Analytical Solutions and Sensitivity Analyses for Sediment Transport in WEPS

L. J. Hagen, L. E. Wagner, E. L. Skidmore

Abstract. *The Wind Erosion Prediction System (WEPS) is a process-based, daily time-step model that simulates weather and field conditions. When wind speed exceeds the threshold, the EROSION submodel of WEPS simulates soil loss and deposition on a sub-hourly basis. The objectives of this study were to: (1) assemble the erosion process equations in a manner that allows analytic solutions; (2) develop analytic solutions for a uniform surface; and (3) evaluate the response to parameters in these solutions using linear sensitivity tests. Based on the principle of conservation of mass, an analytic solution was developed for a quasi-steady state equation of the saltation/creep discharge. This equation simulates two sources (entrainment of loose material and entrainment of material abraded from clods and crust) and three sinks (breakage of saltation/creep to suspension-size, trapping of saltation/creep, and interception by plant stalks). An analytic solution also was developed for the horizontal discharge of the suspension component. This equation simulates three sources (entrainment of loose material, entrainment of material abraded from clods and crust, and breakage of saltation/creep to suspension-size). Sensitivity tests of the simulation equations showed that soil loss by wind erosion was most sensitive to wind speed and surface-soil moisture content.*

Keywords. *Wind speed, Erosion, WEPS, Model equations, Evaluation, Sediment.*

The Wind Erosion Prediction System (WEPS) is a process-based, daily time-step model that simulates weather, field conditions, and wind erosion on crop lands (Hagen et al., 1995). The WEPS is modular in structure and includes a weather simulator and five submodels that simulate surface conditions: crop growth, residue decomposition, soil aggregate/crust status, hydrology, and management. When wind speed exceeds the threshold for erosion, the erosion submodel simulates erosion on a subhourly basis.

Development of a physically based model requires both development of the model equations and evaluation of the model.

In prior research, equations for various processes that occur during wind erosion were formulated and solved using finite difference methods (Hagen et al., 1995). However, those solutions imposed stringent requirements for automated grid generation and required significant computer time to converge. The objectives of the current study were to assemble the erosion process equations in a manner that permits analytic solutions, develop analytic solutions for a uniform surface, and evaluate these solutions using linear sensitivity tests.

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Unfortunately, fields often vary both temporally and spatially. However, by partitioning complex areas into a series of small, uniform areas and periodically updating the surface conditions, one may thereby encompass both the spatial and temporal variations in fields and still use the solutions in this report to predict wind erosion. Moreover, such an extension of this work is compatible with typical geographical information systems (Fotheringham and Rogerson, 1994).

Theory

Soil transport during wind erosion occurs in three modes (Chepil and Woodruff, 1963): creep-size aggregates (0.84-2.0 mm diameter) roll along the surface, saltation-size aggregates (0.10-0.84 mm diameter) hop over the surface, and suspension-size aggregates (<0.10 mm diameter) move above the surface in the turbulent flow. Obviously, as either wind speeds, turbulence or sediment loads change, the diameter of aggregates moving in the various modes also may change slightly (Pye, 1987).

In WEPS, we have assumed that the combined saltation/creep mode of transport has a distinct transport capacity for each surface, based on the surface roughness and wind speed. This assumption generally is supported by both field and wind tunnel measurements of the saltation/creep discharge (Greeley and Iversen, 1985). We also assumed that the suspension component does not reach a transport capacity on most eroding fields. Thus, separate equations were developed for saltation/creep and suspension discharge, because they respond differently to both the wind forces and sediment load (Gillette et al., 1998). Separating these erosion components also is useful, because they have different potential off-site impacts.

Wind erosion occurs over a wide range of surface conditions. To aid in delineating erosion rates among the various surfaces, we identified several individual erosion processes in WEPS (Hagen et al., 1995). These processes include direct entrainment (emission) of loose soil by wind and/or saltation impacts, abrasion of soil from clods/crust by saltation impacts, and breakage of saltation/creep-size aggregates to suspension size. These processes were selected for individual simulation, because they differ from one another by approximately an order of magnitude in their ability to supply new suspension or saltation/creep-size mass to the airstream in response to a saltation impact (Mirzamostafa et al., 1998). When the saltation/creep discharge exceeds transport capacity over a local area of the surface, trapping of saltation/creep also occurs. We also assumed that the coarse fraction of the suspension component will be deposited when moving over local areas that are not eroding.

