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Review

A history of wind erosion prediction models in the United States Department of Agriculture prior to the Wind Erosion Prediction System ☆

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ABSTRACT

The Great Plains experienced an influx of settlers in the late 1850s–1900. Periodic drought was hard on both settlers and the soil and caused severe wind erosion. The period known as the Dirty Thirties, 1931–1939, produced many severe windstorms, and the resulting dusty sky over Washington, DC helped Hugh Hammond Bennett gain political support for the Soil Conservation Act of 1937 that started the USDA Soil Conservation Service (SCS). Austin W. Zingg and William S. Chepil began wind erosion studies at a USDA laboratory at Kansas State University in 1947. Neil P. Woodruff and Francis H. Siddoway published the first widely used model for wind erosion in 1965, called the Wind Erosion Equation (WEQ). The WEQ was solved using a series of charts and lookup tables. Subsequent improvements to WEQ included monthly magnitudes of the total wind, a computer version of WEQ programmed in FORTRAN, small-grain equivalents for range grasses, tillage systems, effects of residue management, crop row direction, cloddiness, monthly climate factors, and the weather. The SCS and the Natural Resources Conservation Service (NRCS) produced several computer versions of WEQ with the goal of standardizing and simplifying it for field personnel including a standalone version of WEQ was developed in the late 1990s using Microsoft Excel. Although WEQ was a great advancement to the science of prediction and control of wind erosion on cropland, it had many limitations that prevented its use on many lands throughout the United States and the world. In response to these limitations, the USDA developed a process-based model know as the Wind Erosion Prediction System (WEPS). The USDA Agricultural Research Service has taken the lead in developing science and technology for wind erosion prediction.

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1. Introduction

Wind erosion has been an agricultural issue in the semi-arid central United States Great Plains since settlers first plowed prairie grasslands to produce food and fiber. The years from 1931 to 1939 saw very low rainfall in the U.S. High Plains region centered in Texas, New Mexico, Colorado, Oklahoma, and Kansas. The resulting severe wind erosion caused concern over the loss of our soil resources, and a national effort to quantify and control the amount of wind erosion on our nation's farmland began. The US Soil Erosion Service established in 1933, later know as the Soil Conservation Service (SCS) and now the Natural Resources Conservation Service (NRCS), along with the Agricultural Research Service (ARS) and land grant universities have worked 75 years to advise growers about the care of wind-erodible land. Throughout this time, research has been conducted and many soil loss prediction methods have been developed to better understand and predict soil erosion. This paper summarizes the development of wind erosion prediction models in the United States Department of Agriculture prior to the development of the current Wind Erosion Prediction System (WEPS) model in the mid-1980s. The history and development of the WEPS model is described in detail in a separate work by Wagner (see this issue).

2. Early observations of wind erosion

Farmers and ranchers settled the US Great Plains region in the late 1800s. From 1850 to 1900, the population of the area increased from 300,000 to 7,000,000 (Anderson and Hill, 2004) with a concurrent large increase in the land converted to cropland, most of which was planted to wheat. Mechanization using tractors allowed farmers to cultivate previously unplowed areas of the short grass prairie (Armbrust, 1999).

Early wind erosion literature focused on the scope of the problem and control measures. The first scientific report of wind erosion on cultivated US land was made by King (1894) in Wisconsin. King recommended strip-cropping, green manure, roughening the surface, and windbreaks to control wind erosion. Udden (1896) published some of the first quantitative estimates of solid, suspended material in dust storms. He reported 160 to 126,000 tons per cubic mile of dust and indicated that an average of 850 million tons of dust was being carried 1440 miles each year in the Western United States. Free and Westgate (1910) discussed four actions to control soil blowing: (1) increasing the water content of the soil, (2) increasing the amount of humus (organic matter in soil), (3) providing a cover of growing vegetation; and (4) leaving the stubble of the last crop standing on the land until next planting. A comprehensive review of wind erosion science from the perspective of Aeolian geology was published by Free (1911) with additional control methods to those mentioned by Free and Westgate (1910) including decreasing summer fallow and planting trees in rows to slow the wind. Free was also one of the earlier writers to describe wind erosion and windblown dust as an agent of soil formation and modification. Several periods of dry conditions from 1890s as well as the 1910s caused severe wind erosion (Chepil, 1957).

