Wind Erosion Prediction System: Erosion Submodel

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INTRODUCTION

Developing simulation models of wind erosion presents a challenging problem. The wind erosion equation (Woodruff and Siddoway, 1965) is the most widely used but is largely empirical. The empirical nature makes it difficult to adapt to areas outside the Great Plains of the U.S., where it was developed. Hence, considerable effort has been expended to develop other models.

Recently developed models show a trend toward including more physically-based equations. However, significant differences exist among these models in their representation of wind erosion processes. For example, the Revised Wind Erosion Equation (RWEQ) (Fryrear et al., 1998) proposes that total horizontal discharge of soil along the wind direction reaches a maximum transport capacity at a relatively short distance (X_{max}) downwind from a field boundary. Beyond X_{max} no net soil loss is assumed to occur. Another major assumption in RWEQ is that threshold wind speed at which erosion begins is 5 ms^{-1} at a 2 m height for all surfaces. The Texas Erosion Analysis Model (TEAM) (Gregory et al., 1994) also assumes that horizontal discharge reaches a maximum at some X_{max}, but assumes that a variable threshold friction velocity initiates erosion. The structure of these two models seems best suited for predictions of erosion on small fields with nonerodible boundaries where saltation/creep discharge dominates the soil loss.

In contrast, other models are concerned mainly with dust generation. These models assume the saltation/creep discharge to be at transport capacity over the entire simulation region. They then multiply the discharge by a dimensional coefficient to arrive at a vertical dust flux. Examples of the latter models include those of Gillette and Passi (1988), Shao et al. (1996), and Marticornea and Bergametti (1995). Because these models ignore field boundary effects, they seem best suited for use on large source areas where dust generation dominates the soil loss.

Among the wind erosion models, the Wind Erosion Prediction System (WEPS) (Hagen et al., 1995) is unique in that it provides submodels which simulate stochastic variations in the daily weather and also simulate surface conditions that respond to the generated weather. The erosion submodel is one of seven major submodels in WEPS.

In developing simulation equations for the erosion submodel of WEPS, the goals were: a) to provide a firm physical basis by including the major wind erosion processes in the equations, and thus, make them applicable for a wide range of conditions; b) to separate the saltation/creep from suspension components to allow improved evaluation of on-site and off-site erosion impacts; and c) to define the individual processes in such a way that they could be measured directly in wind tunnels and instrumented field sites to allow parameter development.

The objective of this report is to provide a brief overview of the erosion submodel of WEPS with emphasis on the saltation/creep and suspension prediction equations used in WEPS. For ease of understanding, the equations are presented in their one-dimensional, quasi-steady state form for a uniform surface. Additional papers in development discuss the analytic solutions for these equations and compare predictions over a range of surface conditions. Results comparing predictions from the erosion submodel and measured erosion obtained from a series of daily storms in field experiments are also in preparation.

EROSION SUBMODEL TASKS

The erosion submodel calculates erosion over a user-defined simulation region that can be about 260 ha. but whose size is limited mainly by computer resources of the user. To account for spatial variability in the simulation region, the equations are applied to individual uniform, small, grid cells. Surface conditions can vary among the grid cells. Additional equations are used to update the surface conditions in response to erosion. The steps in the simulation procedure are as follows: the erosion submodel determines static threshold friction velocity at which erosion begins for each cell. The threshold is calculated based on surface conditions of: random and oriented roughness; flat biomass, crust, and rock cover; cover of loose, erodible aggregates on the crust; aggregate size distribution and density of uncrusted surface; and surface wetness.

Soil loss and deposition are calculated for subhourly periods when friction velocity exceeds the static friction velocity threshold. The wind simulator currently provides a single wind direction for each day. To aid in evaluation of off-site impacts, the soil loss is subdivided into components and reported as saltation/creep, total suspension, and fine particulate matter (PM-10) for each grid cell. Additional details about the erosion submodel tasks are discussed in the WEPS technical documentation (Hagen et al., 1995)

THEORY

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:

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

where

q = saltation/creep discharge (kgm^{-1}s^{-1}),
x = downwind distance from nonerodible boundary (m),
G_{en} = vertical flux from emission of loose aggregates (kgm^{-2}s^{-1}),
G_{an} = vertical flux from abrasion of clods and crust (kgm^{-2}s^{-1}),
G_{ss} = vertical flux from breakage of saltation/creep (kgm^{-2}s^{-1}),
G_{tp} = vertical flux from trapping of saltation/creep (kgm^{-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:

The net emission source term for loose aggregates is

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

where

$SFss_{en}$ = fraction of suspension-size among loose aggregates (i.e., < 0.84 mm diameter),

C_{en} = coefficient of emission (m^{-1}), and

q_{en} = transport capacity based on dynamic threshold friction vvelocity where emission begins ($kgm^{-1}s^{-1}$).

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).

