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SEASONAL CHANGE OF WEPP ERODIBILITY PARAMETERS ON A FALLOW PLOT

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SEASONAL CHANGE OF WEPP ERODIBILITY PARAMETERS ON A FALLOW PLOT

D.K. McCool[1], S. Dun[2], J.Q. Wu[3], W.J. Elliot[4]

ABSTRACT

In cold regions, frozen soil has a significant influence on runoff and water erosion. Frozen soil can reduce infiltration capacity, and the freeze-thaw processes degrade soil cohesive strength and increase soil erodibility. In the Inland Pacific Northwest of the USA, major erosion events typically occur during winter from low-intensity rain, snowmelt, or both as frozen soil thaws and exhibits low cohesion. The Water Erosion Prediction Project (WEPP) model is a physically-based simulation tool for water erosion, and has been widely used for conservation planning on agricultural, range, and forest lands. WEPP estimates runoff and sediment yield by simulating major hydrological and erosion processes. Previous applications of WEPP to continuous bare fallow (CBF) runoff plots at the Palouse Conservation Field Station (PCFS) in southeastern Washington State showed that WEPP reproduced the occurrence of the major observed erosion events but the amount of sediment yield was either under- or over-estimated. The inability of WEPP to fully reproduce field-observed erosion events at the PCFS suggests a need for an examination of the dynamic changes in soil properties and for improving the representation of such dynamics. The objective of this study was to evaluate the seasonal changes of rill erosion parameters on a CBF runoff plot at the PCFS.

One-hundred and twenty-six runoff and erosion events were observed on CBF runoff plot #13 during 1984–1990, which included 24 summer (May–October) events. Sixteen winter events occurred on frozen soil, and 86 on thawing or non-frozen soils. The mean runoff and sediment yield of the summer events were 3.2 mm and 3.0 T ha^{-1}; for the winter events on frozen soil, the means were 9.8 mm and 1.2 T ha^{-1}; and for winter events on non-frozen or thawing soils, the means were 7.1 mm and 13.4 T ha^{-1}, respectively. Single-event simulations by WEPP were performed with the aim of reproducing the observed runoff and sediment yield for each event. Soil effective hydraulic conductivity (K_e) was adjusted to best fit the observed runoff. Critical shear stress (τ_c) and rill erodibility (K_r) are the principal WEPP rill erosion parameters. A previous laboratory study on erosion of thawed Palouse soil showed a significant inverse relationship between critical shear stress and rill erodibility ($K_r = -0.011\tau_c + 0.031$). Following this regression relationship, we adjusted the critical shear stress and rill erodibility to best fit the observed sediment yield for each event on the CBF plot.

For summer events, winter events on frozen soil, and winter events on non-frozen or thawing soils, averaged best-fit K_e values were 2.3, 0.80, and 1.2 mm h^{-1} respectively, the averaged best-fit τ_c values were 1.3, 1.4, and 0.8 Pa, respectively. A two-sample *t*-test with the assumption of unequal variances at α= 0.05 indicated that K_e for winter events on frozen soil and on non-frozen or thawing soil were significantly lower than K_e for summer events. However, there were no significant differences between winter events on frozen soil and on non-frozen or thawing soil for the fitted K_e values; τ_c for winter events on frozen soil and summer events were significantly greater than for winter events on non-frozen or thawing soil; no significant differences between the τ_c for winter events on frozen soil and summer events were indicated by the *t*-test. The adjustment factor for critical shear stress and rill-erodibility for soil freezing and thawing in the WEPP model may need to be modified to better reflect the changes induced by soil freezing and thawing processes.

KEYWORDS. Critical shear, Rill erodibility, Frozen soil, Thawing soil, Soil erosion, WEPP.