Saltation/Creep Component

Based on conservation of mass in a control volume (fig. 1), a one-dimensional, quasi-steady-state equation for the physical processes involved in saltation/creep is:

$$\frac{dq}{dx} = G_{en} + G_{an} - Gss_{bk} - G_{tp} \qquad (1)$$

where (table 1)

- q = horizontal saltation/creep discharge (kg m^{-1} s^{-1})
- x = downwind distance from nonerodible boundary (m)
- G_{en} = vertical flux from emission of loose aggregates (kg m^{-2} s^{-1})
- G_{an} = vertical flux from abrasion of surface clods and crust (kg m^{-2} s^{-1})
- Gss_{bk} = vertical flux of suspension aggregates from breakage of saltation/creep aggregates (kg m^{-2} s^{-1})
- G_{tp} = vertical flux from trapping of saltation/creep aggregates (kg m^{-2} s^{-1})

Each of the vertical fluxes represents either source or sink terms in the control volume and can be estimated by the equations that follow.

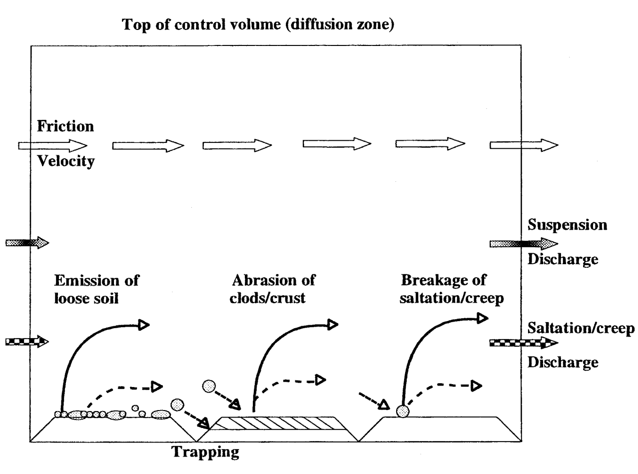

Figure 1–Schematic of the control volume of the WEPS EROSION submodel with bare soil. (Dashed lines denote saltation/creep and solid lines denote suspension component.)

Table 1. List of symbols, definitions, and units

Symbols	Definitions	Units
C_{ani}	Coefficient of abrasion	m^{-1}
C_{bk}	Coefficient of breakage of saltation/creep	m^{-1}
C_{dp}	Coefficient of deposition of suspension-size	m^{-1}
C_{en}	Coefficient of emission	m^{-1}
C_i	Coefficient of plant interception	m^{-1}
C_m	Coefficient of mixing at soil surface	m^{-1}
C_s	Saltation transport parameter	kg m^{-4} s^2
C_t	Coefficient of surface trapping	m^{-1}
F_{ani}	Mass fraction of saltation impacting clods and crust	
G_{an}	Vertical flux from abrasion of surface clods and crust	kg m^{-2} s^{-1}
G_{en}	Vertical flux from emission of loose aggregates	kg m^{-2} s^{-1}
G_{tp}	Vertical flux from trapping of saltation/creep aggregates	kg m^{-2} s^{-1}
Gss_{an}	Vertical flux of suspension-size aggregates created by abrasion of clods and crust	kg m^{-2} s^{-1}
Gss_{bk}	Vertical flux of suspension-size aggregates created by breakage of saltation/creep	kg m^{-2} s^{-1}
Gss_{dp}	Vertical flux (deposition) of suspension-size aggregates above a non-eroding surface	kg m^{-2} s^{-1}
Gss_{en}	Vertical emission flux of loose, suspension-size aggregates	kg m^{-2} s-1
I_1,I_2	Least and greatest input values, respectively, used in the sensitivity analysis	
I_{12}	The average if I_1 and I_2	
O_1,O_2	Output values for I_1 and I_2, respectively, in sensitivity analysis	
O_{12}	The average of O_1 and O_2	
q	Horizontal saltation/creep discharge	kg m^{-1} s^{-1}
q_{cp}	Transport capacity of the surface, when 40% or more is armored	kg m^{-1} s^{-1}
q_{en}	Transport capacity of saltation/creep	kg m^{-1} s^{-1}
q_s	Horizontal discharge of primary (non-breakable) sand particles	kg m^{-1} s^{-1}
qss	Horizontal discharge of suspension component	kg m^{-1} s^{-1}
qss_o	Maximum value of qss entering deposition region	kg m^{-1} s^{-1}
Sfer	Soil mass fraction of loose, erodible-size, less than about 2.0 mm diameter at soil surface	
Sfss	Soil mass fraction of loose, suspension-size less than about 0.1 mm diameter at soil surface	
$SFss_{an}$	Mass fraction of suspension-size (<0.10 mm) of total (<2.0 mm diameter) created by abrasion	
$SFss_{en}$	Mass fraction of suspension-size (<0.10 mm) emitted from loose aggregates (<2.0 mm diam.)	
U_*	Friction velocity	m s^{-1}
U_{*t}	Dynamic threshold friction velocity	m s^{-1}
x	Downwind distance from nonerodible boundary	m

