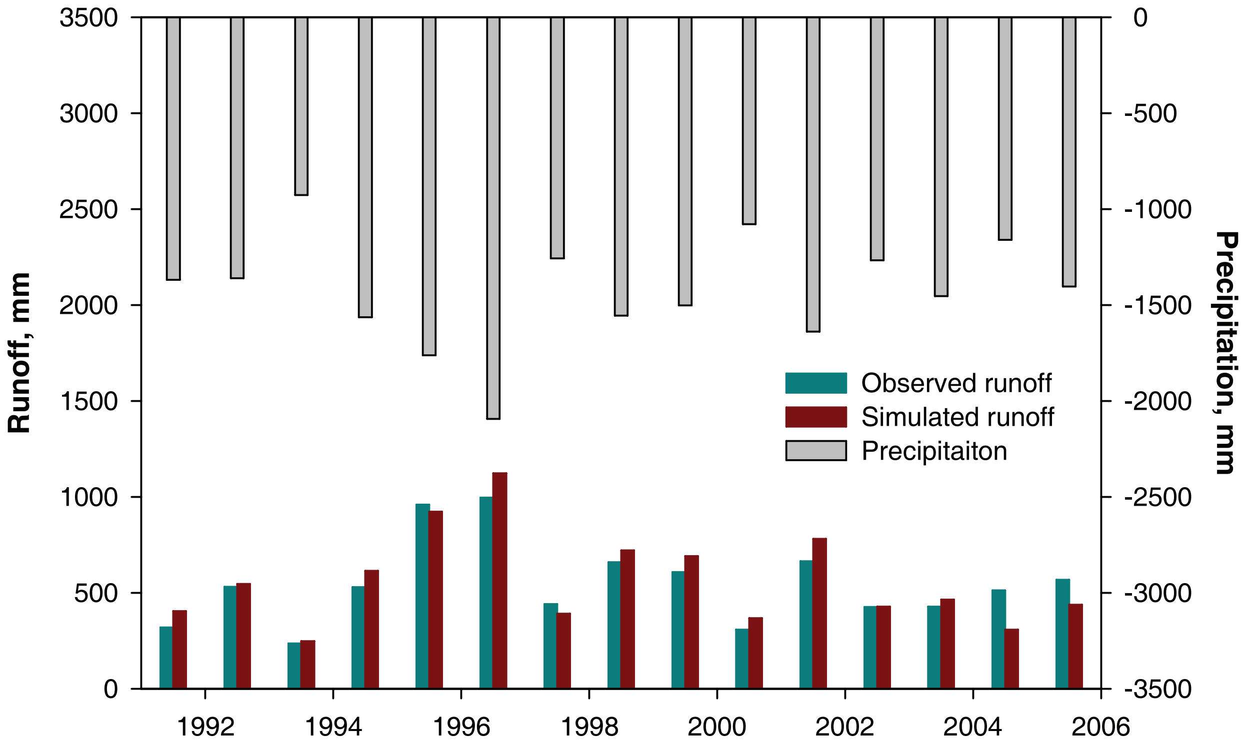

Figure 5.3. WEPP-simulated and field-observed annual watershed discharges for subwatershed 3 (SWD3) in MCEW (1991–2006)

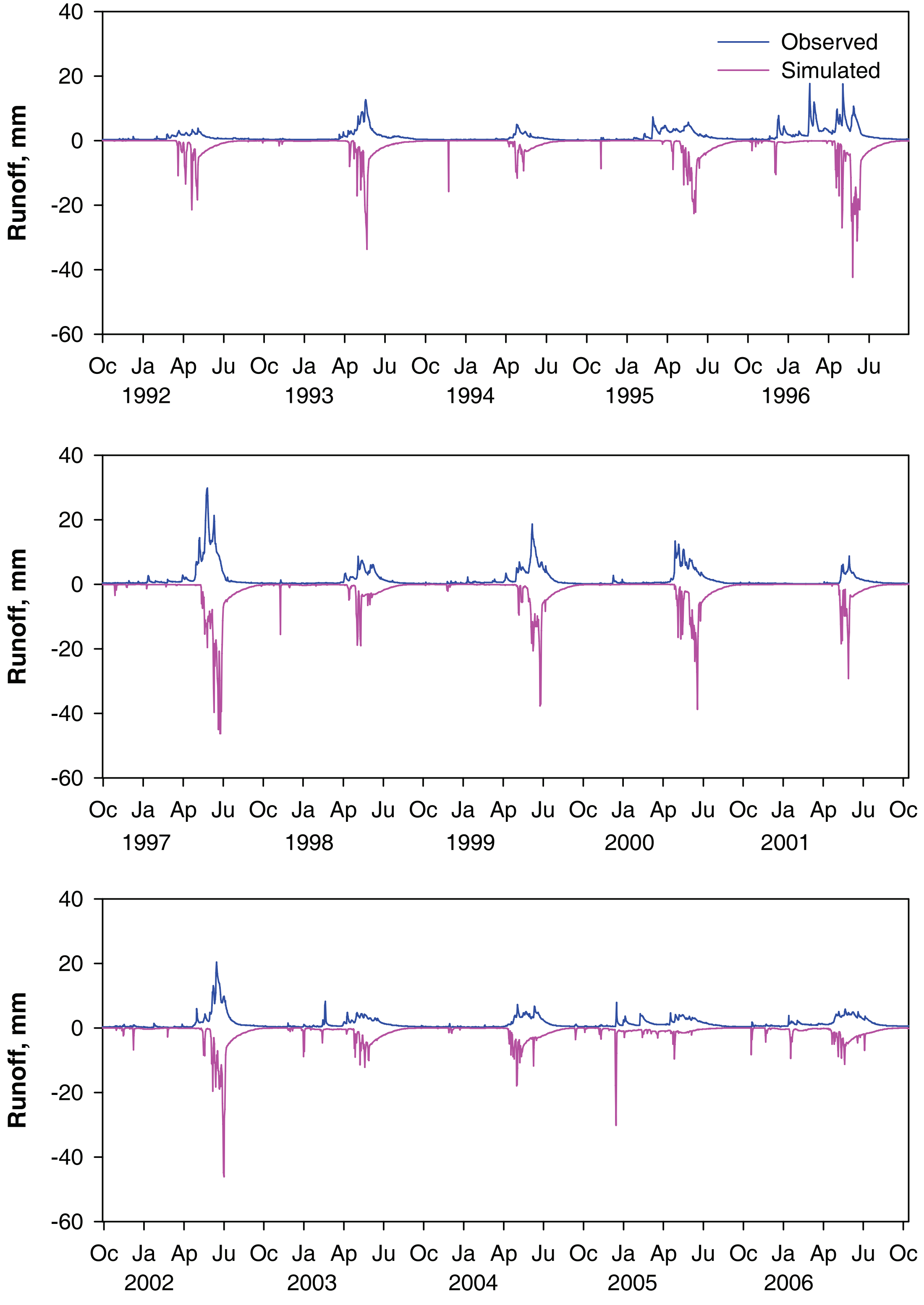

Figure 5.4. WEPP-simulated and field-observed streamflow for subwatershed 3 (SWD3) in MCEW (1991–2006). Note that the entire simulation was presented in three panels for clarity

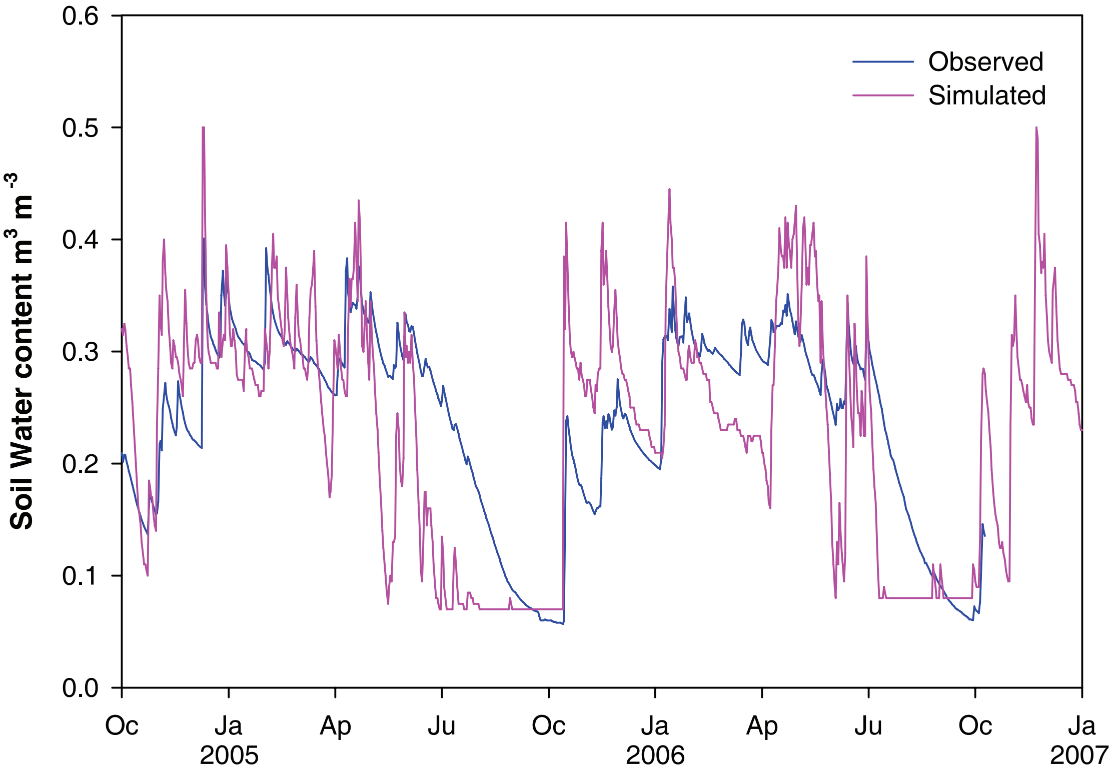

Figure 5.5. WEPP-simulated and field-observed soil water content for subwatershed 3 (SWD3) in MCEW (2004–2006)

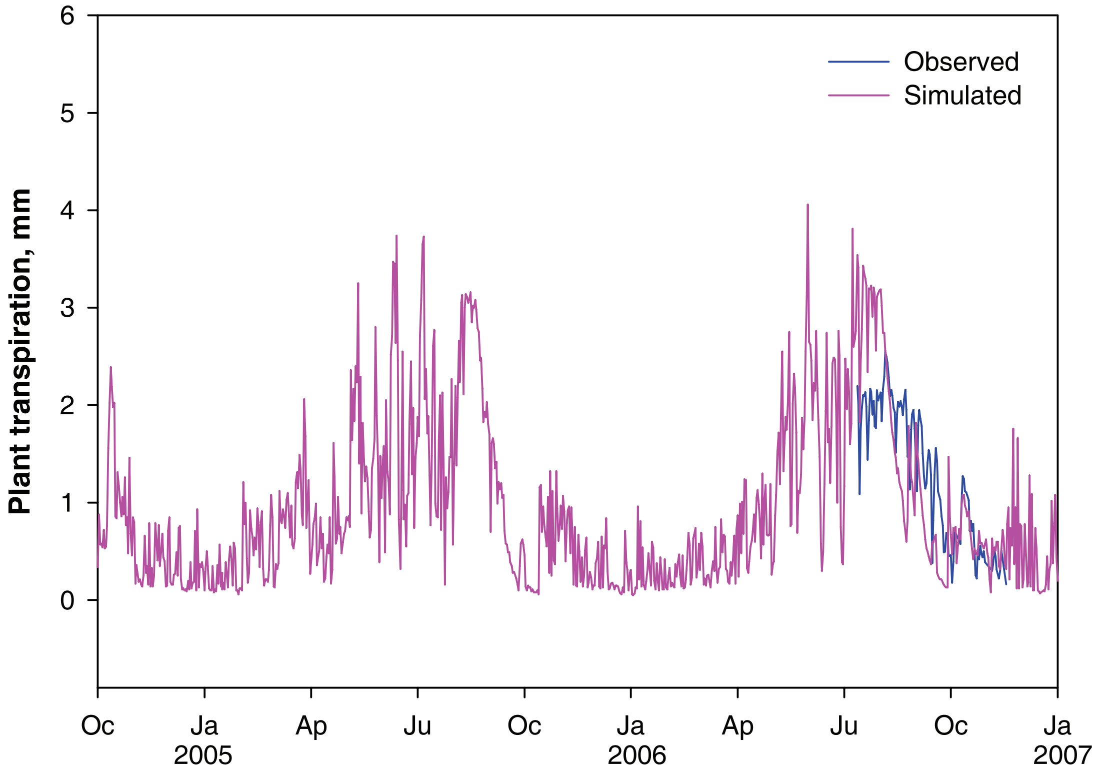

Figure 5.6. WEPP-simulated plant transpiration and field-observed sapflow for subwatershed 3 (SWD3) in MCEW (2004–2006)

5.5. Summary and Conclusion

This study aimed to present field-observed water balance (including streamflow, tree transpiration, transient soil water content) for a subwatershed, SWD3, in the Experimental Watershed, Mica Creek, ID, USA, and to assess the performance of a physically-based watershed hydrology model in simulating the field-observed hydrologic processes at the study watershed.

Daily discharge from the SWD3 observed during 1992–2006 exhibited prominent seasonality. Daily streamflow peaked during the snowmelt season with the flow accounting for more than 60% of annual discharge. Measured flows occurred year round and even during dry summer months, suggesting the contribution of ground-water base flow. Annual watershed discharge was affected by annual precipitation and varied substantially, ranging 237–996 mm with an average of 546 mm accounting for 38% of annual precipitation.

Field-measured daily volumetric soil water content for the top 0–0.2 m of soil during the water years of 2004–2006 varied from less than 0.06 $m^3 m^{-3}$ in summer to more than 0.40 $m^3 m^{-3}$ in winter and was closely related to precipitation. Field-measured sap-flux-based transpiration for the monitored species during the main growing season of late June to October in 2006 was 155 mm with an average daily value of 1.2 mm d^{-1} and a maximum of 2.6 mm d^{-1}. Daily sap-flux-based transpiration declined with the attenuation of solar radiation and fluctuated in response to soil water content.

WEPP v2008.9-simulated annual watershed discharge for the SWD3 during 1992–2006 was agreeable with field observation. WEPP-simulated daily watershed discharge was generally compatible with field measurement except for certain peak flows and lags between the simulated and observed peak streamflow for the warm winters. Without accounting for tree water storage, WEPP over predicted plant transpiration in the drying period in late summer. As a consequence, WEPP simulated abrupt drop in soil water during this time period. Future efforts should be devoted to assessing the influence of snowmelt timing on streamflow and including tree water storage in estimating plant transpiration and soil water dynamics.

CHAPTER SIX

SUMMARY AND CONCLUSION

This doctoral research is part of a comprehensive project developing and improving winter hydrology components for water erosion models. The goal of this dissertation study was to adapt a modeling approach for winter hydrology based on mass- and energy conservation, and to implement this approach into a physically-oriented hydrological model, such as WEPP; and to assess this modeling approach through case applications to different geographic conditions. This dissertation has four major chapters, each adapted as a refereed manuscript for publication. The development, implementation into the WEPP model (v2008.9), and assessment of a new winter hydrology routine was in Chapter 2, and the application and additional evaluation of this and alternative winter routines were in Chapters 3–5. The main conclusions from this study were:

1. A study assessing WEPP v2004.7 with an alternative simplified winter routine based on energy-budget (Lin and McCool, 2006) compared model results with field observations from the Palouse Conservation Field Sation near Pullman, WA for 2003–2006 . Simulated snow cover, frost penetration, runoff and erosion using WEPP v2004.7 were in reasonable agreement with field observations for certain monitored periods, and for other study periods, the agreement was poor.
2. The new frost routine developed based on a mass-energy-balance approach in this study has the ability to account for multiple sandwiched frost layers, soil water migration to freezing front, and change of soil water due to unsaturated soil water movement. The successful implementation of the new frost simulation routines in WEPP v2008.9 allows for interaction between hourly frost simulation and other daily water balance computations.