3. The impacts of the Dust Bowl on research and modeling

Probably the most severe period of wind erosion occurred in the 1930s in the US Great Plains. Fig. 1 shows the rainfall patterns for southwest Kansas that resulted in the severe erosion of the 1930s. Starting in 1931, rainfall was below average for the subsequent 9 years. Rainfall in 1937 was 208 mm (8 inches) below the average of 478 mm (18.8 inches), which resulted in consecutive years of winter wheat crop failure. At that time, knowledge of wind erosion soil loss was limited. The Great Depression compounded the difficult times brought on by the drought's effects.

The severity of the drought resulted in large amounts of erosion throughout the Great Plains of North America with the most severe damage occurring in New Mexico, Colorado, Kansas, Oklahoma, and Texas. Fig. 2 is a typical photograph of the Dust Bowl era (USDA-NRCS, 2012). Even before the Dust Bowl, Hugh Hammond Bennett, a soil scientist at the US Bureau of Chemistry and Soils, thought much more could be done to manage natural resources wisely. Bennett and Chapline (1928) made their case for soil conservation in *Soil Erosion: A National Menace*. Later, in April, 1935, Bennett used a big dust storm to persuade Congress to address the problem (Brink, 1951; Egan, 2006). On a day he was testifying before Congress in support of the Soil Conservation Act, Bennett was able to prolong his presentation long enough for legislators to see a large storm settle dust over the Capitol as the bill came to a vote. The act which was, in part, intended to reduce the nation's soil loss also established the United States Soil Conservation Service (SCS) and was the first soil conservation act in history (Brink, 1951). Bennett served as the first chief of the SCS until his retirement in 1951. Later, the SCS published several regional guides for wind erosion control, including "The Guide for Wind Erosion Control in the Northeastern States" (Hayes, 1966) and "The Guide for Wind Erosion Control on Cropland in the Great Plains States" (Craig and Turelle, 1964).

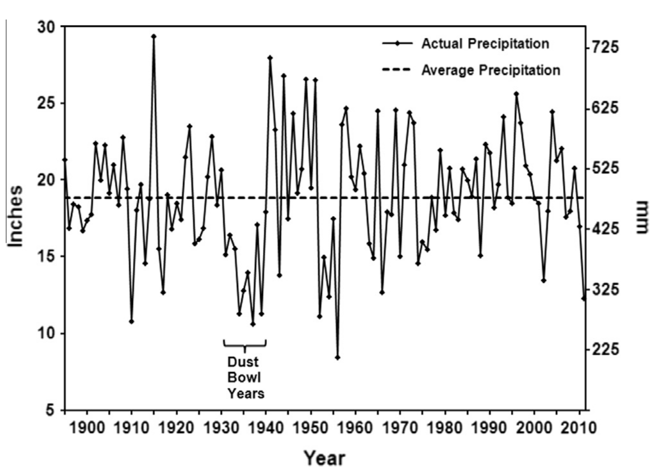

Fig. 1. Southwest Kansas Rainfall, 1895 to 2011 (data from NOAA, 2012). Note the dry years of 1931 to 1940.

Fig. 2. Typical dust storm from the 1930s (USDA-NRCS, 2012).

As wind erosion research in the US was beginning, R.A. Bagnold, Cambridge University, M.A. in engineering, published *The Physics of Blowing Sand and Desert Dunes* (1941). Bagnold (1941, p. xxi) departed from the traditional line of thinking when he said, "The subject of sand movement lies far more in the realm of physics than of geomorphology." Some have called him the father of saltation. Lyles (1985, p. 209) stated that, "Although the 'what' of wind erosion might have been known during the 1930s, the 'how to' or the 'how much' of control principles and practices for the widely diverse soils, crops, and climate of the West were largely unknown." He went on to say, "The goal of erosion researchers has been the quantification of the need for protection and the means to provide it, given those variables of soils, crops, and climate."