The net emission source term for loose aggregates is:

$$G_{en} = \left(1 - SFss_{en}\right) C_{en} \left(q_{en} - q\right) \qquad (2)$$

where

- $SFss_{en}$ = mass fraction of suspension-size (<0.10 mm) among loose aggregates (<2.0 mm diameter)
- C_{en} = coefficient of emission (m^{-1})
- q_{en} = transport capacity (kg m^{-1} s^{-1})

Stout (1990) derived the general form of equation 2 and applied it to describe total mass flux at a given height from the surface. However, subsequent research (Hagen, 1991) showed that the abrasion flux from immobile clods and crust was controlled by other factors. Hence, in this report, equation 2 applies only to the loose, mobile components of the soil. A typical value for C_{en} on a loose, bare field is about 0.06 m^{-1}, and values for other conditions have been reported (Hagen et al., 1995).

Many transport capacity equations for saltation/creep have been reported (Greeley and Iversen, 1985). One of the most frequently used was developed by Lettau and Lettau (1978) and can be expressed as:

$$q_{en} = C_s U_*^2 \left(U_* - U_{*t}\right) \qquad (3)$$

where

C_s = the saltation transport parameter (kg m^{-4} s^2), with a typical value of about 0.3 or more for surfaces armored with stones

U_* = friction velocity (m s^{-1})

U_{*t} = dynamic threshold friction velocity (m s^{-1})

The suspension-size aggregates are assumed to be mixed intimately with the saltation/creep-size and emitted with them. Although the suspension-size aggregates absorb part of the aerodynamic and impact energy (represented by the emission coefficient) in order to rise from the surface, they do not contribute toward reaching the transport capacity of saltation/creep. Hence, they are subtracted from the total emission of loose aggregates in equation 2.

The net source term for entrainment of saltation/creep aggregates abraded from immobile clods and crust by impacting saltation/creep is:

$$G_{an} = \left(1 - SFss_{en}\right)\left[\sum_{i=1}^{2}\left(F_{ani}C_{ani}\right)q\right]\left(\frac{q_{en} - q}{q_{en}}\right) \qquad (4)$$

where

$SFss_{an}$ = mass fraction of suspension-size from abrasion

F_{ani} = mass fraction saltation impacting clods and crust

C_{ani} = coefficient of abrasion (m^{-1})

An index of two was used in equation 4 because, in general, only two targets, exposed clods and crust, must be considered. Other targets, such as residue and rocks, have a C_{ani} near zero. The first term, $(1 - Sfss_{an})$, is the fraction of abraded mass that is of saltation/creep-size. Values of $SFss_{an}$ for some Kansas soils have been measured and ranged from 0.14 to 0.27, depending upon soil texture (Mirzamostafa, 1996). The middle, bracketed term on the right-hand side of equation 4 represents the total soil abraded from clods and crust, as confirmed by wind tunnel experiments (Hagen, 1991). Values for C_{ani} also have been measured for a range of soils and related to their crushing energy (Hagen et al., 1992). The final term in equation 4 is the mass fraction entrained in the air stream. Note that the entrainment rate of this newly created saltation/creep is assumed to be similar to that of loose, saltation/creep-size aggregates already present on the surface, and that the entrainment approaches zero at transport capacity.