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INTRODUCTION

Soil freezing and thawing has a significant influence on runoff and water erosion in cold regions (Zuzel et al., 1982; Seyfried and Flerchinger, 1994; McCool et al., 2006). Frozen soil can reduce infiltration capacity (McCauley et al., 2002), and the freeze-thaw processes degrade soil cohesive strength (Kok and McCool, 1990) and increase soil erodibility (Van Klaveren and McCool, 2010). In the Inland Pacific Northwest of the USA, major erosion events typically occur over large areas during winter from long-duration, low-intensity rain, snowmelt, or both as frozen soil thaws and exhibits low cohesion, and in the summer from infrequent but intense rainstorms over small areas (Horner et al., 1944; McCool et al., 2006).

The Water Erosion Prediction Project (WEPP) model is a physically-based simulation tool for water erosion, and has been widely used for conservation planning on agricultural, range, and forest lands (Flanagan et al., 2007). WEPP estimates runoff and sediment yield by simulating major hydrological processes, including infiltration, ET, surface runoff and subsurface-flow, and major erosion processes, such as interrill erosion, rill erosion, and sediment deposition (Flanagan and Livingston, 1995). The model also includes a winter hydrology component to simulate snow accumulation and snowmelt as well as soil freeze and thaw for winter runoff and erosion simulation (Flanagan and Nearing, 1995; Dun et al., 2010).

Previous applications of WEPP to continuous bare fallow (CBF) runoff plots at the Palouse Conservation Field Station (PCFS) in southeastern Washington (Dun et al., 2010) showed that the WEPP model reasonably reproduced the observed snow accumulation and snowmelt, soil freeze and thaw, runoff, and the occurrence of the major observed erosion events but the amount of sediment yield was either under- or over-predicted. The inability of WEPP to fully reproduce field-observed erosion events at the PCFS suggests a need for an examination of the dynamic changes in soil erosion properties and for improving the representation of such dynamics. The objective of this study was to evaluate the seasonal changes of rill erosion parameters on a CBF runoff plot (#13) at the PCFS.

LAB-MEASURED EROSION PARAMETERS ON PCFS SOIL

Rill erodibility and critical shear of previously frozen Palouse silt loam (fine-silty, mixed Mesic Pachic Ultic Haploxeroll) topsoil sample from the PCFS, were measured by Van Klaveren and McCool (2010) using a tilting flume with a radiant freezing plate. The lab experiments included nine rill erosion tests at three flow rates (approximately 2, 3, and 4 L min^{-1}) and three preset surface soil water tensions (50, 150, and 450 mm) and two additional tests at low flow rate of approximately 1 L min^{-1} at 50 and 150 mm soil water tensions (Van Klaveren and McCool, 2010). Rill erodibility and critical shear stress were estimated for each surface soil water tension at testing times of 10, 20, 30, 45, 60, and 90 min by fitting the rill detachment capacity equation in the WEPP model (eq. 1).

$$D_c = K_r(\tau - \tau_c) \quad (1)$$

where D_c is detachment capacity by rill flow (kg s^{-1} m^{-2}), K_r is a rill erodibility parameter (s m^{-1}), τ is flow shear stress acting on the soil particles (Pa), and τ_c is the rill detachment threshold parameter, or critical shear stress, of the soil (Pa). Rill detachment is considered to be zero when flow shear stress is less than the critical shear stress of the soil (Flanagan and Nearing, 1995).

The experiments by Van Klaveren and McCool (2010) covered a spectrum of soil conditions from highly susceptible to water erosion when the surface is near saturation (50 mm soil water tension) after frozen soil thawed, to much less erodible at 450 mm soil water tension that resembles soil under summer conditions (Van Klaveren and McCool, 2010). The highly erodible soil has low critical shear stress and high rill erodibility. We conducted regression analysis (SAS, 2004) on the erosion parameters from the experiments that shows a significant and inverse linear correlation between rill erodibility and critical shear stress at a significance level of α = 0.05 (eq. 2, Figure 1, Table 1).

