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Application of WEPS Generated Soil Loss Components to Assess Off-site Impacts

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ABSTRACT

Typical wind erosion studies have focused on mass flux rates and soil loss from source locations. Correspondingly, wind erosion prediction models focus on those same elements. Thus, most wind erosion control measures have been designed for and evaluated based upon their cost-effectiveness at mitigating on-site impacts. Yet, the true costs of wind erosion events often occur offsite. With the advent of the Wind Erosion Prediction System (WEPS), a physically based, daily time-step wind erosion model, many off-site impacts of wind erosion can now be successfully explored and addressed. Two examples of off-site wind erosion effects - filling of roadside drainage ditches and reduced visibility along roadways- are examined. These examples show how WEPS can benefit in the design and/or selection of effective practices for controlling off-site wind erosion effects.

INTRODUCTION

Wind erosion results in both on-site and off-site costs. On-site, wind erosion often reduces both production and crop quality (Lyles, 1975; Armbrust, 1984). Indirectly, it increases operating costs because of the need for additional soil management and other inputs. In contrast, off-site costs are borne by households, private firms, and government agencies in the form of increased cleaning, maintenance and replacement expenditures, and reduced consumption and production opportunities (Huszar, 1991).

Evaluations of soil conservation programs typically assess only on-site benefits and costs. The major costs of wind erosion, however, are likely to be off-site. For example, in New Mexico alone, on-site costs are estimated to be $10 million annually (Davis and Condra, 1989). Yet, the estimated off-site costs to New Mexico households are $458 million (Huszar and Piper, 1986). Recent estimates of off-site wind erosion costs on a national basis show that it could be as high as 9.6 billion dollars annually (Pimentel, et al., 1995).

Unfortunately, direct monetary losses associated with off-site effects of wind erosion are not the only costs that society bears. Wind erosion affects air quality, visibility, and water quality, which in turn affects human health and safety (Ostro, et al., 1999).

Historically, wind erosion studies have focused primarily on understanding the physics of wind erosion and related processes, measurement, monitoring, and prediction of wind erosion events, and control practices to mitigate its effects. However, assessment of these control practices has almost exclusively been measured in terms of on-site effects. This is partly due to landowners and managers bearing at least a portion of the costs for typical control practices; thus, their primary economic incentive concerns on-site benefits. Another factor has been the difficulty in quantifying most off-site effects.

The consequences of off-site effects of wind erosion have been known for some time, as evident by E.E. Free's (1911) statement: "*All strong winds pick up much dust from the soil surface, and if loose material be plentiful, the windstorm will become a dust storm and the air so thickly filled with dust that it will be difficult to see or to breathe.*" Blowing dust storms in the 1930's became so dense in the Great Plains that they became known as "black blizzards", killing livestock, birds, wild game and humans. An estimated 1600 people died from the effects of dust and heat in 1936 alone (Svobida, 1940). Blowing dust also obscures visibility, interfering with air traffic and causing major automobile accidents. When left uncontrolled, it buries drainage channels, irrigation ditches, fences, and even roads (Woodruff and Hagen, 1972).

As a result, research has been conducted to quantify specific wind erosion off-site effects. For example, concentrations of dust leaving agricultural fields during wind erosion events have been measured, along with visibility levels adjacent to those fields (Langham, et. al., 1938; Chepil and Woodruff, 1957). Subsequent studies (Smith and Twiss, 1965; Brown, et al., 1968; and Hagen and Woodruff, 1973; Orgill and Sehmel, 1976) have looked at dust deposition rates and frequency of high dust concentrations in the United States. Yet, visibility and dust concentrations have never been related back to specific storm levels and frequency of occurrence. Wind erosion prediction models available in the past were not capable of providing the necessary information to determine such relationships.

Other off-site impacts of wind erosion, such as enrichment ratio of wind blown soil (Hagen and Lyles, 1985; Zobeck and Fryrear, 1986), have also been investigated. But again, few of these studies related those effects back to specific storms or frequency of occurrence.

During development of WEPS (Wind Erosion Prediction System), a process-based, daily time-step wind erosion model (Wagner, 1996), features to effectively evaluate many

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off-site effects of wind erosion were incorporated into the model. Thus, WEPS can be applied to design control practices for mitigating off-site effects, evaluating their effectiveness, and determining the frequency and severity of storm events with off-site impacts.

WEPS can be applied to off-site wind erosion problems that have not been easily addressable by earlier wind erosion models. In this paper, examples are presented and discussed to demonstrate how WEPS can be used to address two common off-site problems: 1) deposition of wind blown material into adjacent irrigation or drainage channels and 2) the hazard of reduced visibility along nearby roadways during wind erosion events.