A sink for the saltation/creep discharge occurs when these aggregates are broken into suspension-size and carried away by convection and diffusion (Mirzamostafa et al., 1998). This effect is simulated as:

$$Gss_{bk} = C_{bk}\left(q - q_s\right) \qquad (5)$$

where

C_{bk} = coefficient of breakage (m^{-1})

q_s = discharge of primary (non-breakable) sand particles (kg m^{-1} s^{-1})

The saltation/creep aggregates are more stable than the surface clods and crust, so measured abrasion coefficients average about nine times more than the breakage coefficients on the same soils (Mirzamostafa, 1996). The wind tunnel experiments also demonstrated that the breakage coefficient remained constant during breakdown of the aggregates to primary particles. The means and variances of these coefficients are related to soil texture. Given q, values for q_s can be estimated directly from soil sand content.

Another sink term is the removal of saltation/creep from the air stream by trapping mechanisms (Hagen and Armbrust, 1992). In WEPS, surface trapping and plant interception are simulated as:

$$G_{tp} = C_t\left(1 - \frac{q_{cp}}{q_{en}}\right)q + C_i q\,, \qquad q_{en} \geq q_{cp} \qquad (6)$$

where

C_t = coefficient of surface trapping (m^{-1})

C_i = coefficient of plant interception (m^{-1})

q_{cp} = transport capacity of the surface, when 40% or more is armored (kg m^{-1} s^{-1})

When erosive winds cross rough surfaces, such as tillage ridges, that are highly erodible, large amounts of soil are entrained, but a portion of the entrained saltation/creep is often trapped in succeeding downwind furrows. This phenomenon results in a local rearrangement of the surface and reduces net removal of the entrained soil. Our conventionally defined transport capacity, q_{en}, is based on the threshold velocity where erosion begins. But, when trapping of saltation/creep occurs on rough surfaces, one may hypothesize that q_{en} has been exceeded, and that the true transport capacity of the surface is some value, q_{cp}, that is less than q_{en}. However, q_{en} still appears to be the appropriate limiting value to drive the emission process, because more soil is emitted than can be transported from the local area.

In WEPS, the first term on the right-hand side of equation 6 simulates trapping of saltation/creep by surface roughness. The true transport capacity of the surface, q_{cp}, is based on the threshold friction velocity needed to remove saltation/creep from the furrows. It is calculated using equation 3 for a given roughness at the level of clod and crust cover of the surface but with a minimum set at 40% of the surface armored. Under this condition, wind tunnel observations show that loose material is removed, but minimal local trapping of saltation/creep occurs.

The second term of equation 6 represents interception of saltation/creep by standing plant stalks or other near-surface plant parts. This term arises, because for a given soil surface friction velocity, more transport occurs without than with stalks. This term also is used to assign a higher transport capacity for wind direction parallel to crop rows than for wind direction perpendicular to rows. For saltation normal to the row direction, interception can reduce transport capacity 5 to 10%. Comparisons to measured data have been reported previously (Hagen and Armbrust, 1994).

Solution for Saltation/Creep Discharge

When the source and sink terms are collected on the variable q, equation 1 for saltation/creep can be written in the form:

$$\frac{dq}{dx} = A + B\ q - C\,q^2 \tag{7}$$

where

$$A = \left(1 - SFss_{en}\right) C_{en} q_{en} \tag{8}$$

$$B = \left(1 - SFss_{an}\right) \sum \left(F_{ani} C_{ani}\right) - \left(1 - SFss_{en}\right) C_{en} - C_{bk} - C_i - C_t \left(1 - \frac{q_{cp}}{q_{en}}\right) \tag{9}$$

and

$$C = \left(1 - SFss_{an}\right) \sum \left(F_{ani} C_{ani}\right) \left(\frac{1}{q_{en}}\right) \tag{10}$$