3. WEPP v2008.9, with the new frost routines, satisfactorily simulated the distinct characteristics of the temporal and long-lasting snow cover and soil frost under different climate conditions of the Pacific Northwest and the North Central Region of the USA. WEPP-simulated snow and frost depths, snow cover period and frost duration, as well as runoff and erosion were in reasonable agreement with field observations for both study sites.
4. The performance of WEPP v2008.9 was assessed by applying the WEPP model to two headwater drainages in the dryland farming area of the Pacific Northwest near Pendelton, OR. The two drainages were under no-tillage (NT) and conventional tillage (CT) respectively where 0.03% or 0.3% of the overall precipitation became runoff. WEPP was able to generate observed major runoff and erosion events and to simulate the differences in the hydrologic and erosion processes under the two tillage treatments. WEPP v2008.9 also reasonably reproduced field-measured crop yields, above-ground biomass, soil water content, and deduced ET for the CT and NT cropping systems, respectively.
5. The improvement of WEPP snow simulation routines rendered satisfactory simulation in snowmelt and snow accumulation for the Experimental Watershed, Mica Creek, ID a typical forested watershed in the Pacific Northwest. For the forested watershed with snow-dominated hydrology, WEPP v2008.9-simulated annual and daily watershed discharge was agreeable with field observation for 1991–2006. Simulated temporal changes in ET and soil water were compatible with field observations during 2005 and 2006.
6. Compared to WEPP v2006.5, WEPP v2008.9 exhibited substantially improved applicability. Version 2008.9 can better simulate winter hydrologic processes in cold regions.
7. Continued efforts are needed to further improve the ability of WEPP to better simulate snow pack dynamics, frost thawing process, and the transient change of soil hydraulic and erosion

properties.

References

Lin, C., and D. K. McCool. 2006. Simulating snowmelt and soil frost depth by an energy budget approach. Trans. ASABE 49: 1383–1394.

APPENDICES

Appendix A. Limitations of the Frost Routines in WEPP v2006.5

Major limitations in the frost simulation routines of WEPP v2006.5 included: (i) coarse discretization of the whole soil profile into two layers (tillage and non-tillage) without using the finer soil profile discretization for daily water balance; (ii) incorrect use of energy flux for the amount of energy; (iii) inadequate assumption of a constant temperature (7 °C) for the unfrozen soil 1m below the freezing front; (iv) no simulation of movement of unsaturated water; (v) accounting for only one frost "sandwich" layer; (vi) insufficient adjustment of saturated hydraulic conductivity of frozen soil (Greer et al., 2006); and (vii) programming errors in computing unsaturated hydraulic conductivity, soil water potential, and upward water movement to a freezing front. A detailed description of these limitations is included in the following.

Soil layers

In the WEPP model, the soil profile is discretized into two 10-cm thick soil layers for the top 20-cm tillage zone, and subsequently 20-cm thick soil layers for the remainder. However, only two layers (tilled and untilled layer) were used in the original frost simulation routines in WEPP v2006.5, causing substantial errors in computing soil water movement and ice content at different depths within a frozen zone. Only one sandwiched frost layer was allowed in WEPP v2006.5.

Soil temperature 1m below bottom-most frozen soil

It was assumed that soil temperature 1 m below the frozen zone is a constant 7 °C, which was equivalent to a soil temperature gradient of 7 °C m^{-1} for the unfrozen soil underlying the frozen zone. However, both soil temperature and soil temperature gradient change with time and soil depth (Fig A.1).

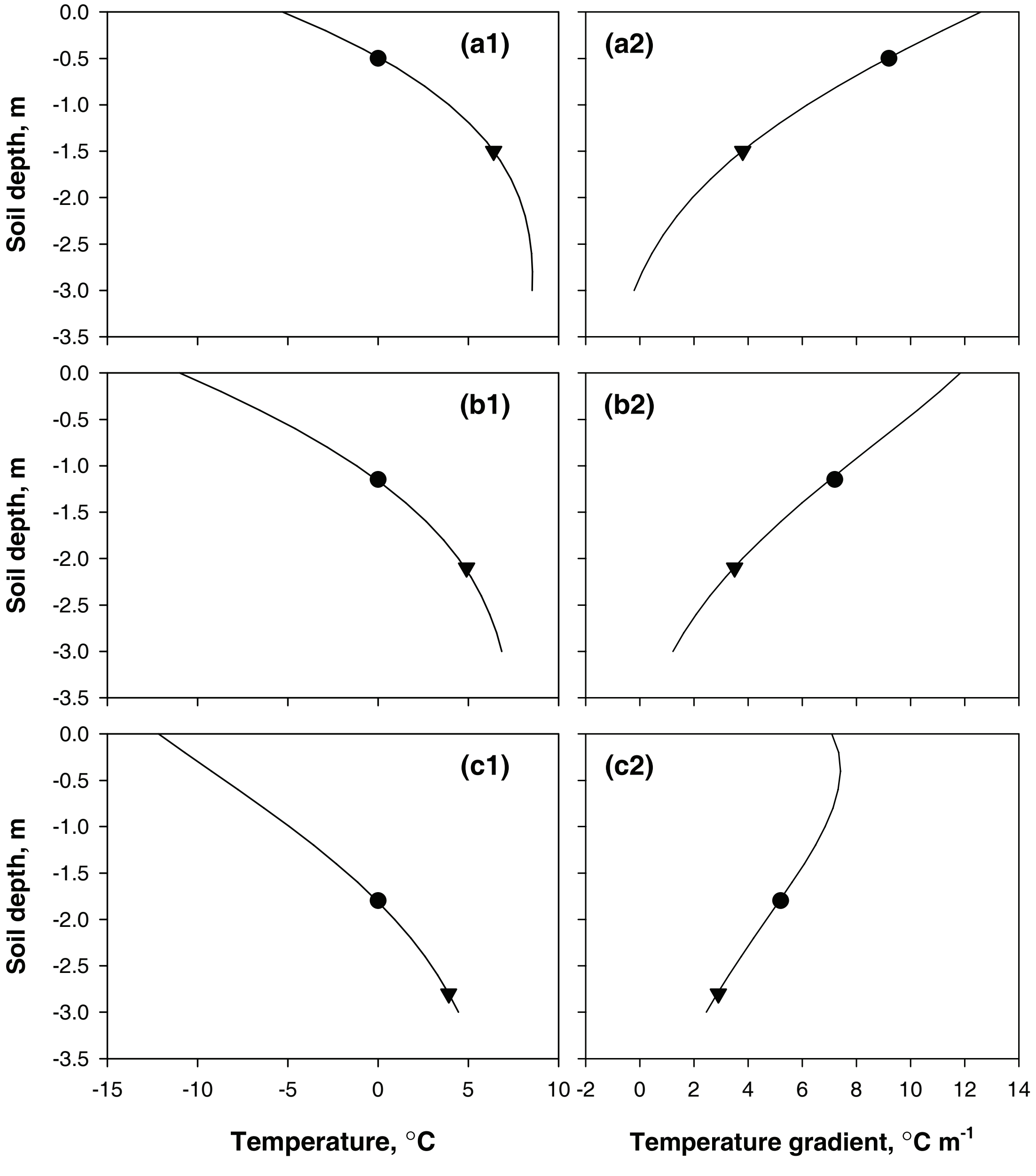

Figure A.1. Estimated soil temperature (left panel) and temperature gradient (right panel) for Julian days (a) 330, (b) 360, and (c) 30. Circles and triangles refer to positions of the freezing fronts and 1 m below. Annual average and amptitude of fluctuation of temperature at the soil surface were 5.5 and 18 °C, respectively, and phase shift to time was 110 d based on climate data for Morris, MN. Damping depth used was 2 m.

Unsaturated hydraulic conductivity, soil water potential, and upward water movement

In WEPP v2006.5, regression equations were used to determine unsaturated hydraulic conductivity based on transient soil water content and soil hydraulic properties, including porosity and soil water contents at field capacity and wilting point (Eq. A1–A6).

$$P_{cm} = 10.0 \times 10^{1.518514 \frac{\phi - \theta}{\theta_{fc} - \theta_{wlt}}} \tag{A1}$$

$$K = K_{sat} \qquad P_{cm} \leq 15 \tag{A2}$$

$$K = K_{sat} \times 10^{1.06 - 0.98 \log_{10}(P_{cm})} \qquad P_{cm} \leq 41 \tag{A3}$$

$$K = K_{sat} \times 10^{-131.3 + 265.0 \log_{10}(P_{cm}) - 199.4 (\log_{10}(P_{cm}))^2 + 66.2 (\log_{10}(P_{cm}))^3 - 8.2 (\log_{10}(P_{cm}))^4} \qquad P_{cm} \leq 450 \tag{A4}$$

$$K = K_{sat} \times 10^{-12.1 + 7.58 \log_{10}(P_{cm}) - 1.63 (\log_{10}(P_{cm}))^2} \qquad P_{cm} \leq 10000 \tag{A5}$$

$$K = 0 \qquad P_{cm} > 10000 \tag{A6}$$

where P_{cm} [cm] is water potential; ϕ [m m^{-3}] is soil porosity; θ, θ_{fc}, and θ_{wlt} are transient soil water content, and soil water contents at field capacity and wilting point, respectively; K and K_{sat} are hydraulic conductivity for unsaturated and saturated soil, respectively.

These equations were improperly coded in WEPP v2006.5, i.e., the power of the log terms in Eq. A4 and A5 were mistakenly placed on the water potential terms. The upward water movement from unfrozen soil to a freezing front was simulated using Darcy's law in WEPP v2006.5. However, instead of computing soil water potential at a freezing front and the difference in water potential between a freezing front and the underlying soil for hydraulic gradient, the hydraulic gradient was approximated by the water potential of the unfrozen soil, leading to inaccuracy.

Saturated hydraulic conductivity of frozen soil

In WEPP v2006.5, saturated hydraulic conductivity of frozen soil was estimated by multiplying the saturated hydraulic conductivity of the unfrozen soil by a factor. The factor, ranging 0.1–2.0, is an exponential function of the ratio of ice content to field capacity

$$f_{fz} = 3.75\, e^{(-0.026\, \theta_{ice}/\theta_{fc})} \tag{A7}$$

where f_{fz} [-] is the adjustment factor, θ_{ice} and θ_{fc} are ice content and field capacity of a soil layer.

For the Palouse region of the US Pacific Northwest, evaluation of WEPP winter routines showed that this factor needs to be about 0.001 to reproduce the observed runoff (Greer et al., 2006).

References

Greer, R.C., J.Q. Wu, P. Singh, and D.K. McCool. 2006. WEPP simulation of observed winter runoff and erosion in the U.S. Pacific Northwest. Vadose Zone J. 5:261–272.

Appendix B. Modular Flowcharts for Snow and Frost Simulation

B.1. One-dimensional simulation of soil freeze and thaw

Major subroutines and functions in frost simulation included a main frost simulation program, and subroutines for simulating (i) surface temperature of the snow-residue-soil system, (ii) soil temperature, (iii) soil freezing from top of the system, (iv) thawing from top of the system, (v) thawing from bottom of the system, (vi) unsaturated soil water movement, and (vii) interaction between frost routines and other water balance components (Figures B.1–B.8).

B.2. Snow accumulation and snowmelt

Snow simulation in the WEPP model included a main snow simulation program calling three subroutines for simulating (i) partitioning precipitation into snow and rain, (ii) snow accumulation, including simulation of snow depth and snow density, and (iii) snowmelt (Figures B.9–B.12).