Deposition of Wind Blown Material into Irrigation and Drainage Channels

A typical off-site problem associated with wind erosion events is the filling of irrigation canals and roadside drainage ditches. It is obvious that deposition of saltating material during wind erosion events into these channels will incur costs associated with cleaning them out, if required. Also, deposited soil can contain pesticides, herbicides, insecticides, or other contaminants that may have been applied to the eroding field (Larney, et al., 1999). In the case of irrigation canals, contaminated water may end up being applied to fields downstream, potentially affecting production and quality of susceptible downstream crops.

Drainage ditches, on the other hand, can eventually transport significant quantities of wind blown deposited material and associated contaminants into running streams and rivers. Elevated levels of nutrients and other contaminants can adversely affect the ecosystems of streams, lakes and other wetlands (Leys and McTainsh, 1999). Reservoirs and detention ponds downstream are also impacted by increased silting rates. In addition, where surface waters are tapped for drinking supplies, drinking water quality can also be affected.

These are only some of the more obvious off-site impacts of wind blown deposition into drainage ditches and irrigation canals. WEPS output can be used to determine how often deposition occurs, and at what rate, into an adjacent irrigation or roadway drainage channel. This is because WEPS has the following features:

1. The WEPS weather simulator gives wind probability by direction. This means that the fraction of erosive wind energy directed toward any field boundary that may be next to a "channel" can be determined.
2. As one of the outputs, WEPS predicts the discharge rate of saltation/creep-sized material (mass/unit length/time) crossing each boundary of an eroding field.

Some soils, such as certain volcanic and organic soils, may have high concentrations of suspension-size material, so they do not readily fill drainage channels. However, typical eroding soils contain significant saltation/creep-size material that cause major deposition in channels. In this case, assuming only saltation/creep material leaving the adjacent field boundary is trapped, the rate of deposition can be determined on a storm basis. Since the frequency and

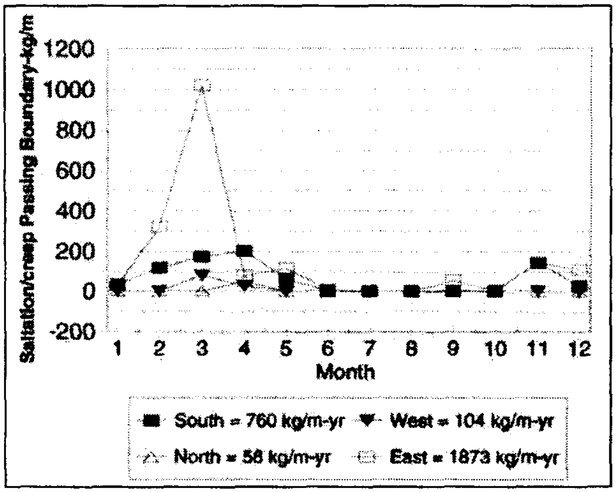

Figure 1. Monthly averages of saltation/creep passing boundaries of smooth, silt-loam soil of 800 X 800 m field.

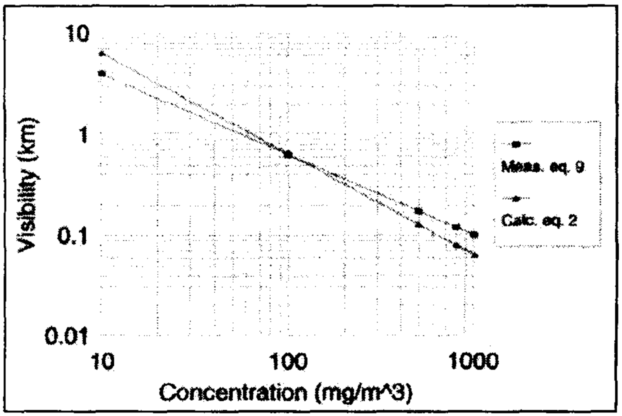

Figure 2. Visibility vs. dust concentration.

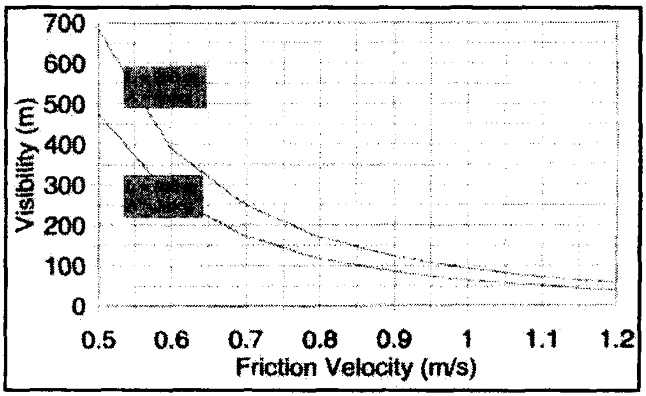

Figure 3. Visibility vs. friction velocity during simulated erosion events at downwind boundaries of 800 m with diffusion zone angle of 3 degrees and 200 m with diffusion zone angle of 4 degrees.

intensity of wind erosion events are known, long-term average channel deposition rates and amounts can be computed. Assuming that natural cleansing of the channel does not occur, estimates on how often a channel will require cleaning can also be made. Typical dust storms are about 6 hours in duration (Hagen and Woodruff, 1973) and will transport about 100 to 1000 kg/m to a downwind road ditch.