Integrating equation 7 along the wind direction, from x1 to x2 and q1 to q2, gives the solution:

$$q2 = \frac{S}{2C} \left\{ -\tan h \left[\left(\frac{S}{2}\right) \left(x1 - x2\right) + 0.5\ \ln \left(\frac{1 + p}{1 - p}\right) \right] + \frac{B}{S} \right\} \tag{11}$$

where

$$S = \left(4AC + B^2\right)^{0.5} \tag{12}$$

and

$$p = \frac{-\,2C\left(q1\right) + B}{S} \tag{13}$$

Suspension Component

Based on conservation of mass in a control volume that extends to the top of the dust cloud, a one-dimensional, quasi steady-state equation for the physical processes generating the suspension component is:

$$\frac{dqss}{dx} = Gss_{en} + Gss_{an} + Gss_{bk} \qquad U_* > U_{*t} \tag{14}$$

or

$$\frac{dqss}{dx} = Gss_{dp} \qquad U_* < U_{*t} \tag{15}$$

where

qss = horizontal suspension component discharge (kg m^{-1} s^{-1})

Gss_{en} = vertical emission flux of loose, suspension-size aggregates (kg m^{-2} s^{-1})

Gss_{an} = vertical flux of suspension-size aggregates created by abrasion of clods and crust (kg m^{-2} s^{-1})

Gss_{bk} = vertical flux of suspension-size aggregates created by breakage of saltation/creep-size aggregates (kg m^{-2} s^{-1})

Gss_{dp} = vertical flux (deposition) of suspension-size aggregates above a non-eroding surface (kg m^{-2} s^{-1})

The source and sink terms for the suspension component are simulated by the equations that follow.

For direct emission of loose, suspension-size material by 'splash' impacts and aerodynamic forces:

$$Gss_{en} = SFss_{en}\, C_{en} \left(q_{en} - q\right) + C_m q \tag{16}$$

where

C_m = a coefficient of mixing, value about (0.0001 $SFss_{en}$) (m^{-1})

Below transport capacity, the driving force causing the emission flux of suspension-size soil is assumed to be similar to that in equation 2 causing the saltation/creep emission flux. This assumption is supported by wind tunnel measurements that show a mixture of suspension-size aggregates and a mixture of saltation-size have about the same threshold velocities (Chepil, 1951).

However, two additional assumptions are inherent in equation 16. The first is that the loose components of saltation/creep and suspension-size aggregates occur as a uniform mixture in the field. As a consequence, during simple net emission, the suspension fraction emitted with the saltation/creep remains the same as it was in the soil. Hence, the suspension fraction can be estimated as:

$$SFss_{en} = \frac{SFss}{SFer} \tag{17}$$

where

SFss = soil mass fraction of loose, suspension-size less than about 0.1 mm

SFer = soil mass fraction of loose, erodible-size, less than about 2.0 mm

The second assumption in equation 16 is that an additional small amount of suspension-size aggregates that are disturbed by the saltation impacts also are entrained, because transport capacity for the suspension component generally is not limiting. The result of this process is gradual depletion of the loose, suspension-size aggregates at the surface. However, when net emission of suspension-size exceeds net emission of saltation/creep-size aggregates, the latter soon dominate the surface area and absorb the impacts, so the process tends to be self-limiting.

For suspension flux created by abrasion of clods and crust:

$$Gss_{an} = SFss_{an} \sum_{i=1}^{2} \left(F_{ani}\, C_{ani}\right) q \tag{18}$$

Additional discussion and measurements of this source term were reported by Mirzamostafa et al. (1998).

For the source of suspension flux created by breakage of saltation/creep aggregates, the term is the same as the sink term in the saltation/creep equation and simulated as:

$$Gss_{bk} = C_{bk}\left(q - q_s\right) \qquad (19)$$

Breakage from impact on immovable targets is assumed to come only from the impacting saltation/creep alone. Breakage coefficients for saltation-size aggregates have been measured in the wind tunnel (Mizamostafa et al., 1998). But the breakage component from impacts on other saltation/creep is assumed to come from both the impacting and target aggregates. Breakage from impact on a movable target is less likely than breakage from impact on immovable targets. However, these assumptions need further experimental verification.