$$K_r = 0.031 - 0.011\tau_c \quad (2)$$

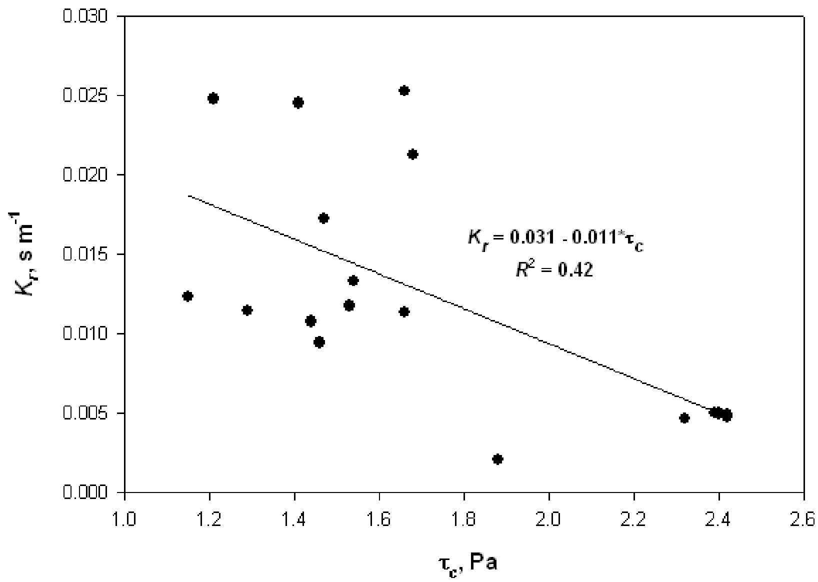

Figure 1. Rill erosion parameters measured in the lab experiments by Van Klaveren and McCool (2010).

Table 1. Regression analysis results on critical shear stress and rill erodibility measured by Van Klaveren and McCool (2010).

		Std. error	*t*-value	*p*-value
Intercept	0.0313	0.0057	5.454	<0.0001
Slope	−0.0110	0.0032	−3.432	0.0034

FIELD-OBSERVED EROSION EVENTS ON THE CBF RUNOFF PLOTS AT THE PCFS

The PCFS (46°45'N, 117°12'W) is located 3 km northwest of Pullman, Washington. Long-term experimental runoff plots have been installed at the PCFS since the 1970s (McCool et al., 2002). Data from these experimental plots included weather, snow and frost depths, and runoff and sediment yield from fall 1978 to spring 1991. A 24-h chart-type recording rain gauge near the runoff plots provided break-point rainfall data for this study (Lin and McCool, 2006). Snow depth was measured with snow stakes, and frost depth was measured with frost tubes (McCool and Molnau, 1984) installed at three locations (top, middle, and bottom) along the edge of each plot. Runoff and sediment yield were measured using runoff collection tanks and pumps with sample splitters (McCool et al., 2006).

In this study, erosion events observed during 1984–1990 on CBF runoff plot #13 were used to examine the seasonal changes of WEPP rill erosion parameters. The chosen plot was 22.3 m long and 3.7 m wide on a 21% south-facing slope (McCool et al., 1995) of Palouse silt loam soil under continuous bare fallow condition.

The observed erosion events were divided into three categories: summer events that occurred during May–October, winter events on frozen soil, and winter events on non-frozen or thawing soils (Figure

2). Of 126 observed runoff and erosion events on plot #13, twenty-four were summer events, sixteen were winter events on frozen soil, and eighty-six were winter events on non-frozen or thawing soils. The mean runoff and sediment yield of summer events were 3.2 mm and 3.0 T ha^{-1}; for the winter events on frozen soil, means were 9.8 mm and 1.2 T ha^{-1}; for winter events on non-frozen or thawing soils, the means were 7.1 mm and 13.4 T ha^{-1}.