The transport capacity for saltation/creep (Greeley and Iversen, 1985) can be expressed as

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

where

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

U_* = friction velocity (ms^{-1}), and

U_{*t} = dynamic threshold friction velocity (ms^{-1}).

In Eq. 2, the suspension-size aggregates are assumed to be mixed intimately with the saltation/creep-size and emitted with them. Although the suspension-size particles 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.

The net source term for loss from immobile clods and crust by abrasion from impacting saltation/creep is

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

where

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

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

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

The middle, bracketed term on the right-hand-side in Eq. 3 represents the total soil abraded from clods and crust, as confirmed by wind tunnel experiments (Hagen, 1991). The first term is the fraction that is of saltation/creep-size, and the final term is the 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. Values for C_{ani} have been measured for a range of soils and related to their crushing energy (Hagen et al., 1992). In general, only two targets, exposed clods and crust, must be considered, because other targets, such as residue and rocks, have a C_{ani} near zero. Values of $SFss_{an}$ for some Kansas soils also have been measured and ranged from 0.14 to 0.27, depending upon soil texture (Mirzamostafa, 1996).

A sink for the saltation/creep discharge occurs when these aggregates are broken to suspension-size and carried away by convection and diffusion. This effect is simulated as

$$G_{ss} = C_{bk} \, (q - q_s) \tag{5}$$

where

C_{bk} = coefficient of breakage (m^{-1}), and
q_s = discharge of primary sand particles ($kgm^{-1}s^{-1}$).

The saltation/creep aggregates are more stable than the clods and crust, so measured abrasion coefficients average about 9 times 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 mean and variance of these coefficients are related to soil texture. Given q, values for q_s can be estimated directly from soil sand content.

Another sink is the removal of saltation/creep from the air stream by trapping mechanisms. In WEPS, two of these are simulated as

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

where

C_t = coefficient of trapping (m^{-1}),
C_i = coefficient of interception (m^{-1}), and
q_{cp} = transport capacity of the surface, when 40 percent or more is armored ($kgm^{-1}s^{-1}$).

The first term on the right-hand-side of Eq. 6 represents trapping of excess saltation/creep by surface roughness. For example, when the tops of tillage ridges are loose and erodible, excess saltation/creep is emitted. But then, the excess is trapped in succeeding downwind furrows, because the true transport capacity of the surface is exceeded. The result is degradation of the ridge tops and filling of the furrows, which is a common phenomenon observed during erosion of sandy soils. The true transport capacity of a surface is based on the threshold friction velocity needed to remove saltation/creep from the furrows. It is calculated using Eq. 3 for a given roughness at the level of clod and crust cover of the surface but with a minimum set at 40 percent of the surface armored. When at least 40 percent of the surface is armored, wind tunnel observations show that loose material is removed, but there is minimal local arrangement of the surface.

The second term of Eq. 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.
In WEPS, this term is used to assign a higher transport capacity for wind directions parallel to crop rows than to transport capacity for wind direction perpendicular to rows. For saltation normal to the

row direction, interception can reduce transport capacity 5 to 10 percent. Comparisons to measured data have been reported previously (Hagen and Armbrust, 1994).

Suspension Component

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

$$\frac{dqss}{dx} = Gss_{en} + Gss_{an} + Gss_{bk} \qquad (7)$$

where

qss = horizontal suspension component discharge ($kgm^{-1}s^{-1}$),
Gss_{en} = vertical emission flux of loose, suspension-size aggregates ($kgm^{-2}s^{-1}$),
Gss_{an} = vertical flux of suspension-size aggregates created by abrasion of clods and crust ($kgm^{-2}s^{-1}$), and
Gss_{bk} = vertical flux of suspension-size aggregates created by breakage of saltation/creep-size aggregates ($kgm^{-2}s^{-1}$)

Over portions of the simulation region where saltation occurs, trapping of suspension is assumed to be zero. However, when all the other suspension source terms are zero, i.e., no saltation, then trapping of the coarse fraction of the suspension component is simulated as

$$\frac{dqss}{dx} = -Gss_{tp} \qquad (8)$$

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

$$Gss_{en} = SFss_{en}\, C_{en}\, (q_{en} - q) + C_m\, q \qquad (9)$$

where

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

Two assumptions are inherent in Eq. 9. 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

$$SFss_{en} = \frac{SFss}{SFer} \qquad \textbf{(10)}$$

where

SFss = soil fraction of loose, suspension-size less than about 0.1 mm, and
SFer = soil fraction of loose, erodible-size, less than about 0.84 mm.