Finally, the sink term for trapping of suspension flux occurs when the suspension discharge passes over grid cells without active saltation to maintain the suspension flux from the surface. Typically, this implies the presence of a vegetated, water, or rough armored surface. The largest suspension particles, 0.05 to 0.10 mm, comprise roughly half the mass of the suspension discharge (Chepil, 1957; Zobeck and Fryrear, 1986). Through diffusion and settling, they move rapidly toward noneroding surfaces in the simulation region, which serve as sinks. The process is simulated as:

$$Gss_{dp} = C_{dp}\left(qss - 0.5\ qss_0\right) \qquad qss > 0.5\ qss_0 \quad (20)$$

where

qss_o = maximum value of qss entering deposition region (kg m^{-1} s^{-1})

C_{dp} = coefficient of deposition of suspension-size (m^{-1})

The maximum value of C_{dp} is about 0.02, but less for smooth surfaces or large upwind areas that produce high dust clouds thus, moving a large portion of the soil away from the deposition surface.

Simulation equations for particles with aerodynamic diameters less than 10 µm (PM-10 component) of the suspended soil also have been developed along with equation parameters for some Kansas soils utilizing similar suspension component equations (Hagen et al., 1996).

Solution for Suspension Discharge

When the source terms are collected, equation 14 can be written in the form:

$$\frac{dqss}{dx} = F + G\ q \qquad (21)$$

where

$$F = SFss_{en}C_{en}q_{en} \qquad (22)$$

and

$$G = -\ SFss_{en}C_{en} + SFss_{an}\sum\left(F_{ani}\,C_{ani}\right) + C_{bk} \quad (23)$$

Substituting the general solution of equation 7, q(x), into equation 21 and integrating along the wind direction from x1 to x2 and qss1 to qss2 give the following equation for suspension discharge:

$$qss2 = qss1 + \frac{1}{2C}\Big\{ \left(+GS + GB + 2FC\right)\left(x2 - x1\right)$$
$$+ 2G\left[\ln\left[\exp\left(S\left(-x2\right)\right)\left(B + S\right) - B + S\right]\right.$$
$$\left.- \ln\left[\exp\left(S\left(-x1\right)\right)\left(B + S\right) - B + S\right]\right]\Big\} \qquad (24)$$

In regions of deposition of suspension component, integration of equation 20 from location x1, with discharge qss1, gives the following for suspension discharge, qss2, at downwind location x2:

$$qss2 = \left(0.5\ qss_1\right)\left\{1 + \exp\left[-C_{dp}\left(x2 - x1\right)\right]\right\}$$
$$x2 > x1 \qquad (25)$$

Sensitivity Analyses

Methods

A linear sensitivity model was selected for initial sensitivity testing of the WEPS erosion submodel. A similar analysis has been reported for the WEPP water erosion model (Nearing et al., 1990). The sensitivity parameter, SS, is given by:

$$SS = \frac{\dfrac{O_2 - O_1}{O_{12}}}{\dfrac{I_2 - I_1}{I_{12}}} \qquad (26)$$

where

I_1 and I_2 = the least and greatest values of input used, respectively

I_{12} = the average of I_1 and I_2

O_1 and O_2 = the output values for the two input values

O_{12} = the average of O_1 and O_2

The parameter SS represents the ratio of a relative normalized change in output to a normalized change in input that allows a comparison of sensitivities of input parameters which have different orders of magnitude. For many of the input parameters in WEPS, the response is nonlinear. Hence, the value of SS will be a function of the range of the input parameters. Additional limitations on the linear sensitivity analyses have been discussed by McCuen and Snyder (1983).

In the current analyses, relatively wide ranges of the input parameters were selected for testing. Generally, for each test, one parameter was varied and the other parameters were set at fixed, base values. Using this procedure, SS values were calculated for a number of parameters that affect the response of the WEPS erosion submodel.

Results of Sensitivity Analyses

The parameters tested, their base values, the input values, and the calculated SS values are listed in table 2. To adequately reflect the physical system, varying two parameters simultaneously was occasionally necessary. For example, a plant height had to be assigned when a leaf area index was assigned.

Simulation results using the base values in table 2 that represent a crusted, sandy soil are illustrated in figure 2. The discharge has been normalized by the saltation/creep transport capacity. The transport capacity is approached about 100 m downwind, and only the suspension component causes total erosion to increase beyond that point.