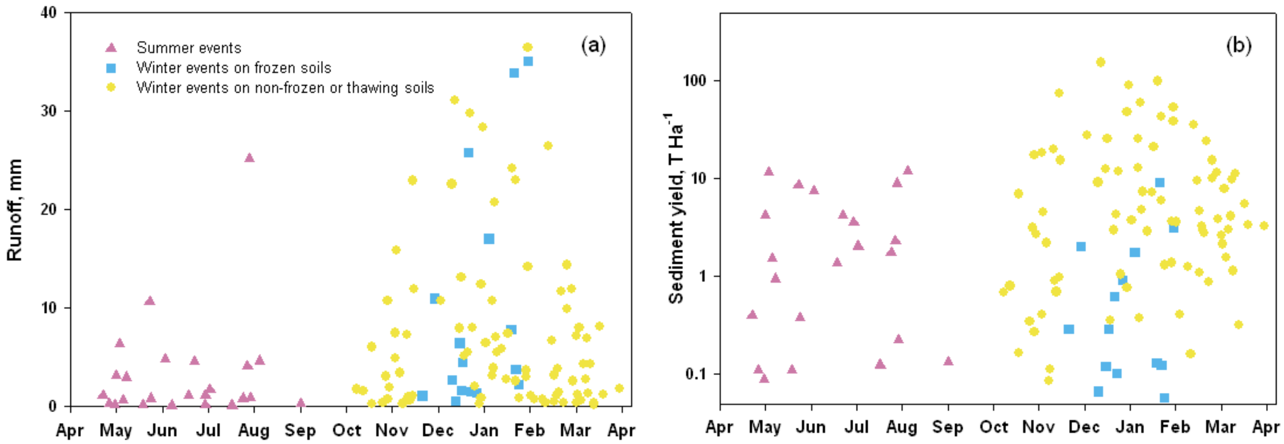

Figure 2. Observed runoff and sediment yields from events on CBF Plot #13 at the PCFS from 1984 to 1990.

ESTIMATING SOIL EROSION PARAMETERS USING FIELD-OBSERVED EVENTS AND THE WEPP MODEL

The WEPP model has been used to estimate infiltration and erosion parameters from rainfall simulation data using single-storm mode of WEPP applications (Copeland and Foltz, 2009; Foltz et al., 2009). The WEPP model simulates interrill erosion, rill erosion, and sediment deposition processes (Flanagan and Livingston, 1995). A steady-state sediment continuity equation is used in the WEPP model to describe the movement of sediment in a rill (eq. 1, 3 and 4; Flanagan and Livingston, 1995)

$$\frac{dG}{dx} = D_f + D_i \qquad (3)$$

$$D_f = D_c\left(1 - \frac{G}{T_c}\right) \qquad (4)$$

where G is sediment load (kg s^{-1} m^{-1}), D_i is interrill sediment delivery to the rill (kg s^{-1} m^{-2}), D_f is rill erosion rate (kg s^{-1} m^{-2}), D_c is detachment capacity by rill flow (kg s^{-1} m^{-2}), T_c is sediment transport capacity in the rill (kg s^{-1} m^{-1}), and x represents distance downslope (m).

In estimating sediment yield from hillslopes to streams and water-bodies with the WEPP model, soil rill erodibility and critical shear stress are among the most important and sensitive parameters. In this study, single-event WEPP simulations were carried out with the intention to reproduce the observed runoff and sediment yield for each erosion event on plot #13. Soil effective hydraulic conductivity (K_e) was adjusted to best fit the observed runoff. While maintaining regression relation (eq. 2) between lab-measured critical shear stress and rill erodibility from Van Klaveren and McCool, (2010), τ_c and K_r were adjusted to best fit the observed sediment yield of each observed event on the CBF plot.