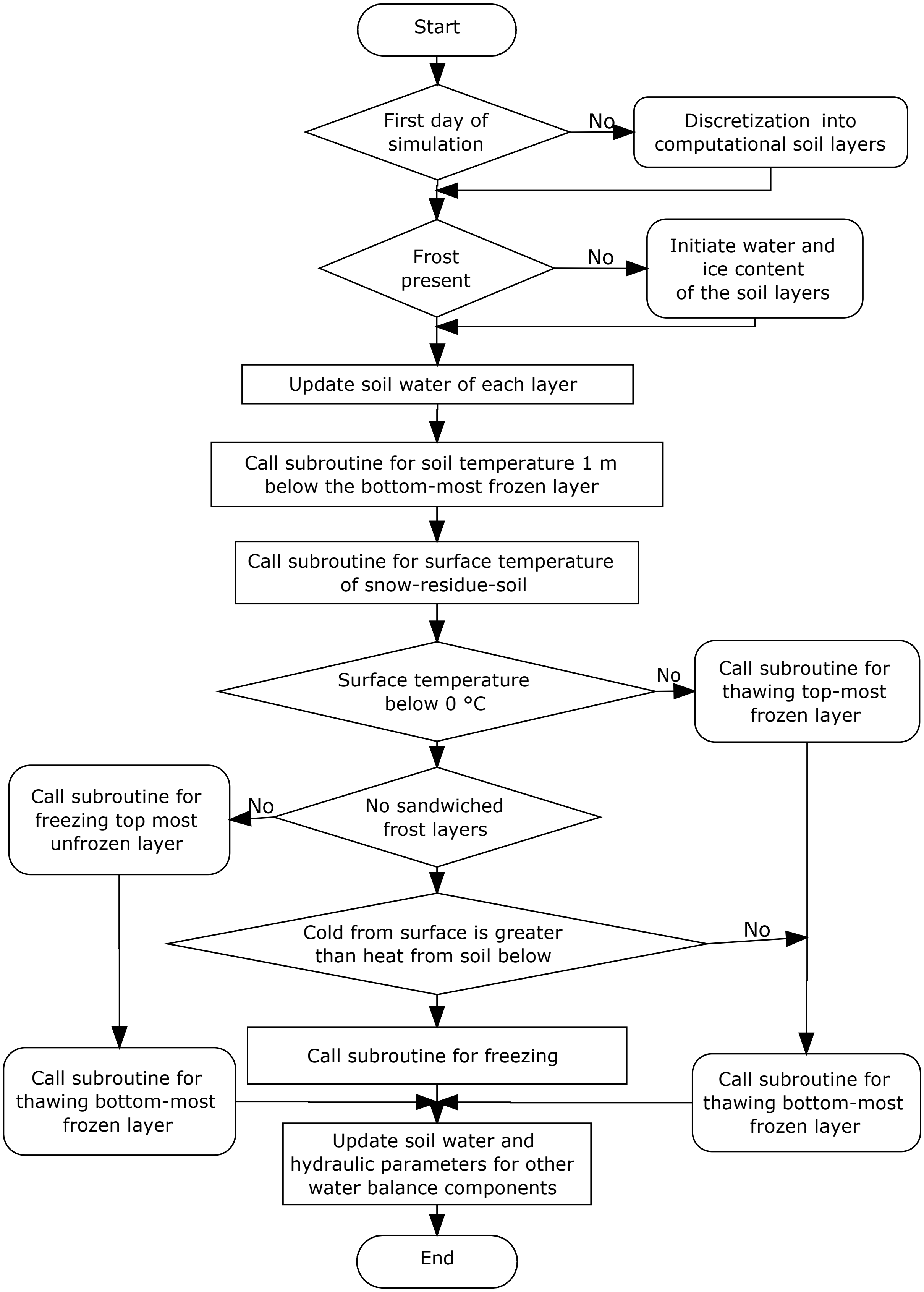

Figure B.1. Flowchart of the main frost simulation program

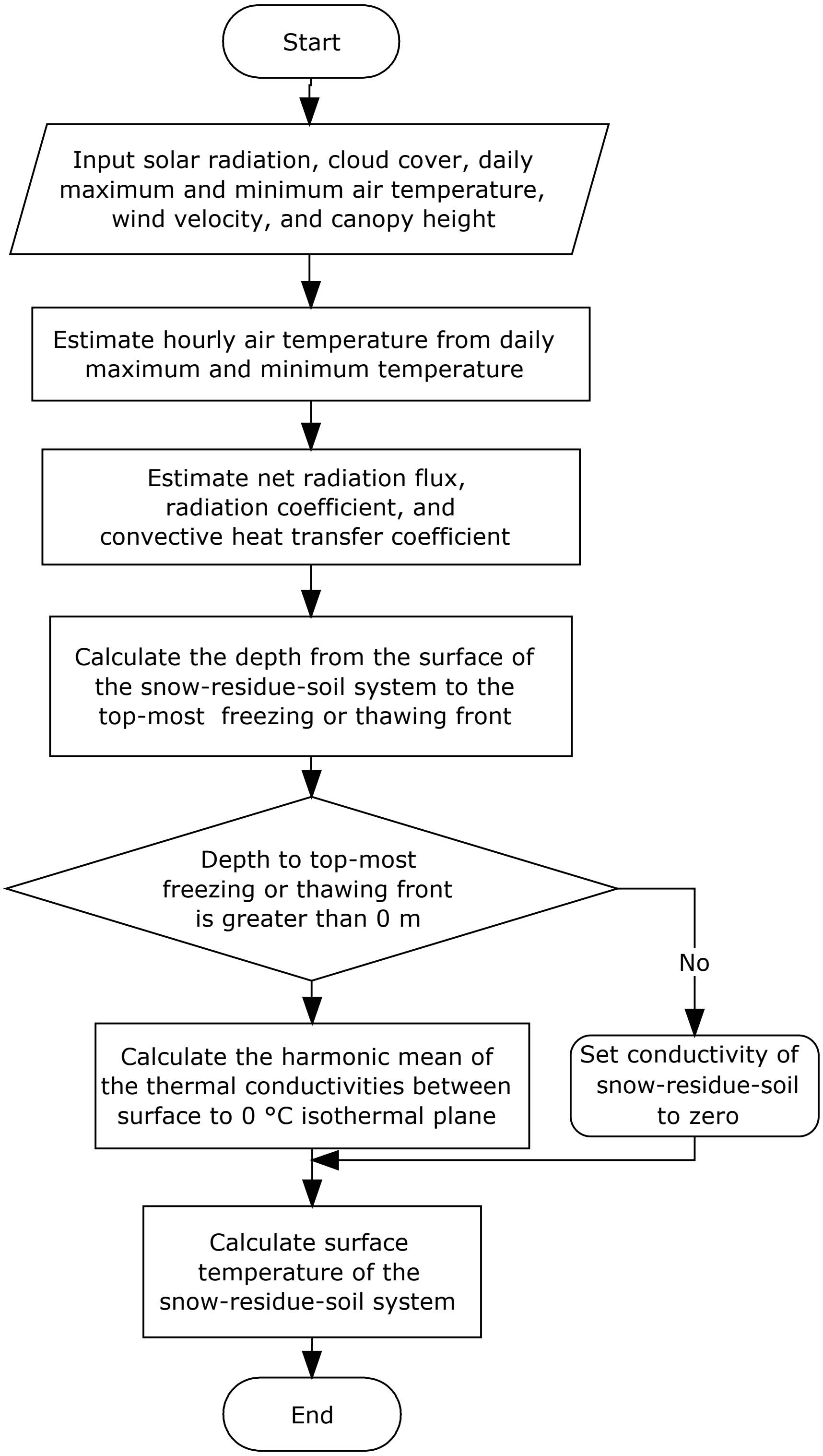

Figure B.2. Flowchart for estimating surface temperature of the snow-residue-soil system