Results from simulating a crusted, medium-texture soil are illustrated in figure 3. Here, the approach toward transport capacity is much slower than on the sandy soil, and continuous downwind breakage of the saltation/creep prevents the system from reaching the potential transport capacity of the surface. The suspension component also increases at a faster rate than in the previous example with sandy soil. In both examples, the suspension discharge will exceed the saltation/creep discharge on long fields.

Table 2. Erosion model parameters, constant (base) values used in tests, input values for test parameter, and calculated sensitivity values (SS)

Parameter	Units	Base	Input 1	Input 2	(SS)	Rank
Dry clod/crust stability	Ln (J/kg)	3.5	1.0	5.0	–1.04	3
Aggregates:						
Fraction <2.0 mm		0.8	0.3	1.0	0.03	15
fraction <0.84 mm			0.3	0.7		
Fraction <0.84 mm		0.7	0.05	1.0	0.78	9
fraction <2.0 mm			0.8	1.0		
Fraction <0.10 mm		0.15	0.05	0.5	0.39	13
Random roughness	mm	2.0	1.0	50.0	–0.77	10
Ridge height	mm	0.0	0.0	250.0	–1.00	4
ridge spacing		0.0	0.0	1000.0		
Ridge spacing	mm	0.0	400.0	1600.0	0.22	14
ridge height	mm		100.0	100.0		
Soil volume fraction rock		0.0	0.0	0.8	–0.52	11
Soil wetness	Wc/Wc15*	0.0	0.2	1.0	–1.50	2
Biomass flat cover fraction		0.0	0.0	0.6	–0.87	7
Leaf area index		0.0	0.0	0.2	–1.00	5
biomass height	mm		0.0	100.0		
Silhouette area index		0.0	0.00	0.02	–0.91	6
biomass height	mm		0.0	100.0		
Biomass height	mm	0.0	100.0	300.0	0.39	12
silhouette area index			0.02	0.02		
Wind speed at 10 m	m s^{-1}	12.0	8.0	20.0	2.18	1
Field length	m	800.0	100.0	1600.0	–0.80	8

* Wc and Wc15 are surface soil water content and 1.5 Mpa soil water content, respectively.

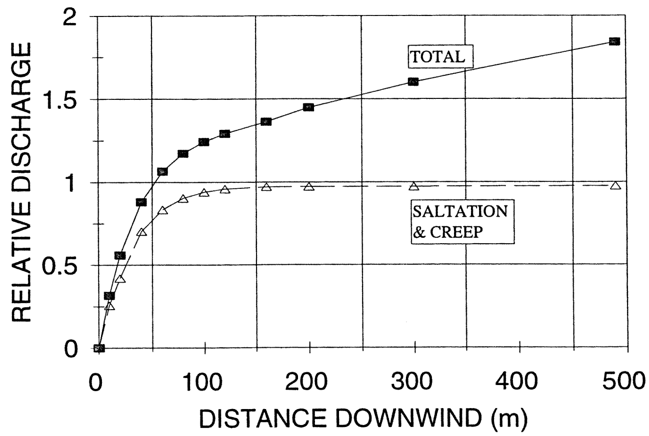

Figure 2–Relative horizontal discharge [(kg m^{-1})/(kg m^{-1})] of saltation/creep and total, which includes suspension discharge on crusted, sandy soil with base conditions shown in table 2.

As shown in table 2, erosion was most sensitive to wind speed. This result is not surprising, because erosion varies roughly with the cube of the wind speed at values above the erosion threshold. However, it does emphasize the necessity to use high quality wind speed data when simulating wind erosion or validating erosion models with measured data.

Erosion also was sensitive to soil surface wetness. Because as the soil surface wetness increases from dry toward the wilting-point moisture content, the wind speed threshold for erosion rises sharply. Because of this high sensitivity to soil moisture, the hydrology submodel of WEPS was designed to specifically simulate the surface soil moisture in the upper 1 mm of soil (Durar et al., 1995). However, the weather generator simulates precipitation and wind speed as variables that are independent from each other. Future research is needed to determine the conditions where these variables are not independent and to incorporate their dependence into weather generators.