Four inputs describing climate, topography, land use and management, and soil are required for WEPP simulation. The same settings were used for WEPP simulation for each runoff and erosion event except the break-point rainfall data in the climatic inputs. Observed rainfall and snowmelt data during each erosion event were used as the break-point rainfall values. Other required climate data including temperature, wind, humidity, and solar radiation, were from the NOAA Pullman 2 NW, 0.6 km to the east of the runoff plots, for a typical summer day. Soil inputs were the Palouse silt loam data from the WEPP soil database with an initial soil saturation level assumed 100% and adjusted K_e, τ_c, and K_r. Topographic inputs were a uniform slope configuration with respective slope gradients, slope aspects, and dimensions of plot #13. The management condition was continuous-tilled fallow for the PCFS plot (Lin and McCool, 2006)

To best fit an observed runoff, we adjusted K_e is following a bi-section method. Repeated WEPP runs were performed while varying K_e until the difference between the observed and simulated runoff was within a tolerance level of 0.05 mm. Fitting sediment yield for the event was conducted after the observed runoff was reproduced. To best fit the observed sediment yield, we changed τ_c from 0.01–2.84 Pa with an interval of 0.01 Pa, and estimated K_r using the regression relation (eq. 2) for each τ_c. Among those sediment yield values obtained from the repeated WEPP simulations varying τ_c and K_r, the sediment yield closest to the observed value was considered as the best-fit sediment yield. The corresponding τ_c and K_r were considered as the critical shear stress and rill erodibility parameter for the soil during the runoff and erosion event.

RESULTS AND DISCUSSION

Seasonal changes in soil infiltration and erosion parameters were evident from the best-fit K_e, τ_c, and K_r values (Fig 3). Descriptive statistics of the resultant K_e, τ_c, and K_r are presented in Table 2. For summer events, winter events on frozen soil, and winter events on non-frozen or thawing soils, the means of K_e were 2.3, 0.8, and 1.2 mm h^{-1} and the means of τ_c were 1.3, 1.4, and 0.8 Pa respectively. With observed runoff as weighting factor, the weighted averages of K_e were 2.1, 0.4, and 0.5 mm h^{-1}, respectively. Using observed sediment yield as weighting factor, the weighted averages of τ_c were 1.3, 1.5, and 0.5 Pa, and the weighted averages of K_r were 0.017, 0.014, and 0.026 s m^{-1}. For the weighted average, τ_c for frozen soils was 1.2 times that for summer soils, K_r for frozen soils was 0.8 times that for summer soils; τ_c for non-frozen or thawing soils in winter was 0.4 times that for summer soils, K_r for non-frozen soils in winter was 1.5 times that for summer soils.

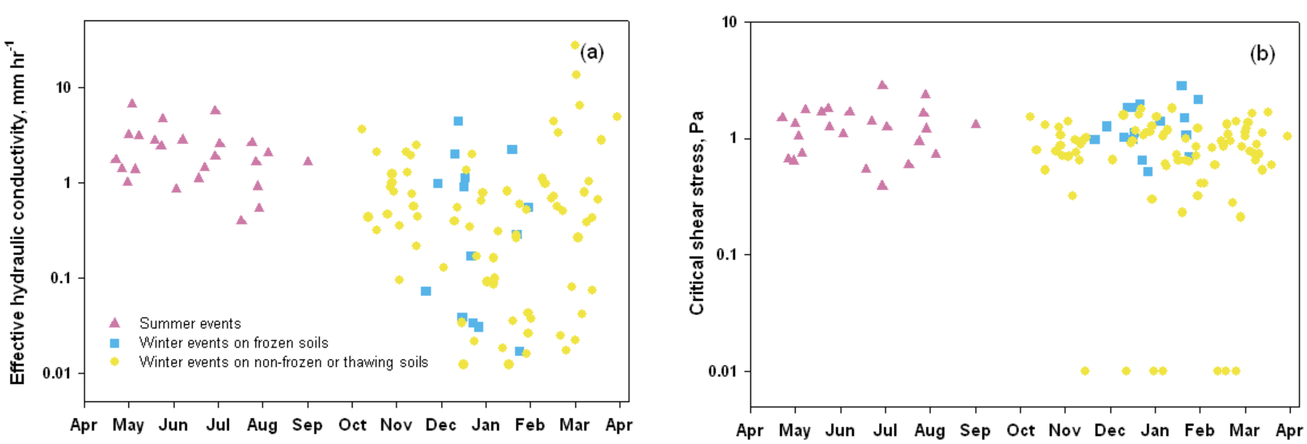

Figure 3. Best-fit effective hydraulic conductivity and critical shear stress values for runoff/erosion events on CBF Plot #13 at the PCFS from 1984 to 1990.