4. Early wind erosion research in the USDA

The Flannagan-Hope Bill, officially known as The Agricultural Marketing Act of 1946 (public Law 733, 79th Congress), was passed, in part, "... to provide further research into basic laws and principles relating to agriculture ..." and was the source of much of the funding for establishing the Wind Erosion Project in Manhattan, Kansas, which was administered by the Research Division of the SCS. A laboratory was established on the campus of Kansas State Agriculture College in 1947. The management of this laboratory was transferred to the ARS in 1953 (Armbrust, 1999).

Austin W. Zingg, a mechanical engineer, was the first supervisor of the facility, officially known as the High Plains Wind Erosion Laboratory. William S. Chepil, a soil scientist, became project leader in 1953 until his death in 1963. Initial work focused on developing research equipment such as laboratory and portable wind tunnels and procedures to characterize the soil surface response to wind erosion. Developing a fundamental understanding of the processes of wind erosion and soil properties that affect wind erosion were also primary goals of the project. Chepil's groundbreaking work focused on five key factors that affect wind erosion (Chepil, 1960; Chepil and Woodruff, 1954; Chepil et al., 1962; Chepil and Woodruff, 1963): (1) soil cloddiness, (2) ridge roughness, (3) climate, (4) field length, and (5) vegetative material. The initial attempt by Chepil to model soil loss by wind was based on wind tunnel experiments and consisted of a simple equation relating soil loss to degree of cloddiness, roughness, and vegetation (Chepil and Woodruff, 1959; Woodruff and Siddoway, 1965). This initial model had the following relationship:

$$X = a(I/(RK)^b)$$

where X = wind tunnel erodibility in tons per acre, I = soil erodibility based on percent of soil fraction greater 0.84 mm in diameter, R = amount of crop residue in pounds per acre, K = ridge roughness equivalence in inches compared to a standard height-spacing ratio of 1:4, a and b = constants that depend on past erosional history, type of residue and roughness, and condition of surface crust.

The equation was continually improved as new research and data became available.

5. The Wind Erosion Equation

The first published comprehensive attempt to model wind erosion on agricultural fields was based largely on the work of Chepil and published by Woodruff and Siddoway in 1965. The Wind Erosion Equation (WEQ) was an empirical model with the following functional form:

$$\mathrm{E} = \mathrm{f}(\mathrm{I}, \mathrm{K}, \mathrm{C}, \mathrm{L}, \mathrm{V})$$

where E = soil loss (mass/area/yr), I = soil erodibility, K = ridge roughness, C = climatic factor, L = field length; and V = vegetative factor.

These factors were developed from wind tunnel and field research and are derived from the interactions of eleven primary parameters. The soil erodibility factor (I) is a measure of the potential soil loss from a wide, bare, smooth, unsheltered, and non-crusted surface and can be adjusted to account for the presence of hills, knoll topography, and mechanical stability of soil crust if necessary. Woodruff and Siddoway (1965), however, recommend that crusts be disregarded because of their transience. The ridge roughness factor (K) adjusts soil erodibility for soil surface roughness other than that caused by clods or vegetation and is typically formed by farming implements (e.g., ridges and furrows). The climatic factor (C) includes the effect of wind velocity and soil moisture, which is proportional to the Thornthwaite P-E Index (Thornthwaite, 1931). The field length factor (L) is the distance across the field along the prevailing wind erosion direction. The rate of erosion is zero at the upwind field edge and increases with distance across the field downwind. If the field is long enough, soil movement by wind reaches a maximum for the given wind. If wind barriers are present, L is adjusted to account for the shelter effect of the barriers. The vegetative factor (V) adjusts the soil loss given by the other factors to account for any vegetative material on the soil surface. The V factor accounts for the quantity, kind, and orientation of vegetative cover. The relationships between these factors are complex, and interactions occur among them such that labor-intensive graphical and tabular solutions were required.