The second assumption in Eq. 9 is that an additional small amount suspension-size aggregates that are disturbed by the saltation impacts also are entrained, because transport capacity for this 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, 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

$$Gss_{an} = SFss_{an} \sum_{i=1}^{2} (F_{ani} \; C_{ani}) q \qquad \textbf{(11)}$$

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

$$Gss_{bk} = C_{bk} \; (q - q_s) \qquad \textbf{(12)}$$

In WEPS, breakage from impact on immovable targets is assumed to come only from the impacting saltation/creep alone. But the breakage component from impacts on other saltation/creep is assumed to come from both the impacting and target aggregates. These assumptions was made because breakage from impact on a movable target is less likely than breakage from impact on immovable targets. However, they 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 and Woodruff, 1958; 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

$$Gss_{dp} = C_{tp}(qss - 0.5 \; qss_o) \qquad \textbf{(13)}$$

where

qss_o = maximum value of qss entering deposition region ($kgm_{-1}s^{-1}$), and

C_{dp} = coefficient of deposition (m^{-1}), maximum value about 0.02, but less for smooth surfaces or large upwind areas that produce thick diffusion zones.

Simulation equations for the PM-10 component of suspended soil also have been developed along with equation parameters for some Kansas soils (Hagen et al., 1996).

DISCUSSION

Over time, the surface of the same soil can display a wide range of conditions. In WEPS, two erodible, bare surface conditions are considered: A loose, aggregated surface and a crusted surface with some loose, erodible aggregates on the crust. A crusted surface without loose aggregates is considered stable, unless abrader is coming in from upwind cells. Any cell can be composed of areal fractions of the two basic surface conditions. These split surfaces are often created by management activities, such as cultivation of a portion of a crusted surface.

The choice of processes to apply to these surface conditions (represented in the theoretical equations) is based mainly on the magnitude of response from the various soil components to saltation impacts. For example, on a typical soil an impact on loose, erodible material would supply 5 to 10 times more new saltation material available for entrainment than a similar impact on clods. In contrast, the breakage rate of saltation/creep upon impact is only about 11 percent of the abrasion rate of clods for the same soil. Thus, the responses to impacts among these three erosion processes differ by roughly an order of magnitude.

The condition of the soil surface dictates which processes will be dominant. On a sandy, loose surface, the solution to Eq. 2 alone adequately simulates the saltation/creep field data (Stout, 1990). However, when clods and crust dominate the surface, their abrasion coefficients largely determine the surface response to erosive winds, so abrasion effects must be included.

During wind erosion, breakage of saltation/creep aggregates occurs over the entire surface. These aggregates typically are then replaced by other saltation/creep aggregates entrained either from the initial loose material or those newly created by abrasion. Inclusion of the breakage term in the equations produces interesting results. First, it implies that to sustain continual entrainment of additional saltation/creep aggregates, transport capacity for saltation/creep is not achieved, even on long fields. Second, it implies that a net loss of saltation/creep aggregates occurs over the entire field, because they are being entrained into the flow to replace the breakage. Both of these effects generally have been ignored in simple, physically-based erosion models.

Finally, large field soil losses accompanied by only small accumulations in road ditches or other nearby saltation/creep traps areas are frequently observed. The WEPS theoretical equations predict that this phenomenon occurs when both the fraction of loose suspension-size material in the soil and the saltation/creep breakage coefficient are large.

Several of the coefficients in the saltation/creep and suspension component equations are temporal soil or plant properties. These properties are predicted on a daily time-step by other sections of WEPS, such as the management, soil, crop growth, or decomposition submodels. For temporal soil properties, such as abrasion coefficients, a typical procedure is to determine the mean and variance of the property for each soil based on intrinsic soil properties. The soil submodel then is used to simulate the abrasion coefficients within a range of two standard deviations about the predicted mean in response to the effects of weather.

SUMMARY AND CONCLUSIONS

An overview of the tasks of the erosion submodel of the Wind Erosion Prediction System (WEPS) is presented. These tasks begin with calculation of surface threshold velocities and end with periodic updates in surface conditions caused by the soil loss and deposition that occur during erosion.

Based on the principle of conservation of mass, one-dimensional, quasi-steady state, wind erosion equations for a uniform surface were developed. In the first equation, the major processes involved in saltation/creep creation and transport were simulated. These processes include: the vertical flux of loose, saltation/creep aggregates emitted from the surface; the vertical flux created by abrasion of immobile clods and crust; the breakage of saltation/creep aggregates to create one component of the vertical flux of suspension-size aggregates; downward vertical flux created by trapping entrained saltation/creep aggregates when transport capacity is exceeded during erosion of highly erodible roughness elements; and downward vertical flux created by the interception of saltation/creep by plant stalks.

An equation to simulate the major process involved in creation and transport of suspension component also was developed. These processes include: vertical flux from loose, erodible soil; vertical flux created by abrasion of clods and crusts; and vertical flux created by breakage of saltation/creep-size aggregates. For downwind areas in the simulation region where saltation is absent, trapping of large, suspension-size aggregates was also simulated as a downward vertical flux to the surface.

The initial goals in developing the equations were: to make them physically-based so they apply to a wide range of conditions; to separate simulation of saltation/creep and suspension components of wind erosion; and to define the equation parameters, so they could be measured in a wind tunnel or on instrumented fields. Each of these goals was accomplished.

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