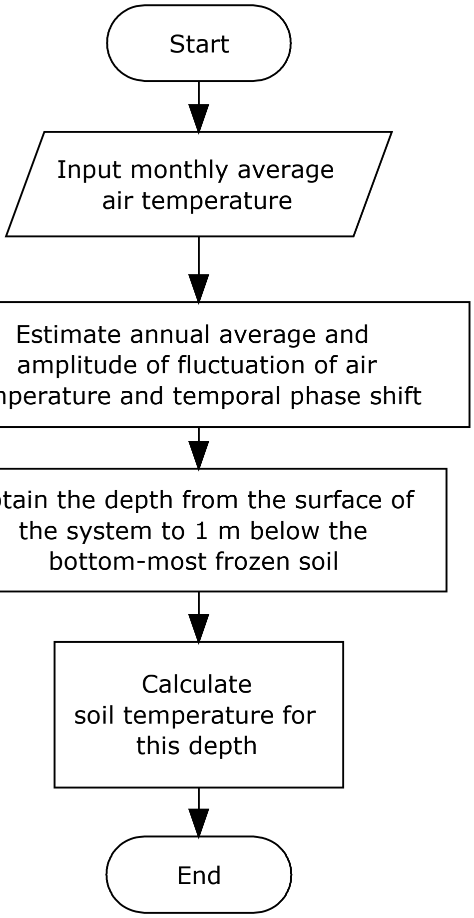

Figure B.3. Flowchart for estimating soil temperature

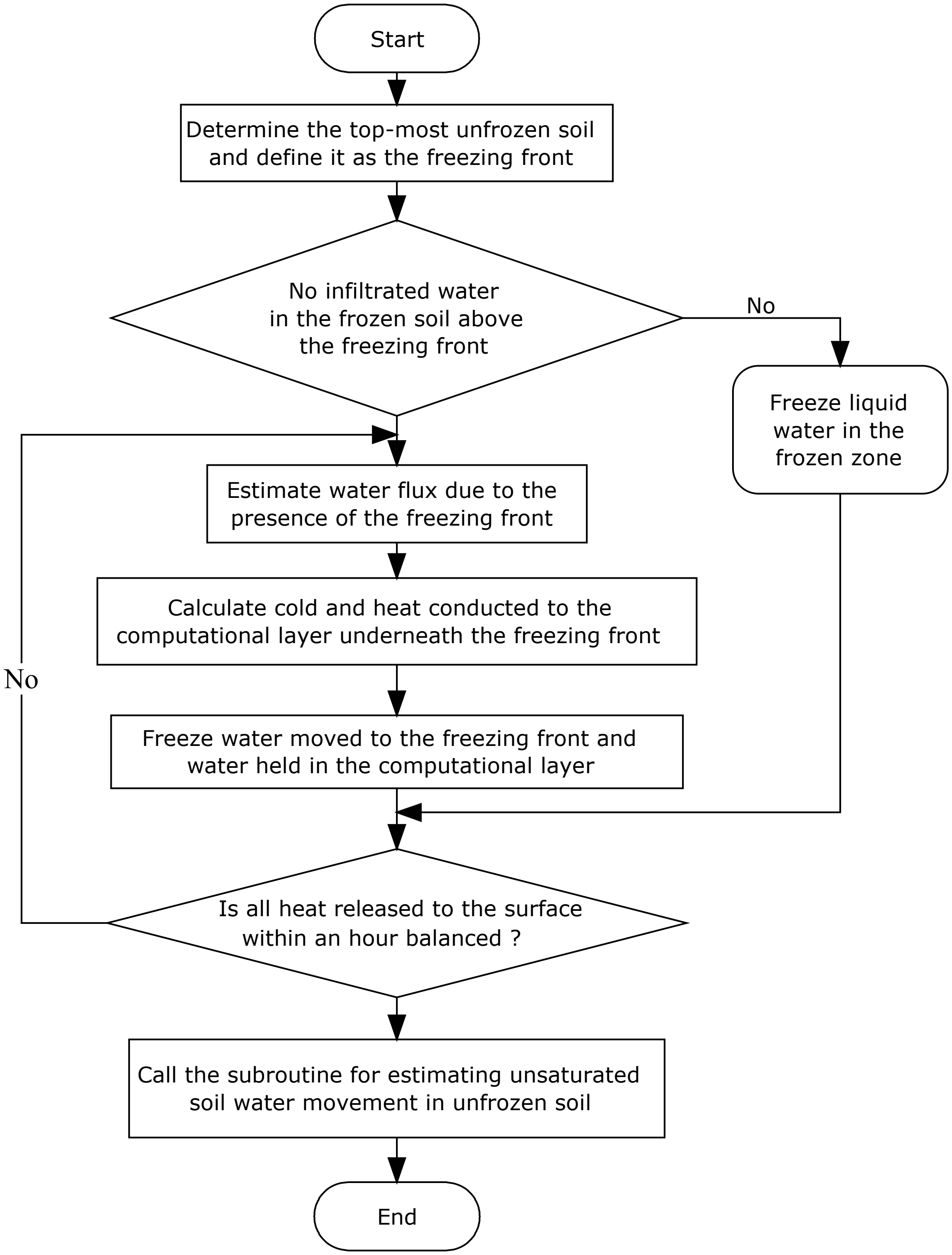

Figure B.4. Flowchart for simulating soil freezing

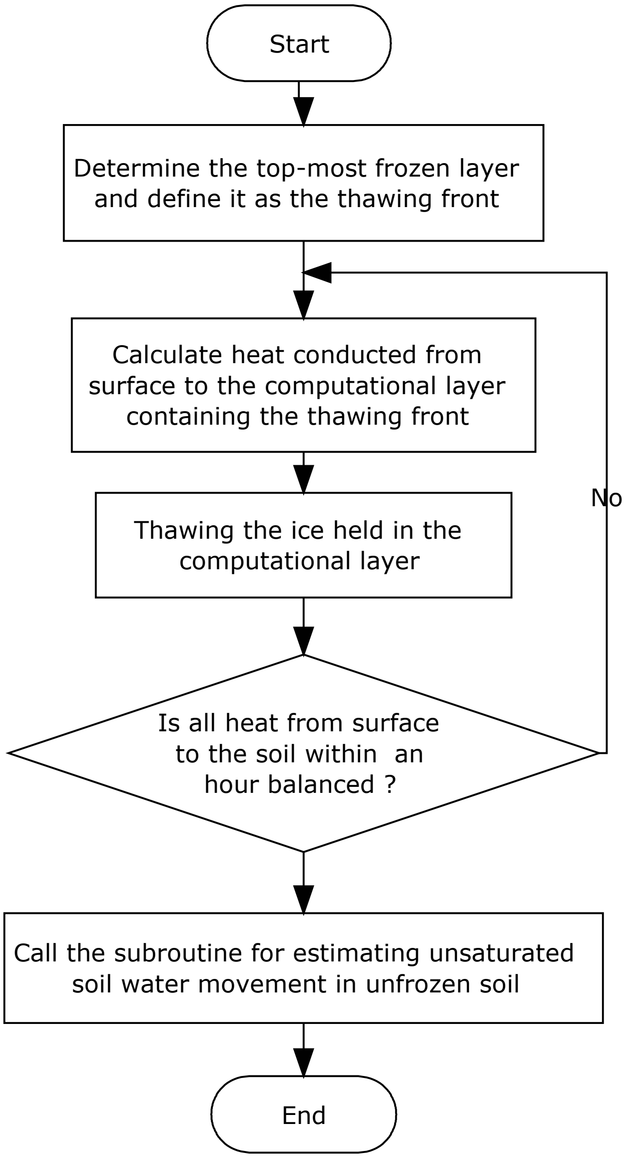

Figure B.5. Flowchart for simulating thawing from the top of the system

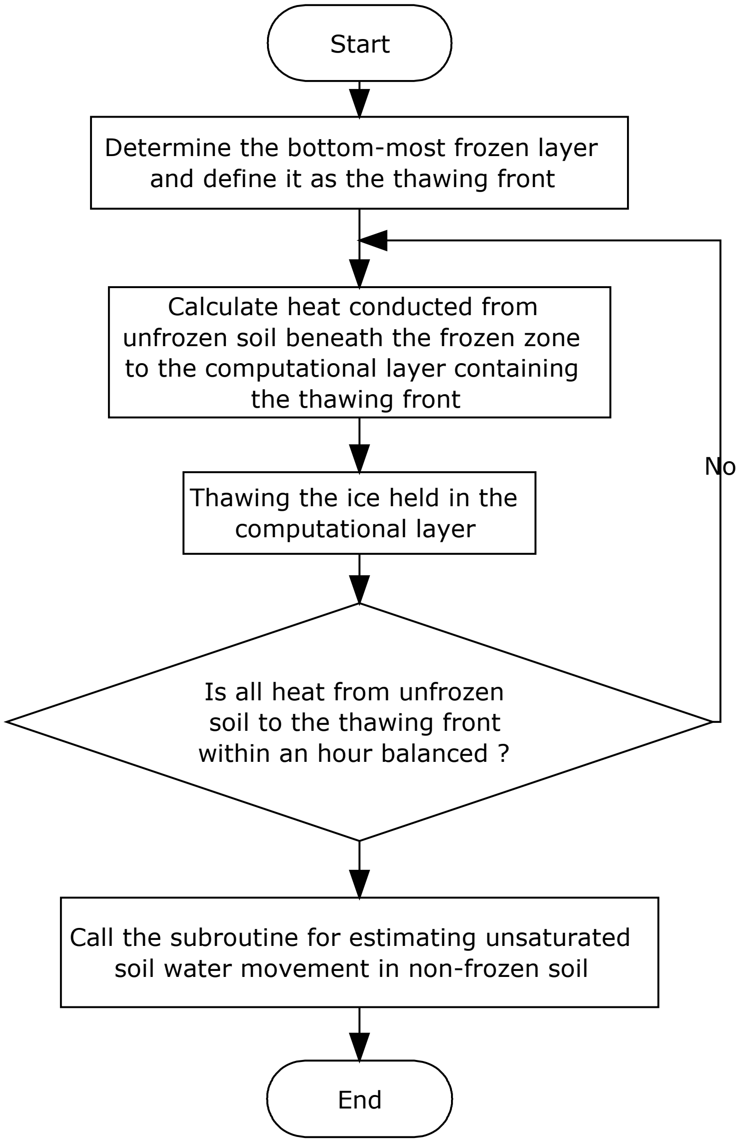

Figure B.6. Flowchart for simulating thawing from the bottom of the system

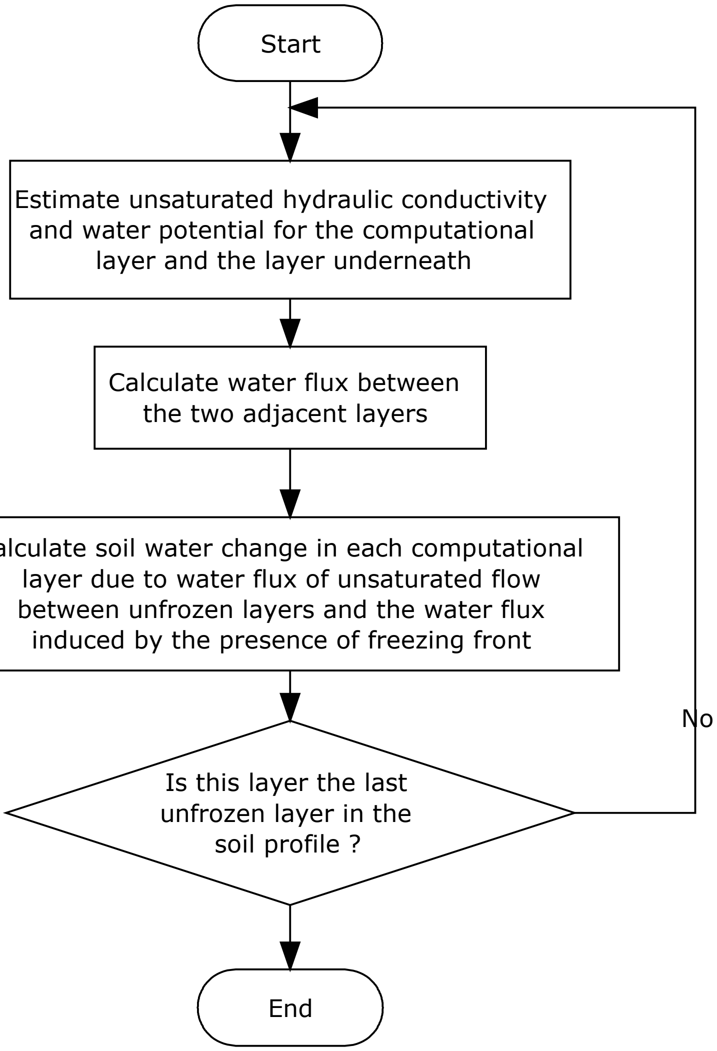

Figure B.7. Flowchart for simulating unsaturated soil water movement

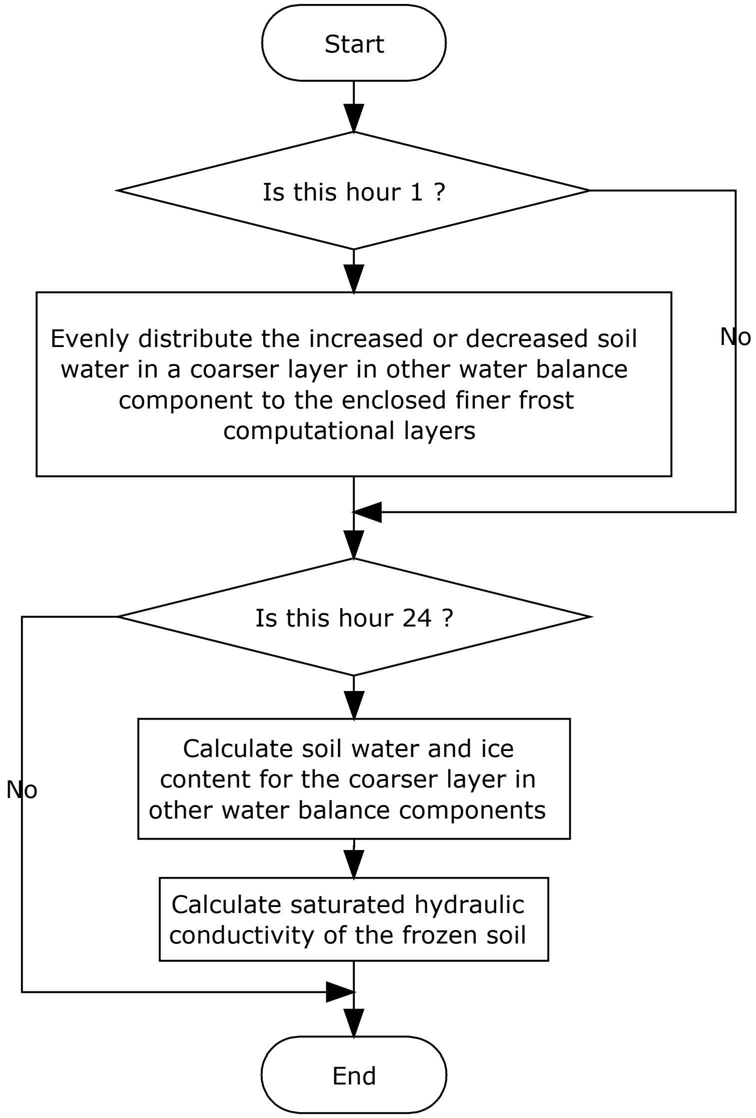

Figure B.8. Flowchart for the interaction between frost routines and other water balance components

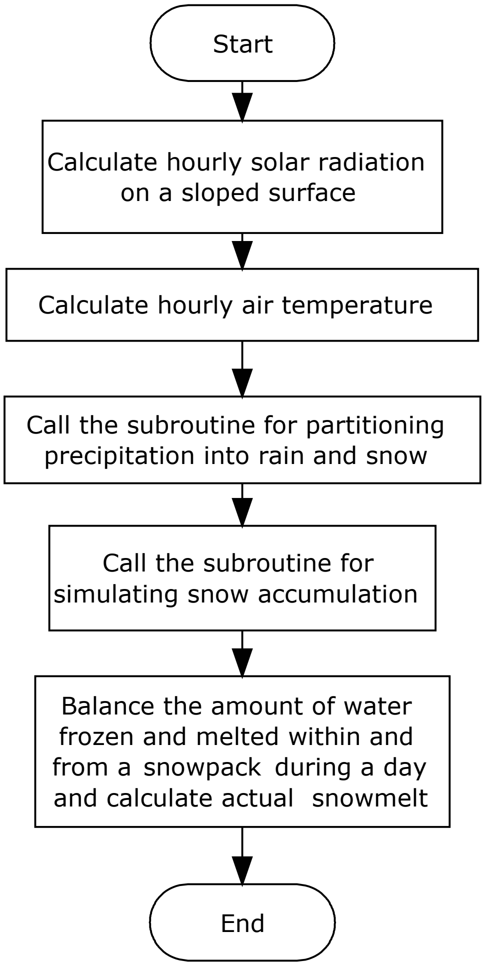

Figure B.9. Flowchart of main snow simulation program

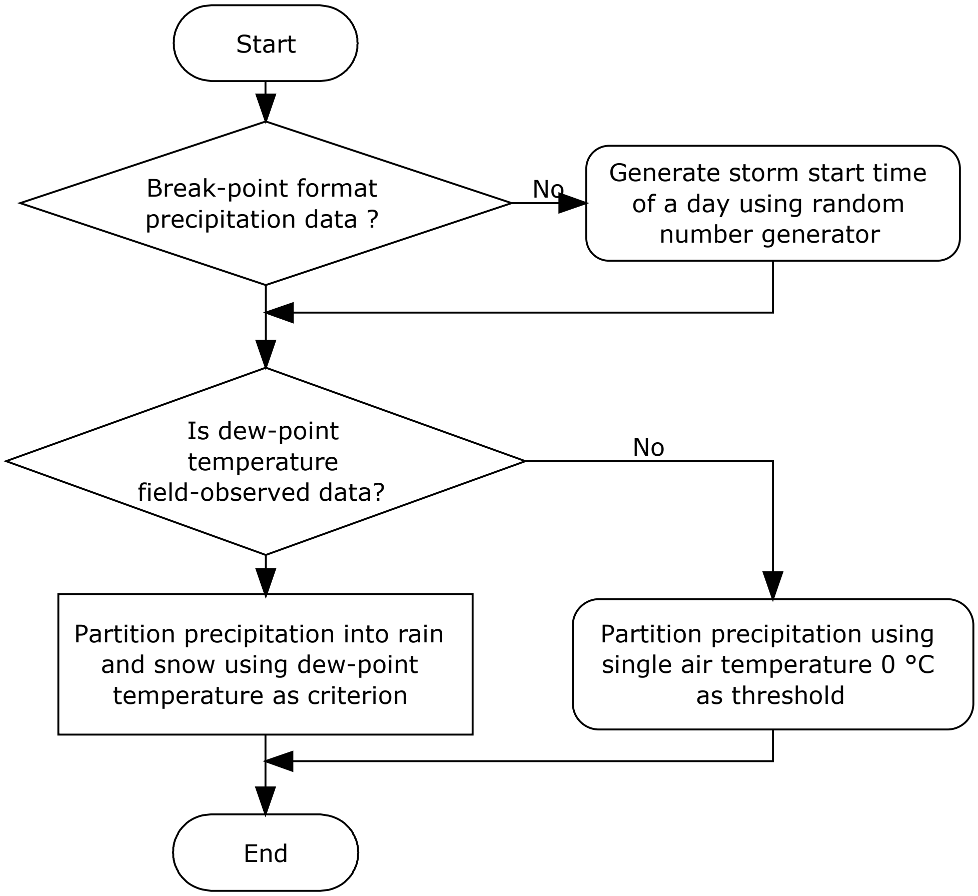

Figure B.10. Flowchart for simulating snow-rain partition

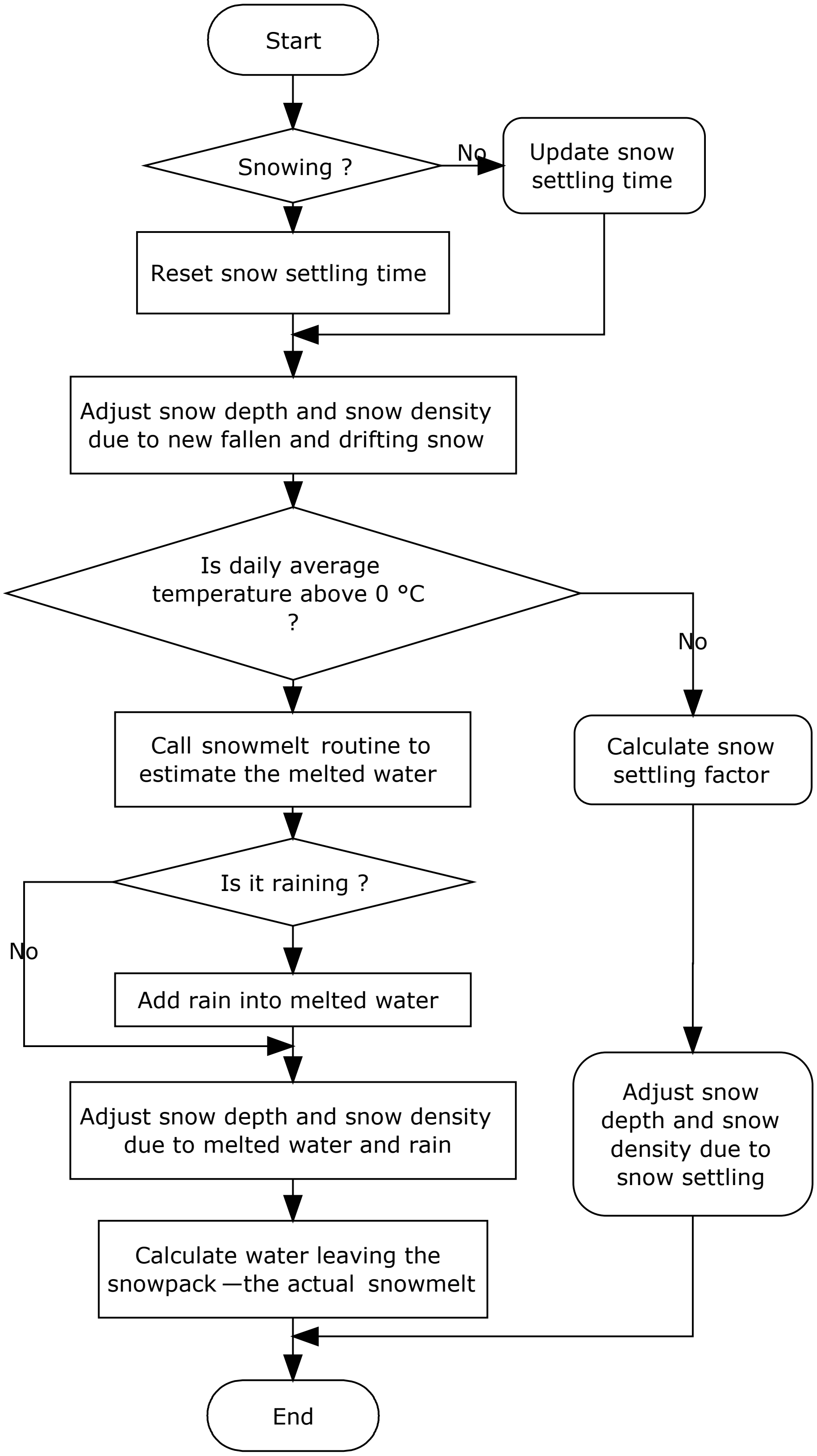

Figure B.11. Flowchart for simulating snow accumulation

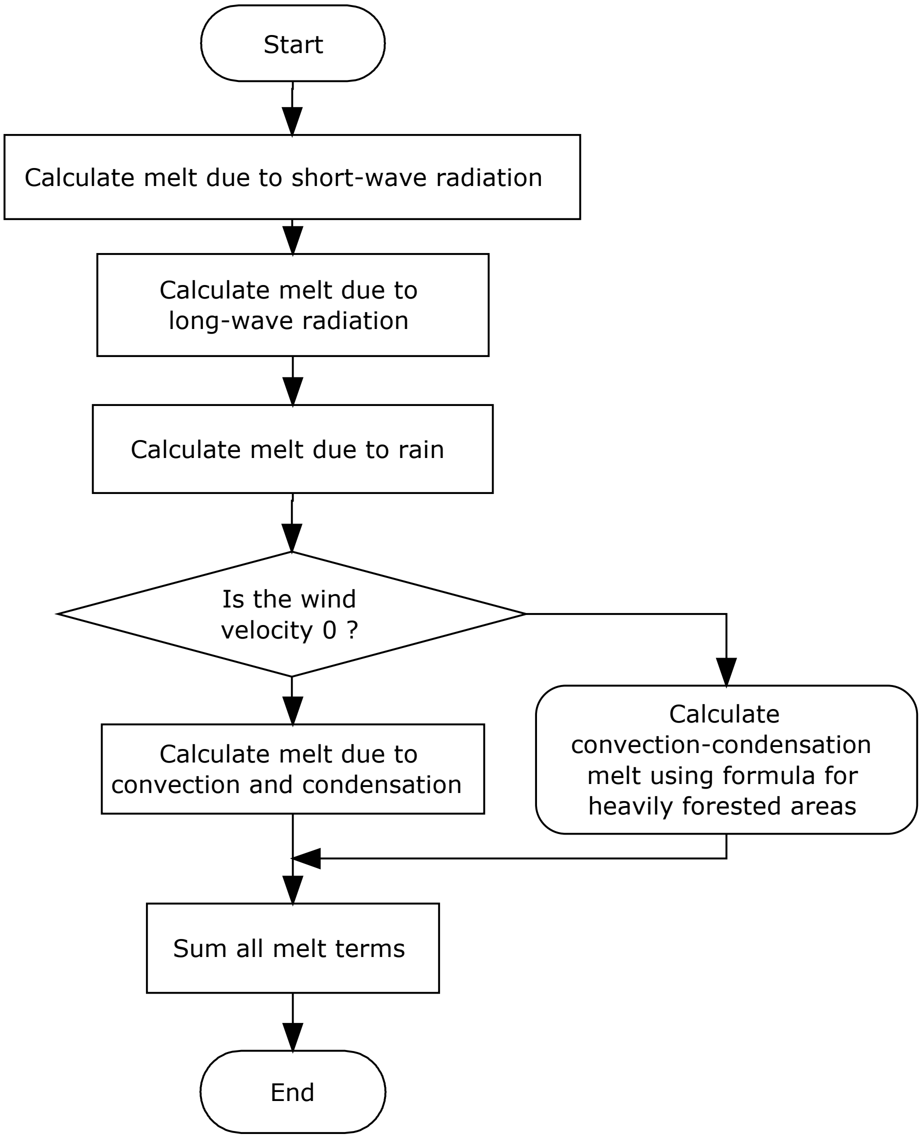

Figure B.12. Flowchart for simulating snowmelt

Appendix C. Estimation of Soil Water Potential at A Freezing Front

Water potential of a frozen soil was estimated from soil temperature using the generalized form of the Clausius–Clapeyron equation (Eq. C1) following Watanabe and Wake (2008)

$$\frac{dP}{dT} = \frac{L_f}{T\Delta V} \tag{C1}$$

where P [Pa] is pressure, T [°K] is temperature, L_f [J kg^{-1}]is the latent heat of fusion, and ΔV [m^3 kg^{-1}] is change in water volume due to phase change.