As an example, we used WEPS to simulate erosion for 20 years on an 800 X 800 m bare, fallow field in eastern Colorado. Three tillage operations were performed each year. The upper soil layer fractions were: 0.66 sand, 0.20 silt, 0.14 clay, and 0.01 organic matter. Because the simulated field was bare and relatively smooth, it was highly erodible. The monthly average saltation/creep component crossing each field boundary is illustrated in Fig. 1. The prevailing wind directions are in the west and north quadrants, and hence, the east and south sides of the field collect 94 percent of the saltation/creep leaving the field. The highest amounts crossed the eastern field boundary in March and likely would necessitate cleaning the ditch.

Wind Erosion and Visibility

Reduced visibility along roadways due to wind erosion events is a significant contributor to many vehicle accidents, including some of the largest multi-vehicle accidents in the U.S. (31 vehicles on I-10, AZ, Mar. 4, 1989; 104 vehicles on I-5, CA, Dec. 1, 1991; 18 vehicles on I-70, KS, Feb. 15, 1991). The problem is serious enough on Interstate 10 that the Arizona Department of Transportation commissioned a recent study to help develop dust control and mitigation strategies for improving visibility and preventing vehicle accidents during dust storms on the roadway (Cowherd, Grelinger, and Karimvand, 1997). There were 46 dust-related accidents in Arizona on I-10 from 1985 through 1996.

Even though the problem of reduced visibility on roadways due to wind erosion is recognized, studies such as the one in Arizona still do not provide a quantitative assessment of how well the suggested control strategies will succeed in reducing dust-related motor vehicle accidents. The study identified the "hot spots" where such accidents were more prevalent in the past and assessed the likely source of dust emissions, but they were not able to predict the re-occurrence or severity of visibility problems.

With WEPS, visibility levels along adjacent roads can be estimated on a storm-by-storm basis, as well as the probability of specific visibility levels occurring during storms. The following discussion outlines a possible theoretical approach to determining visibility levels from WEPS storm output.

Size Distribution and Concentration Gradient of Suspended Soil

Calculating the reduced visibility caused by wind erosion requires assumptions about both the size distribution and the vertical concentration gradient of the suspended soil. Neither of these variables are currently output by WEPS, but estimates are available from both theory and measurements.

First, we will consider the theoretical role of the particle size distribution on visibility.

The visual range of targets, such as buildings and automobiles, can be estimated as (McCartney, 1976):

$$R_V = \frac{1}{b_{sc}} \ln\left(\frac{C_t}{e}\right)$$

where:

R_v = visual range (m)
C_t = contrast of target against the background
b_{sc} = Mie scattering coefficient (1/m)
e = is the threshold of contrast for the observer.

To provide a standard basis for observation, meteorological range is defined with values of $C_t = 1$ and $e = 0.02$ as:

$$R_V = \frac{3.912}{b_{sc}}$$

The absorption by atmospheric particles is usually neglected, so only the scattering coefficient must be determined to obtain an estimate of meteorological range (McCartney, 1976). For a polydisperse group of particles,

$$b_{sc} = \int \frac{\pi D^2}{4} Q_{sc}\, n(D)\, dD$$

where:

D = particle diameter (μm)
n(D) = concentration by number of particles of diameter D
Q_{sc} = particle scattering efficiency defined as ratio of extinction cross-section to geometric cross-section.

For suspension-size particles from wind erosion with a refractive index of about 1.5, the value of Q_{sc} varies as a damped sinusoid between about 1.7 to 2.5 with an average value of about 2.2 with the wavelength of light at 525 nm, where human vision is the most sensitive. Suspension-size particles sampled in wind erosion are generally reported as mass concentrations and approximate a log-normal distribution (Chepil and Woodruff, 1957). Substituting a log-normal distribution by mass of particles into eq. 3 and assuming spherical particles gives:

$$b_{sc} = 0.0015 \frac{Q_{sc}}{\rho_p} \frac{1}{\ln[s_g (2\pi)^{0.5}]} \int \frac{1}{D^2} e^{-\left[\frac{(\ln(D) - \ln(x_g))^2}{2 \ln^2(s_g)}\right]} dD$$

where: ρ_p=particle density (about 2 g cm^{-3}); x_g=particle distribution geometric mean by mass (μm); s_g = particle distribution geometric standard deviation; D = particle diameter (μm); and Q_{sc}=particle scattering efficiency defined as ratio of extinction cross-section to geometric cross-section.