5.1. Improvements to WEQ

The purpose of WEQ was twofold: (1) to serve as a tool for determining the potential amount of wind erosion for a particular field under existing local conditions, and (2) to serve as a guide for determining the conditions of cloddiness, roughness, vegetative cover, sheltering from wind barriers, or width and orientation of field necessary to control wind erosion (Chepil and Woodruff, 1963). Woodruff and Siddoway (1965) cited several shortcomings and limitations of WEQ, saying that variables that influence wind erosion were lacking and the interaction of the combined factors was not well understood. They listed specific details that were missing in WEQ. First, they argued that information was needed on the influence of different implements on soil cloddiness, soil ridge roughness, and vegetative cover. This information was deemed important in prescribing effective methods of tillage to control erosion. Second, prevailing wind direction had been determined only for the Great Plains and needed to be expanded to the rest of the US. Better information on surface soil moisture related to the climatic factor was also needed. The Thornthwaite Index was considered only a rough estimate of moisture conditions. Third, the climatic factor was needed on a monthly or seasonal basis to permit better evaluation of short-term, highly erosive periods. Fourth, seasonal and annual soil erodibility needed to be determined for various soil types. Fifth, information was needed on the average distance of full and partial protection from wind erosion afforded by barriers of various widths and spacing in various geographic locations and for various soils. Finally, the researchers argued that values of the vegetative cover factor and orientation for crops other than those already investigated were also needed. Research continued for the next 20 years and attempted to address these and other deficiencies to improve WEQ.

Lyles and Allison (1975) modified WEQ equations so that the combined effect of stubble and non-erodible aggregates could be considered. The ridge roughness factor was expanded to include an adjustment for random roughness calculated as standard deviation of soil surface elevation (USDA-NRCS, 2002). Armbrust et al. (1982) determined the effect of crop type and tillage on the number, size distribution, and stability of soil aggregates. Researchers improved the soil ridge roughness factor by determining how long ridges created by grain drills persist for several soil textures and rainfall regimes (Lyles and Tatarko, 1987). The soil erodibility index was also determined for the spring and fall in seven North Central states which could be used to apply the WEQ for critical or other periods of less than one year (Lyles and Tatarko, 1988).

The climatic factor was expanded to include most of the US (Skidmore, 1965; Skidmore and Woodruff, 1968), then the arid southwest (Lyles, 1983). Improvements were also made in accounting for wind erosion direction and the preponderance of wind erosion forces (Skidmore, 1965; Skidmore, 1987). Methods of computing a monthly wind erosion climatic factor were devised (Woodruff and Armbrust, 1968; Skidmore, 1987). Bondy et al. (1980) proposed a method of computing wind erosion by periods (greater or smaller than 1 year) by partitioning wind-energy distributions. Skidmore (1986) developed a physically based climatic factor for long- and short-term and event soil loss estimates that did not require the use of the Thornthwaite P-E Index, which is highly sensitive to low precipitation and underestimates the effects of humid climates in the climatic factor.

Several studies (Hagen and Skidmore, 1971; Hagen et al., 1972, 1981; Skidmore and Hagen, 1977; Hagen, 1976) determined relationships between wind reductions and windbreak porosities, which facilitated better predictions of protection provided by barriers downwind. The effectiveness of annual crops as wind barriers was also considered (Fryrear, 1963), and shelter effects were developed over 12 years of testing for 27 tree and shrub species in the Central Great Plains (Woodruff et al., 1976).