Eq. C2 is used to calculate the pressure at the ice-water interface with the assumption that the pressure is 0 Pa at 0°C. In calculating soil water potential at a freezing front, soil temperature at this point was assumed the same as the freezing depression temperature, typically ranging -0.01–-2.5 °C as a function of soil water content and soil texture (Kozlowski, 2004). Such a temperature range of a freezing front would lead to a water potential range of -15 m to $-3{,}500$ m (Eq. C3–C4).

$$P = \frac{L_f}{\Delta V}\ln(T/T_0) \tag{C2}$$

$$\begin{aligned} P_{-0.01} &= \frac{3.34\times10^5\, J/kg}{9.05\times10^{-5}\, m^3/kg}\ln\left(\frac{273-0.01}{273+0}\right) \\ &= -1.35\times10^5\, Pa \times \frac{1\, mH_2O}{1000\, kg/m^3 \times 9.8\, m/s^2 \times 1\, m} \\ &= -15\, m \end{aligned} \tag{C3}$$

$$\begin{aligned} P_{-2.5} &= \frac{3.34\times10^5\, J/kg}{9.05\times10^{-5}\, m^3/kg}\ln\left(\frac{273-2.5}{273+0}\right) \\ &= -3.40\times10^7\, Pa \times \frac{1\, mH_2O}{1000\, kg/m^3 \times 9.8\, m/s^2 \times 1\, m} \\ &= -3500\, m \end{aligned} \tag{C4}$$

References

Kozlowski, T. 2004. Soil freezing point as obtained on melting. Cold Reg. Sci. Technol. 38:93–101.

Watanabe, K., and T. Wake. 2008. Hydraulic conductivity of frozen unsaturated soil. In *Proc. 9th Int. Conf. on Permafrost.* 147–152.

Appendix D. Thermal Conductivity of Snow, Residue and Soil

Snow thermal conductivity was estimated following Sturm et al. (1997) based on snow density

$$K_{snow} = 0.023 + 0.234\,(\rho_{snow}/1000) \qquad \rho_{snow} \leq 156 \tag{D1}$$

$$K_{snow} = 0.138 - 1.01\,(\rho_{snow}/1000) + 3.233\,(\rho_{snow}/1000)^2 \qquad \rho_{snow} > 156 \tag{D2}$$

where K_{snow} [W m^{-1} °C^{-1}] is snow thermal conductivity, and ρ_{snow} [kg m^{-3}] is snow density.

Thermal conductivity of residue is taken as a constant of 0.05 [W m^{-1} °C^{-1}] in the WEPP model. The equivalent residue depth to this thermal conductivity is estimated based on residue biomass and bulk density

$$Z_{res} = \frac{M_{res}}{\rho_{res}} \tag{D3}$$

where Z_{res} [m] is the thickness of flat residue, M_{res} [kg m^{-1}] is residue biomass, and ρ_{snow} [kg m^{-3}] is residue bulk density.

According to Flerchinger et al. (2003), flat wheat residue of 1 kg m^{-2} has a depth of 0.03 m, and flat corn residue of 0.87 kg m^{-2} has a depth of 0.05 m. Hence, the bulk density used in the WEPP model for pithy, hollow, woody residue were 17.4, 30.0, and 60.0 kg m^{-3}, respectively.

Thermal conductivities of frozen soil in WEPP are 1.75 and 2.1 [W m^{-1} °C^{-1}] for tillage and non-tillage soil layers, respectively. Thermal conductivity of unfrozen soil is estimated based on soil water content and bulk density of the soil

$$K_{soil} = (\,0.5096 + 7.4493\,\theta - 8.7484\,\theta^2\,)\,(\,0.0014139\,\rho_b - 1.0588\,) \tag{D4}$$

where K_{sol} [W m^{-1} °C^{-1}] is the thermal conductivity of unfrozen soil; θ [m^3 m^{-3}] is volumetric soil water content, and ρ_b [kg m^{-3}] is the bulk density of the soil.

References

Flerchinger, G.N., T.J. Sauer, R.A. Aiken. 2003. Effects of crop residue cover and architecture on heat and water transfer at the soil surface. Geoderma 116:217– 233

Sturm M, J. Holmgren, M. König, K. Morris. 1997. The thermal conductivity of seasonal snow. J. Glaciol. 43:26–41.

Appendix E. WEPP Inputs for Case Applications

E.1. PCFS continuous fallow plot near Pullman, WA

E.1.1. Climate file

```
4.30
  1   1   0
  Station:  PULLMAN 2 NW WA                          CLIGEN VERSION 4.3
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated
   46.77      -117.20        777          53          83          8
 Observed monthly ave max temperature (C)
  1.2     4.8     8.3     13.3     17.9     21.8     27.6     27.5     22.4     15.5    6.4     2.3
 Observed monthly ave min temperature (C)
 -4.9    -2.6    -0.8    1.9       5.0       8.0       9.8       9.8       6.8       3.0       -0.9      -3.7
 Observed monthly ave solar radiation (Langleys/day)
 122.0    208.0    321.0    462.0    555.0    615.0    673.0    554.0    406.0    238.0    140.0      88.0
 Observed monthly ave precipitation (mm)
  73.9     58.1     55.8      45.7     51.0     52.7     35.2     42.2     48.4     59.9     76.9     77.4
day    mon    year   n. break   Tmax      Tmin        Rad.       vwind    dwind     Tdew
                                           (C)         (C)        (l/d)       (m/sec)     (deg)      (C)
.....................................

.....................................

.....................................
1            1       84       0       4.44       -3.33       83.47       2.72       166.96       -3.33
2       1       84       2       2.22       -2.78       138.06       3.34       258.61       -2.78
       11       0
       14       2.46
3       1       84       5       1.67       -1.11       44.88       2.35       260.27       -1.11
       2.5       0
       6     10.76
       13.67       10.76
       14.42       12.29
       17       18.14
4       1       84       0       5       1.11       144.57       0       0       1.11
5       1       84       0       6.67       2.22       107.79       2.82       239.15       2.22
6       1       84       0       6.11       2.22       119.3       5.65       138.69       2.22
7       1       84       2       6.11       1.11       157.2       7.14       283.66       1.11
       19       0
       23       2.15
8       1       84       0       6.67       0       167.8       4.61       258.76       0
9       1       84       0       3.33       -1.67       11.79       2.43       113.29       -1.67
10      1       84       2       2.78       -2.22       97.17       2.52       71.98       -2.22
       14       0
       22       3.99
11      1       84       0       2.78       -0.56       109.55       2.39       174.09       -0.56
12      1       84       0       1.67       -0.56       97.59       4.69       121.56       -0.56
13      1       84       0       0.56       -2.22       116.43       6.76       325.78       -2.22
14      1       84       0       1.11       -8.33       132.17       3.91       189.99       -8.33
15      1       84       0       -1.67       -10.56       88.1       2.67       174.99       -10.56

.....................................

.....................................

.....................................
```

E.1.2. Soil file

```
2006
comments: soil file
1   1
'Palouse'     'silt loam'     6     0.230000     0.750000     4946000.000000     0.012          0.08     0.5
   200     9.8     20.1     2.616     19.6     0.0
   410     8.3     22.3     1.136     20.5     0.0
   620     8.3     21.5     0.832     21.2     0.0
   910     8.5     18.8     0.608     21.0     0.0
   1170     9.5     17.8     0.352     21.0     0.0
   1570     8.9     15.0     0.240     21.1     0.0
0       1       4.5
```

E.1.2. Topographic file

```
95.1
#
#           Created on 05Aug95 by `WSLP', (Ver. 26Aug94)
#           Author: Chris Pannkuk, Pannkuk@WSU.EDU
#
1
200         4
2           22.3
0,   0.21     1,     0.21
```

E.1.3. Management file

```
95.7
#
#           Created on 10Apr00 by `wman', (Ver. 15Apr95)
#           Author: YourNameHere
#

1           # number of OFEs
8           # (total) years in simulation

#################
# Plant Section #
#################

1           # looper; number of Plant scenarios

#
#           Plant scenario 1 of 1
#
WINT0001
`winter wheat' (units: bushels wheat/acre)
From converted V93 file `BAREF.MAN'

1           # `landuse' - <Cropland>
bushels wheat/A
5.2         3           25          3           6.5         60          0           0           1           0.0064
0.9         0           0           0.99        3           1200        0.42        0.91
2           # `mfo' - <Non-fragile>
0.0085      0.0085      15          0           0.005       2           0.25        0           14          0
```

```
0         5         0

#####################
# Operation Section #
#####################

1         # looper; number of Operation scenarios

#
#         Operation scenario 1 of 1
#
HAPR
`Harrow-packer roller'
(from WEPP distribution database)

1         # `landuse' - <Cropland>
0.1       0.05      0
4         # `pcode' - <Other>
0.025     0.08      0.1       0.05      0.01      1         0.051

##############################
# Initial Conditions Section #
##############################

1         # looper; number of Initial Conditions scenarios

#
#         Initial Conditions scenario 1 of 1
#
WINT0001
From converted V93 file `BAREF.MAN'


1         # `landuse' - <Cropland>
1.2       0         86        60        0         0
1         # `iresd' - <WINT0001>
3         # `mgmt' - <Fallow>
150       0.025     0.1       0.025     0
1         # `rtyp' - <Temporary>
0         0         0.01      0.02      0
0         0

###########################
# Surface Effects Section #
###########################

1         # looper; number of Surface Effects scenarios

#
#         Surface Effects scenario 1 of 1
#
FALLOW
Conventionally-tilled peas


1         # `landuse' - <Cropland>
1         # `ntill' - <number of operations>
          274       # `mdate' - <10/1 >
          1         # `op' - <HAPR>
          0.01
          2         # `typtil' - <Secondary>
```

```
######################
# Contouring Section #
######################

0       # looper; number of Contouring scenarios

####################
# Drainage Section #
####################

0       # looper; number of Drainage scenarios

##################
# Yearly Section #
##################

1       # looper; number of Yearly scenarios

#
#       Yearly scenario 1 of 1
#
WINT0001
From converted V93 file `BAREF.MAN'


1       # `landuse' - <Cropland>
1       # `itype' - <WINT0001>
1       # `tilseq' - <FALLOW>
0       # `conset' - <NotUsed>
0       # `drset' - <NotUsed>
3       # `mgmt' - <Fallow>
        0       # `jdharv' - <>
        0       # `jdplt' - <>
        0
        5       # `resmgmt' - <Residue Removal>
                274     # `jdmove' - <10/1 >
                1

######################
# Management Section #
######################
BAREF2
rototilled continuous bare fallow


1       # `nofe' - <number of Overland Flow Elements>
        1       # `Initial Conditions indx' - <WINT0001>
8       # `nrots' - <rotation repeats..>
1       # `nyears' - <years in rotation>
#
#       Rotation 1 : year 1 to 1
#
        1       # `nycrop' - <plants/yr; Year of Rotation :  1 - OFE : 1>
                1       # `YEAR indx' - <WINT0001>
#
#       Rotation 2 : year 2 to 2
#
        1       # `nycrop' - <plants/yr; Year of Rotation :  1 - OFE : 1>
                1       # `YEAR indx' - <WINT0001>
#
#       Rotation 3 : year 3 to 3
```

```
#
        1       # `nycrop' - <plants/yr; Year of Rotation :  1 - OFE : 1>
                1       # `YEAR indx' - <WINT0001>
#
#       Rotation 4 : year 4 to 4
#
        1       # `nycrop' - <plants/yr; Year of Rotation :  1 - OFE : 1>
                1       # `YEAR indx' - <WINT0001>
#
#       Rotation 5 : year 5 to 5
#
        1       # `nycrop' - <plants/yr; Year of Rotation :  1 - OFE : 1>
                1       # `YEAR indx' - <WINT0001>
#
#       Rotation 6 : year 6 to 6
#
        1       # `nycrop' - <plants/yr; Year of Rotation :  1 - OFE : 1>
                1       # `YEAR indx' - <WINT0001>
#
#       Rotation 7 : year 7 to 7
#
        1       # `nycrop' - <plants/yr; Year of Rotation :  1 - OFE : 1>
                1       # `YEAR indx' - <WINT0001>
#
#       Rotation 8 : year 8 to 8
#
        1       # `nycrop' - <plants/yr; Year of Rotation :  1 - OFE : 1>
                1       # `YEAR indx' - <WINT0001>
```

E.2. Residue removal plot in no-tillage corn field at Morris, MN

E.2.1. Climate file

```
 4.20
  1   0   0
  Station:  MORRIS WC SCHOOL MN                      CLIGEN VERSION 4.2
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated
   45.58       -95.92        344         106         93              4
 Observed monthly ave max temperature (C)
  -7.6    -5.0     2.4      12.6      20.1        25.0       28.1        27.0        21.6        14.8        3.9       -4.2
 Observed monthly ave min temperature (C)
 -18.3    -15.8    -8.1     0.4      6.9     12.7      15.2      13.7      8.3      1.9     -6.5     -14.0
 Observed monthly ave solar radiation (Langleys/day)
 160.0    253.0      360.0    427.0   505.0   545.0   568.0    489.0    368.0    241.0    145.0     119.0
 Observed monthly ave precipitation (mm)
  18.0     16.4     29.2     54.9     74.8     98.9     89.0     76.5     55.2     40.8     24.0     16.7
 da     mo     year       prcp    dur   tp     ip      tmax        tmin       rad      w-vl     w-dir     tdew
                          (mm)    (h)                  (C)         (C)        (l/d)    (m/s)   (Deg)    (C)
1       1        93       0       0       0       0       -6.67    -11.67   96.61    5.28    0       -11.67
2       1        93       0       0       0       0       -5.56    -12.22   156.22   4.55    0       -12.22
3       1        93       0       0       0       0       -5.56    -17.22   122.08   3.9     0       -17.22
4       1        93       0       0       0       0       -2.22    -16.67   127.98   3.19    0       -16.67
5       1        93       0       0       0       0       -4.44    -16.11   128.56   2.59    0       -16.11
6       1        93       0       0       0       0       -2.78    -14.44   165.06   6.14    0       -14.44
7       1        93       0       0       0       0       -2.78    -10.56   75.58    6.8     0       -10.56
8       1        93       0       0       0       0       -4.44    -6.67    149.76   4.3     0       -6.67
9       1        93       0       0       0       0       -3.89    -6.67    147.09   3.57    0       -6.67
10      1        93       0       0       0       0       -3.33    -6.11    147.28   4.55    0       -6.11
11      1        93       0       0       0       0       -2.78    -6.67    86.2     5.18    0       -6.67
12      1        93       0       0       0       0       -3.33    -6.11    154.52   3.94    0       -6.11
13      1        93       0       0       0       0       -3.89    -13.89   59.69    0       0       -13.89
14      1        93       0       0       0       0       -3.33    -12.78   101.3    1.9     0       -12.78
15      1        93       0       0       0       0       -1.11    -11.67   98.4     0       0       -11.67
16      1        93       0       0       0       0       0        -8.89    108.38   3.78    0       -8.89
17      1        93       0       0       0       0       0        -11.11   98.06    2.29    0       -11.11
18      1        93       0       0       0       0       3.33     -4.44    100.72   2.39    0       -4.44
19      1        93       0       0       0       0       3.89     -9.44    129.19   3.7     0       -9.44
20      1        93       3.05    24      0.5     2       3.33     -6.67    165.25   2.44    0       -6.67
21      1        93       5.33    24      0.5     2       0        -2.78    170.57   0       0       -2.78
22      1        93       0       0       0       0       0        -2.78    118.63   2.77    0       -2.78
23      1        93       0       0       0       0       0        -3.33    102.48   4.92    0       -3.33
24      1        93       0       0       0       0       -1.11    -6.11    99.02    4.17    0       -6.11
25      1        93       0       0       0       0       -1.11    -3.89    115.96   5.38    0       -3.89
26      1        93       0       0       0       0       -1.67    -4.44    129.46   10.43   0       -4.44
27      1        93       0       0       0       0       -1.67    -5.56    110.86   3.53    0       -5.56
28      1        93       2.03    24      0.5     2       -2.78    -6.67    165.16   4.68    0       -6.67
29      1        93       2.03    24      0.5     2       -3.89    -6.67    140.75   4.84    0       -6.67
30      1        93       0       0       0       0       -3.89    -23.33   196.6    4.05    0       -23.33
31      1        93       0       0       0       0       -10.56   -22.22   64.74    2.47    0       -22.22
```

....