The results from the two-sample *t*-tests with an assumption of unequal variances at $\alpha = 0.05$ (Table 3) indicated that K_e for winter events on frozen soil and on non-frozen or thawing soil were significantly lower than K_e for summer events. However, there were no significant differences between winter events on frozen soil and on non-frozen or thawing soil for the fitted K_e values; τ_c for winter events on frozen soil and summer events was significantly larger than that for winter events on non-frozen or thawing soil, no significant difference between τ_c for winter events with frozen soil and summer events was found.

Table 2. Descriptive statistics of the infiltration and rill erosion parameters.

Category	Sample size	Parameter	Runoff mm	Sediment yield T ha^{-1}	K_e mm hr^{-1}	τ_c Pa	K_r s m^{-1}
Summer events	24	Mean	3.2	3.0	2.3	1.27	0.017
		Std. Dev.	5.4	3.9	1.6	0.59	0.006
		Max	25.2	12.1	6.6	2.83	0.027
		Min	0.1	0.0	0.4	0.39	0.00017
		Skewness	3.4	1.3	1.5	0.80	−0.80
Winter events on frozen soils	16	Mean	9.8	1.2	0.8	1.37	0.016
		Std. Dev.	11.8	2.3	1.2	0.63	0.007
		Max	35.1	9.3	4.4	2.83	0.026
		Min	0.5	0.0	0.003	0.52	0.00017
		Skewness	1.4	3.1	2.1	0.81	−0.81
Winter events on non-frozen or thawing soils	86	Mean	7.1	13.4	1.2	0.85	0.022
		Std. Dev.	8.3	24.8	3.4	0.43	0.0048
		Max	36.5	154.8	27.2	1.80	0.031
		Min	0.1	0.0	0.00001	0.01	0.012
		Skewness	1.7	3.5	6.2	−0.09	0.081

Table 3. Two sample *t*-tests results.

Parameter	*t*-test	df	*t* Stat	*P*(T<=t) one-tail	*t* critical one-tail
K_e	Summer events vs. winter events on frozen soils	37	−3.35	0.0009	1.69
	Summer events vs. winter events on non-frozen soils	84	−2.19	0.02	1.66
	Winter events on frozen vs. on non-frozen soils	66	0.87	0.19	1.67
τ_c	Summer events vs. winter events on frozen soils	31	0.51	0.31	1.70
	Summer events vs. winter events on non-frozen soils	30	−3.22	0.002	1.70
	Winter events on frozen vs. on non-frozen soils	18	−3.16	0.005	1.73

The adjustment factors for critical shear stress and rill-erodibility for frozen soil in the WEPP model are functions of matric potential of the surface soil (eq. 5, 6; Flanagan and Nearing, 1995).

$$C\tau_{cft} = 0.875 + 0.0543 \times \ln(\psi_{surf}) \quad (5)$$

$$CK_{rft} = 2.0 \times 0.933^{\psi_{surf}} \quad (6)$$

where $C\tau_{cft}$ is the adjustment factor for freezing and thawing effects for critical shear stress, CK_{rft} is the adjustment factor for rill erodibility, and Ψ_{surf} is the matric potential of the surface soil (KPa). During a simulated freeze-thaw cycle, the adjustment is turned off when the soil water content is lower than the soil water content at field capacity, and will be activated at the next freeze and thaw cycle.

The adjustment factor for K_r in WEPP appears reasonable with a range of 0.2–2.0 (Figure 4) provided the surface soil tension can be estimated adequately. The maximum adjustment factor for τ_c is 1.1 (Fig 4.), which is lower than estimated in this study. The adjustment factor for τ_c decreases rapidly once soil water content is near saturation (surface soil matric potential is close to 0). The adjustment method for rill erosion parameters in the WEPP model may need to be modified to reflect the dynamic changes induced by soil freezing and thawing processes.