Studies were also conducted to improve estimations of the protection for erodible soil particles provided by standing stubble based on the stubble's height, size, spacing, and orientation (Skidmore et al., 1966; Lyles et al., 1973; Lyles and Allison, 1975). The vegetative factor was also expanded to include other crops including corn, cotton, grain sorghum, peanuts, and soybean (Lyles and Allison 1981; Armbrust and Lyles, 1985; Skidmore and Nelson, 1992). Small-grain equivalents were determined for several non-crop vegetation species such as range grasses and shrubs (Lyles and Allison, 1980; Hagen and Lyles, 1988). Woodruff et al. (1974) derived curves for converting different amounts of surface-applied and incorporated wet manure to flat, small-grain equivalents.

To improve the shortcomings in WEQ's predictions of annual average soil loss, the model was converted from an annual or period to daily prediction (Cole and Lyles, 1984; Skidmore and Williams, 1991). This work allowed WEQ to be interfaced with the computer program known as the Erosion Productivity Impact Calculator, or EPIC (Williams et al., 1984). Two WEQ factors for this daily prediction in EPIC, soil erodibility and climatic factor, remained constant for each day of the year. The other variables were subject to daily variation as simulated by EPIC.

In addition to the research efforts mentioned above to improve the science behind WEQ, ARS also attempted to make WEQ easier to use. The first attempt to computerize WEQ was known as WEROS (for Wind EROSion), a Fortran IV computer program that implemented the original WEQ that determined soil loss on an annual basis (Skidmore et al., 1970; Fisher and Skidmore, 1970). With WEROS, the user could replace the cumbersome task of solving WEQ using tables and nomographs with a mainframe computer. WEROS was later modified to generate lookup tables for SCS where, if the user knew the soil erodibility, roughness, climatic factor, the field length along the prevailing wind erosion direction and the small-grain equivalent of the vegetation, the soil loss could be found easily. Because many SCS field offices were not equipped with computers at the time, a slide rule–type calculator was developed for solving WEQ (Skidmore, 1983). The calculator was used extensively by SCS field personnel for estimating wind erosion and designing wind erosion control systems.

5.2. SCS/NRCS improvements to WEQ

From 1965 to 1992, SCS/NRCS used WEQ to predict wind erosion on farmers' land for conservation programs. At first, WEQ was applied on an annual basis, but this approach was quickly replaced by the Critical Period Method through which erosion was predicted for the period of the year most susceptible to wind erosion. As ARS was able to determine the average monthly winds, some areas used the Management Period Method, which attempted to predict erosion for specific crop management periods to further pinpoint where the management system needed improved conservation practices. This allowed a conservation planner to offer small changes in tillage or crop rotation to reduce erosion.

SCS/NRCS made several efforts to simplify WEQ for their use. Random roughness photos with associated random roughness values as well as random roughness associated with various cropland field operations were developed (USDA-NRCS, 2002). Desktop computers came to the SCS field offices in 1988, and the agency began attempting to bundle WEQ into comprehensive software packages. These included a 1988 DOS version, a 1989 Computer Assisted Management Planning System (CAMPS) version, various 1994–1997 Field Office Computing Systems (FOCS) versions, and finally, in 1998, a Microsoft Excel spreadsheet version (Carlson et al., 1999). Sporcic and Nelson (1999) developed a spreadsheet version of WEQ that used lookup tables and calculated potential soil loss under the Management Period Method. The spreadsheet version of WEQ was used nationally from 1998 until 2010 and significantly reduced the amount of input time required to calculate the management period procedure by hand.

5.3. Limitations of WEQ

Despite the efforts cited above to improve the science and usability of WEQ, shortcomings of the model persisted and have been recognized by wind erosion researchers. These limitations have been outlined in a number of publications and are summarized below.

Chepil's method of relating short-term (minutes) soil loss data to annual average soil loss and areas that are wide and long compared with a wind tunnel was inherently inaccurate. The measurements in the wind tunnel were of such short duration, due to the limited amount of erodible soil in the sample trays, that the soil flow rate could not be measured. Instead, the mass of soil lost per unit area was measured and used in computing a measure of relative erodibility (Cole et al., 1983).