....

....

E.2.2. Soil file

```
2006
#
#          Created on 04Apr00 by `WSOL', (Ver. 15Apr95)
#          Author: YourNameHere
#
xxx
1          1
'BarnesMN'          'loam'     5          0.23       0.5        4.91794e+006        0.0055     3.11       5.5
50         39.8       25.4       5.8        19.5       6
150        39.3       23.8       4          10.5       16
450        36.8       23.8       3.5        8.7        14
750        44.6       22.5       2          9.8        13
1850       55.5       17.5       1          9.4        10
0          1    3.6E-5
```

E.2.2. Slope file

```
95.7
#
#          Created on 03Apr00 by `WSLP', (Ver. 15Apr95)
#          Author: YourNameHere
#
1
50         12
2          18
0,   0.02    1,   0.02
```

E.2.3. Management file

```
95.7
#
#          Created on 20May00 by `wman', (Ver. 15Apr95)
#          Author: YourNameHere
#

1          # number of OFEs
4          # (total) years in simulation

#################
# Plant Section #
#################

3          # looper; number of Plant scenarios


#
#          Plant scenario 1 of 3
#
CORN0004
`Corn - Medium Fertilization Level'
(from WEPP distribution database)

1          # `landuse' - <Cropland>
bushels corn/A
3.6        3          28         10         3.2        60         0          0.01       0.65       0.051
0.8        0.98       0.65       0.99       0          1700       0.5        2.6
```

```
2         # `mfo' - <Non-fragile>
0.0065    0.065     25        0         0.219     1.52      0.25      0         30        0
0         3.5       0

#
#         Plant scenario 2 of 3
#
CORN0005
`Corn - Medium Fertilization Level'
(from WEPP distribution database)

1         # `landuse' - <Cropland>
bushels corn/A
3.6       3         28        10        3.2       60        0         0.01      0.65      0.051
0.8       0.98      0.65      0.99      0         1700      0.5       2.6
2         # `mfo' - <Non-fragile>
0.0065    0.065     25        0         0.219     1.52      0.25      0         30        0
0         3.5       0

#
#         Plant scenario 3 of 3
#
CORN0006
`Corn - Medium Fertilization Level'
(from WEPP distribution database)

1         # `landuse' - <Cropland>
bushels corn/A
3.6       3         28        10        3.2       60        0         0.01      0.65      0.051
0.8       0.98      0.65      0.99      0         1700      0.5       2.6
2         # `mfo' - <Non-fragile>
0.0065    0.065     25        0         0.219     1.52      0.25      0         30        0
0         3.5       0

#####################
# Operation Section #
#####################

1         # looper; number of Operation scenarios

#
#         Operation scenario 1 of 1
#
CHISTW
Chisel with twisted points
from Nearing

1         # `landuse' - <Cropland>
0.86      0.72      0
4         # `pcode' - <Other>
0.1       0.3       0.86      0.72      0.03      1         0.2

##############################
# Initial Conditions Section #
##############################

1         # looper; number of Initial Conditions scenarios

#
#         Initial Conditions scenario 1 of 1
#
```

```
NOTLCORN
No-Till Corn


1         # `landuse' - <Cropland>
1.2       0         999       77        0         0.01
1         # `iresd' - <CORN0004>
1         # `mgmt' - <Annual>
4000      0.05      0.01      0.034     1
1         # `rtyp' - <Temporary>
0         0         0.1       0.2       0
0         0

###########################
# Surface Effects Section #
###########################

1         # looper; number of Surface Effects scenarios

#
#         Surface Effects scenario 1 of 1
#
NOTLCORN
No-Tilled Corn


1         # `landuse' - <Cropland>
1         # `ntill' - <number of operations>
          130       # `mdate' - <5 /10>
          1         # `op' - <CHISTW>
          0.1
          1         # `typtil' - <Primary>

######################
# Contouring Section #
######################

0         # looper; number of Contouring scenarios

####################
# Drainage Section #
####################

0         # looper; number of Drainage scenarios

##################
# Yearly Section #
##################

3         # looper; number of Yearly scenarios

#
#         Yearly scenario 1 of 3
#
CORNCNSV
Conservation-Tilled Corn


1         # `landuse' - <Cropland>
1         # `itype' - <CORN0004>
1         # `tilseq' - <NOTLCORN>
```

```
0           # `conset' - <NotUsed>
0           # `drset' - <NotUsed>
1           # `mgmt' - <Annual>
            250         # `jdharv' - <9 /7 >
            130         # `jdplt' - <5 /10>
            0.7
            5           # `resmgmt' - <residual removal>
251    # 'residual removal date'
0.99      # 'fraction of flat residual removed'

#
#           Yearly scenario 2 of 3
#
CORNCNSW
Conservation-Tilled Corn


1           # `landuse' - <Cropland>
2           # `itype' - <CORN0005>
1           # `tilseq' - <NOTLCORN>
0           # `conset' - <NotUsed>
0           # `drset' - <NotUsed>
1           # `mgmt' - <Annual>
            250         # `jdharv' - <9 /7 >
            130         # `jdplt' - <5 /10>
            0.7
            5           # `resmgmt' - <residual removal>
251    # 'residual removal date'
0.99     # 'fraction of flat residual removed'

#
#           Yearly scenario 3 of 3
#
CORNCNSX
Conservation-Tilled Corn


1           # `landuse' - <Cropland>
3           # `itype' - <CORN0006>
1           # `tilseq' - <NOTLCORN>
0           # `conset' - <NotUsed>
0           # `drset' - <NotUsed>
1           # `mgmt' - <Annual>
            250         # `jdharv' - <9 /7 >
            130         # `jdplt' - <5 /10>
            0.7
            5           # `resmgmt' - <residual removal>
251    # 'residual removal date'
0.99      # 'fraction of flat residual removed'


#####################
# Management Section #
#####################
MORRIS
No-till Corn

Medium Productivity Level
1           # `nofe' - <number of Overland Flow Elements>
            1           # `Initial Conditions indx' - <NOTLCORN>
1           # `nrots' - <rotation repeats..>
```

```
4       # `nyears' - <years in rotation>
#
#       Rotation 1 : year 1 to 4
#
        1       # `nycrop' - <plants/yr; Year of Rotation :  1 - OFE : 1>
                1       # `YEAR indx' - <CORNCNSV>
        1       # `nycrop' - <plants/yr; Year of Rotation :  2 - OFE : 1>
                2       # `YEAR indx' - <CORNCNSW>
        1       # `nycrop' - <plants/yr; Year of Rotation :  3 - OFE : 1>
                3       # `YEAR indx' - <CORNCNSX>
        1       # `nycrop' - <plants/yr; Year of Rotation :  4 - OFE : 1>
                3       # `YEAR indx' - <CORNCNSX>
```

E.3. No-tillage and conventional tillage drainages near Pendleton, OR

E.3.1. Climate file

```
0.00
  1  1  0
Station: RDWS
 Latitude Longitude Elevation (m) Obs. Years    Beginning year  Years simulated
  45.81   -118.65        547           7         2000           7
 Observed monthly ave max temperature (C)
 5.04     7.74     12.57     15.84     20.62     25.16     31.78     30.20     24.72     17.15     9.01     4.96
 Observed monthly ave min temperature (C)
 -1.86     -1.32     1.61     3.36     7.17     10.32     14.43     14.12     10.19     5.14     0.36     -1.81
 Observed monthly ave solar radiation (Langleys)
 95.2     196.2     295.0     425.4     516.4     585.2     651.9     549.1     401.0     250.3     124.5     76.5
 Observed monthly ave rainfall (mm)
65.3     46.2     50.0     33.1     41.0     36.4     16.4     20.1     22.9     32.7     60.5     77.8
  day    mon    year   nbrkpt    tmax     tmin       rad          w-vel    w-dir      dew
                         (mm)      ( C)      (C)     (ly/day)    m/sec     deg         (C)
           1      1    2000      3    4.6    -0.5    54.8    3.7     240    -2.3
   7.71     0
   7.96   0.25
   20.7     0.5
           2      1    2000      3    3.6    -2.3    73.7    4.9     250    -4.4
   9.2      0
   9.45   0.25
  22.19     0.5
           3      1    2000     36    4.5    -2.8    35.8    2.5     160    -1.3
  10.68      0
  10.93    0.25
  11.48     0.5
  12.03    0.75
  12.58      1
  13.13    1.25
  13.63     1.5
  14.12    1.75
  14.62      2
  15.11    2.25
  15.37     2.5
  15.64    2.75
   15.9      3
  16.16    3.25
  16.54     3.5
  16.93    3.75
  17.31      4
  17.69    4.25
  18.19     4.5
  18.69    4.75
  19.19      5
  19.69    5.25
  19.89     5.5
   20.1    5.75
  20.31      6
  20.52    6.25
  20.62     6.5
  20.72    6.75
  20.83      7
  20.93    7.25
  21.13     7.5
```

```
  21.33   7.75
  21.54      8
  21.74   8.25
  22.63    8.5
  23.51   8.75
             4      1   2000     19      8    1.4   85.3     5.7    240    0.2
   0.15      0
    0.4   0.25
   1.29    0.5
   1.97   0.75
   2.65      1
   3.33   1.25
   4.01    1.5
   4.15   1.75
   4.29      2
   4.43   2.25
   4.56    2.5
   4.74   2.75
   4.91      3
   5.09   3.25
   5.26    3.5
   5.36   3.75
   5.45      4
   5.54   4.25
   5.64    4.5
             5      1   2000      2    6.3   -1.3  147.2     4.6    250   -2.4
   4.75      0
      5   0.25
             6      1   2000      2    7.2   -1.5  115.4     2.3    180   -2.9
   4.11      0
   4.36   0.25
             7      1   2000      2    8.8      1   75.3     1.9    180    0.4
   3.47      0
   3.72   0.25
             8      1   2000      9    8.5    1.9    109     6.7    240   -0.5
   2.83      0
   3.08   0.25
    3.2    0.5
   3.32   0.75
   3.44      1
   3.56   1.25
  10.18    1.5
   16.8   1.75
  23.41      2
.....................................

.....................................

.....................................
```

E.3.2. Soil file for the no-tillage drainage

```
2006
comments: soil file
1 1
'WALLAWAL' 'SIL'   5   0.23  0.38  5418000   0.005   3.5   1.19
   300   27.4   11.5   2.50   11.3   0.0
   600   35.3   14.0   0.83    8.4   0.0
   900   35.3   14.0   0.28    8.4   0.0
  1200   35.3   14.0   0.18    8.4   0.0
  1800   35.3   14.0   0.0    8.4   0.0
0   1   4.5
```

E.3.3. Soil file for the conventional tillage drainage

```
2006
comments: soil file
1 1
'WALLAWAL' 'SIL'   5   0.23  0.38  5418000   0.005   3.5   0.45
   300   27.4   11.5   2.50   11.3   0.0
   600   35.3   14.0   0.83    8.4   0.0
   900   35.3   14.0   0.28    8.4   0.0
  1200   35.3   14.0   0.18    8.4   0.0
  1800   35.3   14.0   0.0    8.4   0.0
0   1   4.5
```

E.3.4. Slope file (hillslope No. 1 in no-tillage drainage)

```
97.5
#
#
#
#
1
90  236.64
10  116.49
0.00, 0.03  0.16, 0.03  0.29, 0.06  0.50, 0.07  0.68, 0.08  0.72, 0.13  0.79, 0.09  0.88, 0.17   0.95, 0.10  1.00, 0.13
```