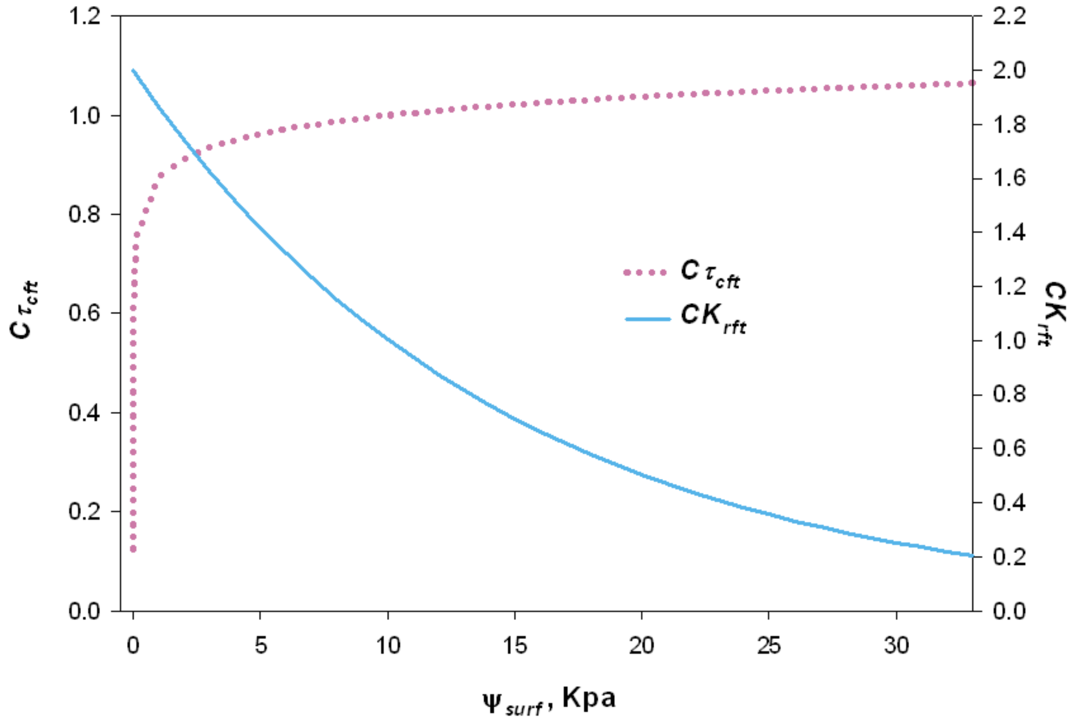

Figure 4. Adjustment factors for soil freezing and thawing in the WEPP model.

SUMMARY

Field-observed runoff and soil erosion events on a continuous fallow runoff plot at the Palouse Conservation Field Station (PCFS) in southeastern Washington in the Inland Pacific Northwest of the USA were used to best fit water erosion parameters (rill erodibility and critical shear stress) for each event using the WEPP model. The observed erosion events were categorized into summer events, winter events on frozen soil, and winter events on non-frozen or thawing soils for examining the seasonal changes in the infiltration and erosion parameters. It was found for the study plot that for frozen soils, τ_c was 1.2 times and K_r was 0.8 times the values for summer soils, and τ_c for non-frozen or thawing soils in winter was 0.4 times and K_r was 1.5 times the values for summer soils. The WEPP adjustment factor for τ_c for soil freezing and thawing seems too small to adequately reflect seasonal changes in τ_c. The adjustment method for rill erosion parameters in the WEPP model may need to be modified to reflect the dynamic changes induced by soil freezing and thawing processes. Future studies on soils of other cold regions are needed to develop systematic and sound approaches to adjusting the erodibility parameters in the WEPP model.

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