Relationships among variables were not accounted for in all combinations of field and climatic conditions (Hagen, 1991). Difficulties in determining single values for factors such as I, L, K, and V appear to have arisen because of the ambiguous methods suggested for their determination (Cole, 1983). Woodruff and Siddoway (1965, p. 606) stated, "The equation actually evaluates the erodibility of a field having certain L, K, and V values in terms of what it would have been during the severe soil blowing time."

Variation of wind and precipitation from the average is not simulated in WEQ (Skidmore, 1976). As a result, extreme weather conditions that in reality greatly influence wind erosion are not easily simulated. Seasonal variation of field erodibility was also difficult to account for in the model. For example, Chepil recognized that all of the factors he defined could change with time. To cope with the wind angle fluctuations, for instance, Chepil et al. (1964) defined a single prevailing wind direction angle for the simulation (Cole, 1983).

Inherent uncertainties also exist in the empiricism of the equation development. The surface of the wind tunnel used to derive erodibility for WEQ does not represent the total field surface that is of interest. Thus, because of the small area of the soil sample tested, soil abrasion is lacking and the time duration of a wind tunnel test is too short, i.e., minutes, compared to hours on a field. A consequence of the small sample was a difference in the measured dependent variable between tunnel and field (Cole, 1984a).

Speaking of the limitations of WEQ, Hagen (1991, p. 106) said, "The current technology represents a mature technology that is not easily adapted to untested conditions or climates far different than that of the central Great Plains where the WEQ was developed." Facing the shortcomings of WEQ, researchers began exploring modeling methods that would overcome the shortcomings of WEQ. Such a model should: (1) determine the percentage of eroded material that enters suspension, (2) convert from a deterministic to a stochastic model, (3) allow modeling of single windstorms, and (4) adjust the model to apply to large-scale, rather than single field sites (Skidmore, 1976). In addition, a new model should: (5) simultaneously simulate effects of a growing crop as well as residues from previous crops and, most importantly, (6) compute soil losses for 1-day rather than 1-year intervals (Cole and Lyles, 1984).

6. Beyond WEQ

Research devoted to overcoming the shortcomings of WEQ lead to an examination of new science and more process-based ways to approach the simulation of soil loss by wind (Cole, 1983, 1984a,b). With these new published approaches to wind erosion simulation as well as the advancement of the personal computing power that would allow adoption by most users of the technology, a new process-based wind erosion simulation model was proposed (Hagen, 1988, 1991).

Early in 1986, the USDA began a more than 20-year effort to develop this next generation of wind erosion prediction technology. The NRCS began using WEPS in its field offices in 2010 to assist land managers in controlling wind erosion, establishing acceptable field level conservation plans, and determining wind erosion susceptibility as part of the Conservation Reserve Program (CRP) and other national conservation program enrollments. The model is a critical component of the USDA strategy to reduce particulate emissions from cultivated agricultural lands. The history and development of the WEPS model and the future of wind erosion modeling is described in detail in a separate work by Wagner (see this issue).

7. Summary and conclusions

Wind erosion in the United States was recognized as early as 1807 by Zebulon Pike (1996). The 1930s brought at least five years of severe drought, which resulted in many dust storms and soil damage to the Great Plains of the US. This hardship was compounded by the Great Depression. The massive wind erosion and dust storms of that period brought attention to the importance of conserving our nation's natural resources, and the Soil Erosion Service was established in response to these events.

The US has had an active research program into wind erosion since 1947 when the Wind Erosion Project was established at Kansas State Agricultural College in Manhattan, Kansas. Many research tools and study methods were developed and a fundamental understanding of the causes and control of wind erosion was advanced. As a result of this research, the Wind Erosion Equation (WEQ) was published in 1965 as a tool to predict soil loss by wind and a means to develop control strategies. A considerable effort followed to improve and expand WEQ. Despite of these efforts, it became clear that WEQ should be replaced with newer wind erosion science and technology. In 1985, an effort was started to develop the process-based Wind Erosion Prediction System.

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