E.3.5. Management file for no-tillage drainage

```
98.4
#
#
#
#

1 # number of OFE's
7 # (total) years in simulation

#######################
# Plant Section       #
#######################

5  # Number of plant scenarios


Garbanzos
'Garbanzos- Medium Fertilization Level'
(from WEPP distribution database)

1  #landuse
WeppWillSet
14.00000 3.00000 35.00000 4.40000 5.20000 30 0.00000 0.15200 0.10000 0.0085
0.90000 0.10000 0.31000 0.99000 0.00000 999 0.40  0.5
1  # mfo - <fragile>
0.01300 0.01300 22.2  0.00000 0.02500  1.3  0.25  0.00000 14 0.00000
0.00000 5.00000 0.00000

DryGreenPeas
`DryGreenPeas - Medium Fertilization Level'
(from WEPP distribution database)

1  #landuse
WeppWillSet
14.00000 3.00000 35.00000 4.40000 5.20000 30 0.00000 0.15200 0.10000 0.0085
0.90000 0.10000 0.31000 0.99000 0.00000 999 0.43  0.7
1  # mfo - <fragile>
0.01300 0.01300 22.2  0.00000 0.02500  0.7  0.20  0.00000 14 0.00000
0.00000 5.00000 0.00000

WinterWheat
`Wheat; Winter - for State of Washington
JML, 3-28-01
(null)
1  #landuse
WeppWillSet
5.20000 3.00000 35.00196 3.00000 5.40026 60.00000 0.00000 0.15200 1.00000 0.00640
0.80000 1.00000 0.65000 0.99000 3.00000 1700.00000 0.40000 1.00001
2  # mfo - <non fragile>
0.00850 0.00850 15.00000 0.25000 0.00500 1.5 0.25000 0.00000 14 0.00000
0.00000 5.00000 0.00000

SpringWheat
`Wheat; Winter - for State of Washington
JML, 3-28-01
(null)
1  #landuse
WeppWillSet
5.20000 3.00000 35.00196 3.00000 5.40026 60.00000 0.00000 0.15200 1.00000 0.00640
```

```
0.80000 1.00000 0.65000 0.99000 3.00000 1700.00000 0.40000 1.00001
2  # mfo - <non fragile>
0.00850 0.00850 15.00000 0.25000 0.00500 1.49989 0.25000 0.00000 14 0.00000
0.00000 5.00000 0.00000

Grass
`Bromegrass-High Fertilization Level'
(from WEPP distribution database)

1  #landuse
WeppWillSet
14.00000 23.00000 35.00000 10.00000 5.00000 30.00000 0.10000 0.15200 0.70000 0.00220
0.85000 0.90000 0.65000 0.99000 12.00000 0.00000 0.90000 0.51000
2  # mfo - <non fragile>
0.00900 0.00900 25.00000 0.00000 0.00600 0.30000 0.33000 0.34000 14 32.00000
1.10000 9.00000 0.00000

#######################
# Operation Section   #
#######################

1  # Number of operation scenarios


ONEPHD
`One pass hoe drill Pendleton OR'
(from John Williams July 10 2007)

1  #landuse
0.50 0.35 12
2 # pcode - other
0.05  0.30 0.50 0.35 0.01 0.50 0.03



###############################
# Initial Conditions Section  #
###############################

1  # Number of initial scenarios


Aft_31305
For continuous winter wheat, no till.  Wheat was planted Oct 1
90   residue cover
175 mm of rain since last tillage in fall prior
1  #landuse
1.10000 0.20000 90 150 0.00000 0.90000
3 # iresd  <Whe_27068>
1 # mang annual
175.00600 0.02000 0.90000 0.01000 0.00000
1  # rtyp - temporary
0.00000 0.00000 0.10000 0.20000 0.00000
0.40005 0.10000




############################
# Surface Effects Section  #
############################
```

```
3  # Number of Surface Effects Scenarios


#
# 1 Surface Effects Scenario Polt 1 Year 1 Garbanzos & Winter Wheat
#
Year 1
From WEPP database
Your name, phone

1  # landuse  - cropland
2 # ntill - number of operations
  106  # mdate  --- 4 / 17
  1  # op --- ONEPHD
     0.15  # depth
     1  # type
  287  # mdate  --- 10 / 15 (one day early)
  1  # op --- ONEPHD
     0.15  # depth
     1  # type

#
# 2 Surface Effects Scenario Polt 1 Year 3 Winter Wheat
#
Year 3
From WEPP database
Your name, phone

1  # landuse  - cropland
1 # ntill - number of operations
    288  # mdate  --- 10 / 15
  1  # op --- ONEPHD
     0.15  # depth
     1  # type

#
# 3 Surface Effects Scenario Polt 1 Year 5 Dry Green Pea & Winter Wheat
#
Year 5
From WEPP database
Your name, phone

1  # landuse  - cropland
2 # ntill - number of operations
  93  # mdate  --- 4 / 3
  1  # op --- ONEPHD
     0.15  # depth
     1  # type
  299  # mdate  --- 10 / 27 (one day early)
  1  # op --- ONEPHD
     0.15  # depth
     1  # type


######################
# Contouring Section  #
######################

0  # Number of contour scenarios
```

```
#######################
# Drainage Section    #
#######################

0  # Number of drainage scenarios


#######################
# Yearly Section      #
#######################

7  # looper; number of Yearly Scenarios
#
# 1 Yearly scenario Plot 1 of yrear 0
#
Year 0



1  # landuse <cropland>
3  # plant growth scenario
2  # surface effect scenario
0  # contour scenario
0  # drainage scenario
1 # management <annual>
   364  # harvest date --- 12 / 30
   293  # planting date --- 10 /20
   0.30  # row width
   6   # residue man - <none>
#
# 2 Yearly scenario Plot 1 of yrear 1
#
Year 1



1  # landuse <cropland>
1  # plant growth scenario
1  # surface effect scenario
0  # contour scenario
0  # drainage scenario
1 # management <annual>
   233  # harvest date --- 8 / 21
   107  # planting date --- 4 /17
   0.30  # row width
   6   # residue man - <none>
#
# 3 Yearly scenario Plot 1 of year 2 and year 4
#
Year 2



1  # landuse <cropland>
3  # plant growth scenario
0  # surface effect scenario
0  # contour scenario
0  # drainage scenario
1 # management <annual>
   211  # harvest date --- 7 / 30
   288  # planting date --- 10 /15
```

```
   0.3  # row width
   6   # residue man - <none>
#
# 4 Yearly scenario Plot 1 of year 3
#
Year 31



1  # landuse <cropland>
5  # plant growth scenario
0  # surface effect scenario
0  # contour scenario
0  # drainage scenario
1 # management <annual>
   85  # harvest date --- 3 / 26
   2  # planting date --- 1 /2
   0  # row width
   6   # residue man - <none>
#
# 5 Yearly scenario Plot 1 of year 3
#
Year 32



1  # landuse <cropland>
3  # plant growth scenario
2  # surface effect scenario
0  # contour scenario
0  # drainage scenario
1 # management <annual>
   211  # harvest date --- 7 / 30
   288  # planting date --- 10 /15
   0.3  # row width
   6   # residue man - <none>
#
# 6 Yearly scenario Plot 1 of year 5
#
Year 5



1  # landuse <cropland>
2  # plant growth scenario
3  # surface effect scenario
0  # contour scenario
0  # drainage scenario
1 # management <annual>
   209  # harvest date --- 7 / 28
   93  # planting date --- 4 /3
   0.3  # row width
   6   # residue man - <none>
#
# 7 Yearly scenario Plot 1 of year 5 and year 6
#
Year 6



1  # landuse <cropland>
```

```
3  # plant growth scenario
0  # surface effect scenario
0  # contour scenario
0  # drainage scenario
1 # management <annual>
   210  # harvest date --- 7 / 27
   300  # planting date --- 10 /27
   0.3  # row width
   6   # residue man - <none>


######################
# Management Section  #
######################

Manage
description 1
description 2
description 3
1   # number of OFE's
    1   # initial condition index
1  # rotation repeats
7  # years in rotation

#
# Rotation 1: year 2000
#

   1          #  <plants/yr 1> - OFE: 1>
      1       # year index

#
# Rotation 1: year 2001
#

   2          #  <plants/yr 1> - OFE: 1>
      2       # year index
      3       # year index

#
# Rotation 1: year 2002
#

   1          #  <plants/yr 2> - OFE: 1>
      3       # year index

#
# Rotation 1: year 2003
#

   2          #  <plants/yr 3> - OFE: 1>
      4       # year index
      5       # year index

#
# Rotation 1: year 2004
#

   1          #  <plants/yr 4> - OFE: 1>
      3       # year index
```

```
#
# Rotation 1: year 2005
#

   2          #  <plants/yr 5> - OFE: 1>
      6       # year index
      7       # year index

#
# Rotation 1: year 6
#

   1          #  <plants/yr 2> - OFE: 1>
      7       # year index
```

E.3.6. Management file for conventional tillage drainage

```
98.4
#
#
#
#

1 # number of OFE's
6 # (total) years in simulation

#######################
# Plant Section       #
#######################

3  # Number of plant scenarios


Whe_27068
`Wheat; Winter - for State of Washington
JML, 3-28-01
(null)
1  #landuse
WeppWillSet
5.20000 3.00000 35.00196 3.00000 5.40026 60.00000 0.00000 0.15200 1.00000 0.00640
0.80000 1.00000 0.65000 0.99000 3.00000 1700.00000 0.40000 1.00001
2  # mfo - <non fragile>
0.00850 0.00850 15.00000 0.25000 0.00500 1.49989 0.25000 0.00000 14 0.00000
0.00000 5.00000 0.00000

Grass
`Bromegrass-High Fertilization Level'
(from WEPP distribution database)

1  #landuse
WeppWillSet
14.00000 23.00000 35.00000 10.00000 5.00000 30.00000 0.10000 0.15200 0.70000 0.00220
0.85000 0.90000 0.65000 0.99000 12.00000 0.00000 0.90000 0.51000
2  # mfo - <non fragile>
0.00900 0.00900 25.00000 0.00000 0.00600 0.30000 0.33000 0.34000 14 32.00000
1.10000 9.00000 0.00000

wiwheat2
`Wheat; Winter - Medium Fertilization Level'
(from WEPP distribution database)

1  #landuse
WeppWillSet
5.20000 3.00000 20.0  4.00000 6.40000 60.00000 0.00000 0.15200 1.00000 0.00640
0.80000 1.00000 0.65000 0.99000 3.00000 1700.00000 0.42000 0.91000
2  # mfo - <non fragile>
0.00850 0.00850 15.00000 0.00000 0.00500  1.5  0.25000 0.00000 14 0.00000
0.00000 5.00000 0.00000

#######################
# Operation Section   #
#######################

6  # Number of operation scenarios
```

```
MBP
`Plow, Moldboard with furrow (Pendleton, OR)'
(for WEPP)

1  #landuse
0.98   0.95   0
4 # pcode - other
0.15   0.20    0.98    0.95   0.05   1.00    0.20

CUL
`Disk, tandem-primary cutting >9" spacing'
From John Williams'

1  #landuse
0.70   0.45   0
4 # pcode - other
0.08    0.30    0.70   0.45   0.02   1.00    0.10

FTL
`Fertilizer Application'
(from John for WEPP similar like the cultivator)

1  #landuse
0.50   0.30   0
4 # pcode - other
0.05  0.38  0.50   0.30   0.04  1.00    0.15

RW
`Rodweeder, plain rotary rod'
(from WEPP distribution database)

1  #landuse
0.4000 0.1000 0
4 # pcode - other
0.0   0.0    0.40   0.10    0.01  1.00   0.05

DRHOE
`Drill, Hoe opener'
(from WEPP distribution database)

1  #landuse
0.5   0.35   0
4 # pcode - other
0.10  0.20  0.50   0.35   0.012   0.80   0.03

Cultiweed
`Rodweeder, rotary rod with semi-chisels'
From John Williams'

1  #landuse
0.35   0.25   0
4 # pcode - other
0.0    0.00    0.35   0.25   0.04   1.00    0.15



###############################
# Initial Conditions Section  #
###############################

1  # Number of initial scenarios
```

```
Aft_7016
After harvest of  Wheat in July
5  residue cover
150 mm of rain since last tillage in fall prior
1  #landuse
1.10000 0.00000 75 150 0.00000 0.05000
1 # iresd  <Whe_27068>
1 # mang annual
152.39999 0.08001 0.05000 0.04999 0.00000
1  # rtyp - temporary
0.00000 0.00000 0.10000 0.20000 0.00000
0.40005 0.60002




############################
# Surface Effects Section  #
############################

4  # Number of Surface Effects Scenarios


#
#  1 Surface Effects Scenario of 2001
#
Year 1
From WEPP database
Your name, phone

1  # landuse  - cropland
6 # ntill - number of operations
  74  # mdate  --- 3 / 15
  1  # op --- MBP
     0.25  # depth
     1  # type
  84  # mdate  --- 3 / 25
  2  # op --- CUL
     0.10  # depth
     2  # type
  130  # mdate  --- 5 / 10
  3  # op --- FTL
     0.10  # depth
     2  # type
  166  # mdate  --- 6 / 15
  4  # op --- RW
     0.050  # depth
     2  # type
  253  # mdate  --- 9 / 10
  4  # op --- RW
     0.050  # depth
     2  # type
  283  # mdate  --- 10 / 10
  5  # op --- DRHOE
     0.050  # depth
     2  # type

#
#  2 Surface Effects Scenario 2002
#
```

```
Year 2
From WEPP database
Your name, phone

1  # landuse  - cropland
1 # ntill - number of operations
  319  # mdate  --- 11/ 15
  1  # op --- MBP
      0.25  # depth
      1  # type

#
# 3  Surface Effects Scenario of 2003
#
Year 3
From WEPP database
Your name, phone

1  # landuse  - cropland
5 # ntill - number of operations
  74  # mdate  --- 3 / 15
  2  # op --- CUL
      0.10  # depth
      2  # type
  130  # mdate  --- 5 / 10
  3  # op --- FTL
      0.10  # depth
      2  # type
  166  # mdate  --- 6 / 15
  4  # op --- RW
      0.050  # depth
      2  # type
  258  # mdate  --- 9/15
  4  # op --- RW
      0.050  # depth
      2  # type
  282  # mdate  --- 10/10 (One day early)
  5  # op --- DRHOE
      0.050  # depth
      2  # type

#
# 4 Surface Effects Scenario of 2005
#
Year 4
From WEPP database
Your name, phone

1  # landuse  - cropland
6 # ntill - number of operations
  105  # mdate  --- 4 / 15
  2  # op --- MBP
      0.10  # depth
      2  # type
  135  # mdate  --- 5 / 15
  2  # op --- CUL
      0.10  # depth
      2  # type
  166  # mdate  --- 6 / 15
  6  # op --- Cultiweed
      0.15  # depth
```

```
    2  # type
  191  # mdate  --- 7 / 10
  4  # op --- RW
    0.050  # depth
    2  # type
  258  # mdate  --- 9 / 15
  4  # op --- RW
    0.050  # depth
    2  # type
  292  # mdate  --- 10 / 20 (One day early)
  5  # op --- DRHOE
    0.050  # depth
    2  # type


#######################
# Contouring Section  #
#######################

0  # Number of contour scenarios


#######################
# Drainage Section    #
#######################

0  # Number of drainage scenarios


#######################
# Yearly Section      #
#######################

8  # looper; number of Yearly Scenarios
#
# 1 Yearly scenario 2001
#
Year 1



1  # landuse <cropland>
1  # plant growth scenario
1  # surface effect scenario
0  # contour scenario
0  # drainage scenario
1 # management <annual>
   211  # harvest date --- 7 /30
   283  # planting date --- 10 /10
   0.3  # row width
   6   # residue man - <none>
#
# 2 Yearly scenario 2002
#
Year 2



1  # landuse <cropland>
1  # plant growth scenario
2  # surface effect scenario
```

```
0  # contour scenario
0  # drainage scenario
1 # management <annual>
   211  # harvest date --- 7 /30
   283  # planting date --- 10 /10
   0.3  # row width
   2   # residue man - <none>
    288      # residue burned date --- 10 /15
    # fraction of standing and flat residue lost
    1   1
#
# 3 Yearly scenario 2003
#
Year 3



1  # landuse <cropland>
1  # plant growth scenario
3  # surface effect scenario
0  # contour scenario
0  # drainage scenario
1 # management <annual>
   211  # harvest date --- 7 /30
   283  # planting date --- 10 /10
   0.3  # row width
   6   # residue man - <none>
#
# 4 Yearly scenario 2004
#
Year 4



1  # landuse <cropland>
1  # plant growth scenario
0  # surface effect scenario
0  # contour scenario
0  # drainage scenario
1 # management <annual>
   211  # harvest date --- 7 /30
   283  # planting date --- 10 /10
   0.3  # row width
   6   # residue man - <none>
#
# 5 Yearly scenario 2005
#
Year 5



1  # landuse <cropland>
1  # plant growth scenario
0  # surface effect scenario
0  # contour scenario
0  # drainage scenario
1 # management <annual>
   209  # harvest date --- 7 /28
   293  # planting date --- 10 /20
   0.3  # row width
   6   # residue man - <none>
```

```
#
# 6 Yearly scenario 2006
#
Year 6



1  # landuse <cropland>
1  # plant growth scenario
0  # surface effect scenario
0  # contour scenario
0  # drainage scenario
1 # management <annual>
   209  # harvest date --- 7 /28
   293  # planting date --- 10 /20
   0.3  # row width
   6   # residue man - <none>
#
# 7 Yearly scenario before planting
#
Year 0



1  # landuse <cropland>
2  # plant growth scenario
0  # surface effect scenario
0  # contour scenario
0  # drainage scenario
1 # management <annual>
   85  # harvest date --- 3 / 26
   2  # planting date --- 1 /2
   0  # row width
   6   # residue man - <none>
#
# 8 Yearly scenario before planting
#
Year 2005



1  # landuse <cropland>
2  # plant growth scenario
4  # surface effect scenario
0  # contour scenario
0  # drainage scenario
1 # management <annual>
   85  # harvest date --- 3 / 26
   2  # planting date --- 1 /2
   0  # row width
   6   # residue man - <none>


#######################
# Management Section  #
#######################

Manage
description 1
description 2
description 3
```

```
1   # number of OFE's
   1   # initial condition index
6  # rotation repeats
1  # years in rotation

#
# Rotation 1: year 2001
#

   2          #  <plants/yr 1> - OFE: 1>
     7        # year index
     1        # year index

#
# Rotation 2: year 2002
#

   1          #  <plants/yr 1> - OFE: 1>
     2        # year index

#
# Rotation 3: year 2003
#

   2          #  <plants/yr 1> - OFE: 1>
     7        # year index
     3        # year index

#
# Rotation 4: year 2004
#

   1          #  <plants/yr 1> - OFE: 1>
     4        # year index

#
# Rotation 5: year 2005
#

   2          #  <plants/yr 1> - OFE: 1>
     8        # year index
     5        # year index

#
# Rotation 6: year 2006
#

   1          #  <plants/yr 1> - OFE: 1>
     6        # year index
```