The aggregate size distribution at the surface affects the erosion amount, particularly the fraction less than 0.84 mm. This fraction typically has been emphasized in wind erosion models, such as the wind erosion equation (Woodruff and Siddoway, 1965). However, the suspension

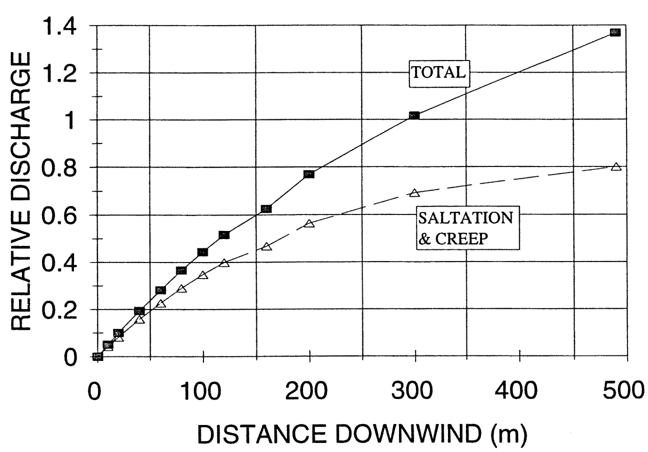

Figure 3–Relative horizontal discharge [(kg m^{-1})/(kg m^{-1})] of saltation/creep and total, which includes suspension discharge on a crusted, medium texture soil.

component fraction less than 0.1 mm partly determines the suspension component of erosion, and its importance as an erodibility indicator increases as field length increases.

Erosion also is sensitive to the dry stability of clods and crusts, which are typically present on cropland fields. The abrasion rate of these elements controls the generation of new saltation and suspension-size aggregates. Their stability is also linked directly in the model to the rate of breakage of saltating aggregates to suspension size.

Several of the parameters, such as soil fraction less than 2.0 mm diameter, ridge spacing, and biomass height, had relatively low sensitivity values. Although biomass height has only small effects, changes in either leaf area index or horizontal silhouette (stem) area index cause significant changes in the surface threshold wind speed and the accompanying wind erosion (Hagen and Armbrust, 1994). Their impact on erosion also is reflected in their sensitivity values.

Summary and Conclusions

Wind erosion occurs over a wide range of surface conditions. However, most of these conditions can be simulated by considering that the transport of eroding soil occurs in both saltation/creep and suspension components in various proportions. The relative proportions depend upon both the surface conditions and downwind distance. Generally, the suspension discharge increases downwind without bound; whereas, the saltation/creep discharge reaches a transport capacity that depends on wind speed and surface roughness. Hence, separation of the transport modes in simulation modeling of wind erosion is needed to estimate both the magnitude of soil loss and its off-site impacts such as nearby deposition or deterioration of air quality.

The surface conditions also dictate the relative magnitude of the various wind erosion processes that occur. Based on the principle of conservation of mass, a quasi-steady state equation was derived for the saltation/creep discharge. In this equation, the major processes involved two sources (entrainment of loose material by wind and saltation impacts and entrainment of material abraded from exposed clods and crust) and three sinks (breakage of saltation/creep aggregates to suspension-size, trapping of saltation/creep when local transport capacity is exceeded, and interception by plant stalks).

A second equation was developed for the horizontal discharge of the suspension-size aggregates considering the major processes of direct entrainment (emission) of loose material, abrasion from exposed clods and crust, and breakage of saltation/creep to form suspension-size aggregates. A downward flux to the surface of the coarse fractions of the suspension component also was simulated to occur in regions of the field where erosion from the surface was not present.

For uniform field conditions, analytic solutions for both the saltation/creep and suspension discharge equations were developed. Together, these analytic solutions provide a rapid means of estimating the components of erosion soil loss/deposition over uniform sections of a field.

Example solutions and linear sensitivity tests of the erosion equations were carried out for a range of field surface conditions and wind speeds. Erosion loss was most sensitive to wind speed and soil moisture and least sensitive to surface fraction aggregates less than 2.0 mm, ridge spacing, and biomass height. The field surface conditions which control wind erosion are all temporal properties of the surface and must be predicted by users or other submodels of WEPS.

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