Then for a mass concentration of 1 mg m^{-3}, and a typical size distribution with x_g=30 μm, and s_g=1.6, integrating eq. 4 from 1 to 130 μm gives b_{sc}=6.14 X 10^{-5} m^{-1}.

Based on observations in dust storms, Chepil and Woodruff (1957) reported a slope of visibility-vs-concentration slightly larger than shown by eq. 2 and 4 above (Fig. 2). Their results suggest that at the lowest visibilities measured, the size distribution became a bit coarser than that shown above. Overall, theory and measurement of visibility near the downwind edge of eroding fields appear to be in good agreement.

Next, we will consider the vertical dust concentrations near eroding fields.

For regions near the downwind edge of a field, the horizontal gradient in dust concentration near the surface may be small. For these conditions, Kind (1992) has derived near-surface vertical gradients of dust concentration. Field measurements of the vertical concentration gradients between 1.5 and 6.0 m were also reported by Chepil and Woodruff (1957). Their measurements provided an average concentration gradient of :

$$\frac{C}{C_{ref}} = \left(\frac{Z_{ref}}{Z}\right)^{0.28}$$

where C and C_{ref} are concentrations (mg m^{-3}) at heights Z and Z_{ref} (m) , respectively.

Example Simulation of Visibilities for a Range of Wind Speeds

The dust concentration at any down wind location is related to qss (flux rate suspension size particles) as:

$$qss = \int_{z2}^{z1} C(z)U(z)dz$$

where the bottom of the diffusion zone was set at z1 = 0.05 m and the top [z2 = L tan(A)] was estimated for angles (A) of both 3 and 4 degrees for field lengths (L) of 200 and 800 m.

The near-surface wind speed (U) at any height (z) was simulated by the well-known log-law as:

$$U = \frac{u^*}{0.4} ln\left(\frac{z}{zo}\right)$$

where u* is friction velocity (m s^{-1}) and zo is aerodynamic roughness set equal to 0.002 m. Setting Z_{ref} = 1.2 m, which is applicable to the line of sight for drivers of many cars, and substituting eq. 5 and eq. 7 into eq. 6 gives:

$$qss = \int_{z1}^{z2} C_{ref}\left(\frac{1.2}{z}\right)^{0.28} \left[\frac{u^*}{0.4} ln\left(\frac{z}{0.002}\right)\right]dz$$

Simulating qss with WEPS and then solving eq. 8 for C_{ref} using an iterative solution procedure (MathSoft Inc., 1997), provides an estimate of the concentration at 1.2 m above the surface, which is applicable for the drivers of many cars.

Finally, the visibility (V) was estimated using a measured relationship from Fig. 2 (Chepil and Woodruff, 1957) as:

$$V = \frac{25035}{(C_{ref})^{0.8}}$$

where C_{ref} (mg m^{-3}) is dust concentration and V (m) is visibility.

We selected a smooth field with a silt loam soil in erodible condition. In this simulation, the suspension component (qss) and saltation/creep (q) components of soil discharge (kg m^{-1} s^{-1}) were equal at 200 m downwind. The predicted visibilities decreased as friction velocity increased for a typical range of wind speeds that may occur in an erosion event (Fig. 3). The simulation results also showed that as upwind field length increased and depth of diffusion zone (angle A) decreased (i.e. atmospheric stability increased), the visibility decreased for a given wind speed.

The simulated results in Fig. 2 are applicable to an ideal black target. However, during many erosion events near roadways, a driver's visual range will be less than the measured meteorological range, because the contrast between target and background, C_t in eq. 1, is smaller than 1. This occurs because the target is not black and may be viewed against a background other than the horizon. Hence, even concentrations of dust that provide adequate meteorological range often pose a visual range hazard for traffic. This is particularly true for drivers of passenger cars that view the road from only about 1.2 m above the surface where dust concentrations may be large.

SUMMARY AND CONCLUSIONS

Historically, the focus of wind erosion studies has been directed at the on-site effects. As the public becomes more sensitive to health and safety issues, the consequences of off-site effects of wind erosion will become increasingly important. Road visibility and deposition into drainage channels adjacent to eroding fields are only two off-site effects of wind erosion events. However, both are important examples of wind erosion related factors affecting human health and safety.

Because WEPS is able to provide information on the frequency and severity of wind erosion events, along with estimates of the quantity of eroding material crossing field boundaries in suspension and saltation/creep mode, off-site effects of wind erosion can now begin to be assessed. Since WEPS is a conservation tool, it will not only be used to estimate the frequency and severity of off-site effects, but also to assist land managers in modifying their practices to reduce the off-site impacts of wind erosion.

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