E.4. Experimental forest watershed, Mica Creek, ID

E.4.1. Climate file

```
4.3
  1   0   0
  Station:  Mica Creek 5 ID                          CLIGEN VERSION 4.2
Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated
   47.15  -116.27        1374          16          1991            100
Observed monthly ave max temperature (C)
 -0.4   2.5   6.1   9.8  14.3  18.1  24.3  24.6  19.0  10.6   2.2  -0.8
Observed monthly ave min temperature (C)
 -5.3  -5.4  -3.6  -1.2   2.3   5.8   9.8   9.8   6.3   1.6  -3.1  -5.6
Observed monthly ave solar radiation (Langleys/day)
125.0 212.0 331.0 455.0 548.0 602.0 661.0 547.0 405.0 241.0 141.0  91.0
Observed monthly ave precipitation (mm)
209.2 134.0 138.6 112.2 114.7  73.9  34.3  31.4  54.2  99.2 207.3 211.5
     da      mo   year    prcp    dur     tp       ip    tmax    tmin     rad    w-vl    w-dir    tdew
                         (mm)     (h)                    (C)     (C)     (l/d)  (m/s)   (Deg)    (C)
      1       1   1991     2.5    3.66    0.01    1.01    -4.4   -11.1      54   3.52     268    -7.9
      2       1   1991       0       0       0       0    -3.9    -5.6      95   1.33     248    -7.1
      3       1   1991       0       0       0       0    -1.7    -8.3     146   3.89     171   -20.2
      4       1   1991       0       0       0       0    -3.9   -11.7     117   1.85     274   -19.6
      5       1   1991       0       0       0       0    -8.3   -11.7      89   1.94     233   -10.1
      6       1   1991     7.6    3.84    0.05    1.01    -8.3   -15.6      83   2.27     237     -12
      7       1   1991    45.7    3.16    0.14    1.01    -3.3     -15     104   2.80     128   -10.4
      8       1   1991    12.7    1.65    0.05    1.01    -2.8    -5.6     149   3.14     186    -9.2
      9       1   1991     7.6    2.75    0.02    1.01    -1.1    -3.3     142   2.55      35    -6.6
     10       1   1991    12.7    2.79    0.08    1.01       0      -5     133   2.73     300    -4.4
     11       1   1991    10.2    3.99    0.05    1.01    -0.6    -3.3     160   3.98       0    -1.9
     12       1   1991    10.2    3.68    0.06    7.55     2.8    -1.1     162   5.57     325    -4.2
     13       1   1991     7.6    2.07    0.01    5.15     3.3       0     120   5.03     285     1.3
     14       1   1991    22.9    4.38    0.02   13.49     2.2       0      85   2.96     222   -13.9
     15       1   1991    12.7     1.7       0    1.01     0.6    -0.6      98   3.51     317   -21.6
     16       1   1991     7.6    1.15    0.05    1.01     0.6    -2.2     102   2.32     148   -15.9
     17       1   1991       0       0       0       0    -0.6    -2.2     121   2.61     247   -14.1
     18       1   1991     5.1    3.82    0.06    1.01     1.1    -1.1     108   1.84     281   -15.8
     19       1   1991     5.1    5.77    0.02    1.01     2.8    -6.1      93   1.74     189    -8.7
     20       1   1991     2.5       1    0.01    1.01    -2.2   -11.1     110   0.68     263   -21.4
     21       1   1991       0       0       0       0    -3.9   -12.2      84   1.04     147    -8.2
     22       1   1991       0       0       0       0    -1.1   -10.6      86   1.71       0    -8.8
     23       1   1991       0       0       0       0    -0.6    -9.4      91   0.56     190    -6.6
     24       1   1991       0       0       0       0       0     -10     147   1.56     199    -9.2
     25       1   1991     2.5    2.38    0.01    1.01    -3.9    -9.4     140   2.43     136    -6.8
     26       1   1991       0       0       0       0    -5.6   -13.3     179   0.81     269    -9.5
     27       1   1991       0       0       0       0    -7.2   -13.3     131   3.24     203   -10.4
     28       1   1991       0       0       0       0    -3.3   -11.7     118   1.17     226   -17.4
     29       1   1991       0       0       0       0    -7.2   -18.9     153   1.61     209   -13.1
     30       1   1991       0       0       0       0    -5.6   -17.2     128   2.47     183   -16.4
     31       1   1991       0       0       0       0       0    -9.4     123   4.33     214    -4.9
.....................................

.....................................

.....................................
```

E.4.2. Soil file

```
2006.2
comments: soil file
1    1
'20-yr forest silt loam' 'silt loam'   5    0.06    0.8     1000000.0     0.0004    1.0    200.00
   50   80.0   10.0   5.000   15.0   0.0
   250   30.0   10.0   5.000   15.0   20.0
   450   30.0   10.0   5.000   15.0   20.0
   1050  30.0   10.0   5.000   15.0   40.0
   1800   80.0   10.0   5.000    1.5    0.0
1    15.0    0.06
```

E.4.3. Slope file (hillslope No. 1)

```
97.5
#
# from slope
#
#
1
213.707        749.117
8      227.067
 0.0, 0.19   0.1429, 0.166   0.2857, 0.153   0.4286, 0.185    0.5714, 0.22    0.7143, 0.253    0.8571, 0.281     1.0, 0.311
```

E.4.4. Management file

```
98.4
#
#
#
#

1 # number of OFE's
16 # (total) years in simulation

#######################
# Plant Section       #
#######################

1  # Number of plant scenarios


Tre_3082
Five year old forest
for disturbed WEPP
W. Elliot  02/99
1  #landuse
WeppWillSet
5.2    3.0    8.0      2.0      5.0      30.0     0.8    0.0   0.70     0.2500
0.85     0.95    0.65      0.99    15.0      0.0     0.42        2.50000
2  # mfo - <non fragile>
0.003   0.006        20.0     0.1      0.4     0.5   0.33     0.50     90     40.0
-40     3.0      0.0

#######################
# Operation Section   #
#######################

0  # Number of operation scenarios




###############################
# Initial Conditions Section  #
###############################

1  # Number of initial scenarios


Tre_6854
Initial conditions for 20-year old forest
for Disturbed WEPP
W.Elliot  02/99
1  #landuse
1.10  0.95  1000 1000 0.00000 0.9500
1 # iresd  <veg_2141>
2 # mang perennial
999.99799 0.10000 0.9500 0.10000 0.00000
1  # rtyp - temporary
0.00000 0.00000 0.10000 0.20000 0.00000
0.50000 0.50000
```

```
############################
# Surface Effects Section  #
############################

0  # Number of Surface Effects Scenarios



######################
# Contouring Section  #
######################

0  # Number of contour scenarios


######################
# Drainage Section    #
######################

0  # Number of drainage scenarios


######################
# Yearly Section      #
######################

1  # looper; number of Yearly Scenarios
#
# Yearly scenario 1 of 1
#
Year 1



1  # landuse <cropland>
1  # plant growth scenario
0  # surface effect scenario
0  # contour scenario
0  # drainage scenario
2 # management <perennial>
   300 # senescence date
   0 # perennial plant date --- 0 /0
   0 # perennial stop growth date --- 0/0
   1.2000  # row width
   3  # neither cut or grazed


######################
# Management Section  #
######################

Manage
description 1
description 2
description 3
1   # number of OFE's
    1   # initial condition index
1  # rotation repeats
16  # years in rotation

#
```

```
# Rotation 1: year 1 to 16
#

   1          #  <plants/yr 1> - OFE: 1>
      1       # year index
#-----------------------------------
   1          #  <plants/yr 2> - OFE: 1>
      1       # year index
#-----------------------------------
   1          #  <plants/yr 3> - OFE: 1>
      1       # year index
#-----------------------------------
   1          #  <plants/yr 4> - OFE: 1>
      1       # year index
#-----------------------------------
   1          #  <plants/yr 5> - OFE: 1>
      1       # year index
#-----------------------------------
   1          #  <plants/yr 6> - OFE: 1>
      1       # year index
#-----------------------------------
   1          #  <plants/yr 7> - OFE: 1>
      1       # year index
#-----------------------------------
   1          #  <plants/yr 8> - OFE: 1>
      1       # year index
#-----------------------------------
   1          #  <plants/yr 9> - OFE: 1>
      1       # year index
#-----------------------------------
   1          #  <plants/yr 10> - OFE: 1>
      1       # year index
#-----------------------------------
   1          #  <plants/yr 11> - OFE: 1>
      1       # year index
#-----------------------------------
   1          #  <plants/yr 11> - OFE: 1>
      1       # year index
#-----------------------------------
   1          #  <plants/yr 11> - OFE: 1>
      1       # year index
#-----------------------------------
   1          #  <plants/yr 11> - OFE: 1>
      1       # year index
#-----------------------------------
   1          #  <plants/yr 11> - OFE: 1>
      1       # year index
#-----------------------------------
   1          #  <plants/yr 11> - OFE: 1>
      1       # year index
```

Appendix F. Statistical Comparison of WEPP-predicted and Field-observed Winter Hydrological Data

SAS codes for two sample Wilcoxon test

```
DATA q_data;
INFILE 'C:\dsh\course\Thesis2\Thesis\Satistic\data.prn';
INPUT type $ q;
run;
proc npar1way data=q_data; * non-parametric test;
where type = 'Obs' or type= 'Sim';
class type;
var q;
run;
```

Sample input file (for PCFS annual runoff from WEPP v2008.9)

```
Sim     134
Sim     187
Sim     162.1
Sim      76
Sim     118.4
Sim     188.5
Sim     69.3
Obs     228
Obs     119
Obs     147
Obs      71
Obs     108
Obs     125
Obs     134
```

Output for snow depth from WEPP v2008.9, Pullman, WA

```
            Wilcoxon Two-Sample Test

          Statistic          22235.0000

          Normal Approximation
          Z                      1.5927
          One-Sided Pr >  Z         0.0556
          Two-Sided Pr > |Z|        0.1112

          t Approximation
          One-Sided Pr >  Z         0.0562
          Two-Sided Pr > |Z|        0.1123

       Z includes a continuity correction of 0.5.
```

Output for frost depth from WEPP v2008.9, Pullman, WA

```
   Wilcoxon Two-Sample Test

Statistic           74729.5000

Normal Approximation
Z                      6.0983
One-Sided Pr >  Z        <.0001
Two-Sided Pr > |Z|       <.0001

t Approximation
One-Sided Pr >  Z        <.0001
Two-Sided Pr > |Z|       <.0001

Z includes a continuity correction of 0.5.
```

Output for event runoff from WEPP v2008.9, Pullman, WA

```
   Wilcoxon Two-Sample Test

Statistic           24423.0000

Normal Approximation
Z                      7.0405
One-Sided Pr >  Z        <.0001
Two-Sided Pr > |Z|       <.0001

t Approximation
One-Sided Pr >  Z        <.0001
Two-Sided Pr > |Z|       <.0001

Z includes a continuity correction of 0.5.
```

Output for event sediment yield from WEPP v2008.9, Pullman, WA

```
   Wilcoxon Two-Sample Test

Statistic           25924.5000

Normal Approximation
Z                      7.0868
One-Sided Pr >  Z        <.0001
Two-Sided Pr > |Z|       <.0001

t Approximation
One-Sided Pr >  Z        <.0001
Two-Sided Pr > |Z|       <.0001

Z includes a continuity correction of 0.5.
```

Output for annual runoff from WEPP v2008.9, Pullman, WA

```
   Wilcoxon Two-Sample Test

  Statistic          53.5000

  Normal Approximation
  Z                  0.0640
  One-Sided Pr >  Z      0.4745
  Two-Sided Pr > |Z|     0.9490

  t Approximation
  One-Sided Pr >  Z      0.4750
  Two-Sided Pr > |Z|     0.9500

Z includes a continuity correction of 0.5.
```

Output for annual sediment yield from WEPP v2008.9, Pullman, WA

```
   Wilcoxon Two-Sample Test

  Statistic          52.0000

  Normal Approximation
  Z                  0.0000
  One-Sided Pr <  Z      0.5000
  Two-Sided Pr > |Z|     1.0000

  t Approximation
  One-Sided Pr <  Z      0.5000
  Two-Sided Pr > |Z|     1.0000

Z includes a continuity correction of 0.5.
```

Output for snow depth from WEPP v2008.9, Morris, MN

```
   Wilcoxon Two-Sample Test

  Statistic          7314.0000

  Normal Approximation
  Z                  -0.8972
  One-Sided Pr <  Z       0.1848
  Two-Sided Pr > |Z|      0.3696

  t Approximation
  One-Sided Pr <  Z       0.1854
  Two-Sided Pr > |Z|      0.3709

Z includes a continuity correction of 0.5.
```

Output for frost depth from WEPP v2008.9, Morris, MN

```
        Wilcoxon Two-Sample Test

      Statistic           26432.5000

      Normal Approximation
      Z                      2.1192
      One-Sided Pr >  Z        0.0170
      Two-Sided Pr > |Z|       0.0341

      t Approximation
      One-Sided Pr >  Z        0.0174
      Two-Sided Pr > |Z|       0.0349

   Z includes a continuity correction of 0.5.
```

Output for snow depth from WEPP v2006.5, Pullman, WA

```
         Wilcoxon Two-Sample Test

      Statistic           28663.0000

      Normal Approximation
      Z                     10.6509
      One-Sided Pr >  Z        <.0001
      Two-Sided Pr > |Z|       <.0001

      t Approximation
      One-Sided Pr >  Z        <.0001
      Two-Sided Pr > |Z|       <.0001

   Z includes a continuity correction of 0.5.
```

Output for frost depth from WEPP v2006.5, Pullman, WA

```
         Wilcoxon Two-Sample Test

      Statistic           70661.0000

      Normal Approximation
      Z                      3.6377
      One-Sided Pr >  Z        0.0001
      Two-Sided Pr > |Z|       0.0003

      t Approximation
      One-Sided Pr >  Z        0.0002
      Two-Sided Pr > |Z|       0.0003

   Z includes a continuity correction of 0.5.
```

Output for event runoff from WEPP v2006.5, Pullman, WA

```
    Wilcoxon Two-Sample Test

  Statistic          30719.0000

  Normal Approximation
  Z                   12.1534
  One-Sided Pr >  Z        <.0001
  Two-Sided Pr > |Z|       <.0001

  t Approximation
  One-Sided Pr >  Z        <.0001
  Two-Sided Pr > |Z|       <.0001

Z includes a continuity correction of 0.5.
```

Output for event sediment yield from WEPP v2006.5, Pullman, WA

```
    Wilcoxon Two-Sample Test

  Statistic          28429.5000

  Normal Approximation
  Z                    9.0090
  One-Sided Pr >  Z        <.0001
  Two-Sided Pr > |Z|       <.0001

  t Approximation
  One-Sided Pr >  Z        <.0001
  Two-Sided Pr > |Z|       <.0001

Z includes a continuity correction of 0.5.
```

Output for annual runoff from WEPP v2006.5, Pullman, WA

```
    Wilcoxon Two-Sample Test

   Statistic          29.0000

   Normal Approximation
   Z                -2.9388
   One-Sided Pr <  Z     0.0016
   Two-Sided Pr > |Z|    0.0033

   t Approximation
   One-Sided Pr <  Z     0.0058
   Two-Sided Pr > |Z|    0.0115

 Z includes a continuity correction of 0.5.
```

Output for annual sediment yield from WEPP v2006.5, Pullman, WA

```
  Wilcoxon Two-Sample Test

 Statistic           49.0000

 Normal Approximation
 Z                  -0.3833
 One-Sided Pr <  Z      0.3507
 Two-Sided Pr > |Z|     0.7015

 t Approximation
 One-Sided Pr <  Z      0.3538
 Two-Sided Pr > |Z|     0.7077

Z includes a continuity correction of 0.5.
```

Output for snow depth from WEPP v2006.5, Morris, MN

```
  Wilcoxon Two-Sample Test

 Statistic           7751.5000

 Normal Approximation
 Z                    0.4170
 One-Sided Pr >  Z       0.3383
 Two-Sided Pr > |Z|      0.6767

 t Approximation
 One-Sided Pr >  Z       0.3386
 Two-Sided Pr > |Z|      0.6772

Z includes a continuity correction of 0.5.
```

Output for frost depth from WEPP v2006.5, Morris, MN

```
  Wilcoxon Two-Sample Test

 Statistic           34154.0000

 Normal Approximation
 Z                   11.7358
 One-Sided Pr >  Z        <.0001
 Two-Sided Pr > |Z|       <.0001

 t Approximation
 One-Sided Pr >  Z        <.0001
 Two-Sided Pr > |Z|       <.0001

Z includes a continuity correction of 0.5.
```