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The development of U. S. soil erosion prediction and modeling

John M. Laflen[1] and Dennis C. Flanagan[2]

Abstract

Soil erosion prediction technology began over 70 years ago when Austin Zingg published a relationship between soil erosion (by water) and land slope and length, followed shortly by a relationship by Dwight Smith that expanded this equation to include conservation practices. But, it was nearly 20 years before this work's expansion resulted in the Universal Soil Loss Equation (USLE), perhaps the foremost achievement in soil erosion prediction in the last century. The USLE has increased in application and complexity, and its usefulness and limitations have led to the development of additional technologies and new science in soil erosion research and prediction. Main among these new technologies is the Water Erosion Prediction Project (WEPP) model, which has helped to overcome many of the shortcomings of the USLE, and increased the scale over which erosion by water can be predicted. Areas of application of erosion prediction include almost all land types: urban, rural, cropland, forests, rangeland, and construction sites. Specialty applications of WEPP include prediction of radioactive material movement with soils at a superfund cleanup site, and near real-time daily estimation of soil erosion for the entire state of Iowa.

Key Words: Universal Soil Loss Equation, Water Erosion Prediction Project, Soil erosion, Erosion prediction, History of erosion prediction

1 Introduction

The objectives of this paper are to describe the development of soil erosion modeling research in the United States, to discuss the current state of such research, and to present a view on future directions in soil erosion modeling in the United States. The focus will be on the Universal Soil Loss Equation (USLE) and its development, followed by the development and application of the Water Erosion Prediction Project (WEPP).

We and others have written on this subject. For a more complete picture, the reader may also wish to read Meyer (1984), Meyer and Moldenhauer (1985), Laflen and Moldenhauer (2003), and Flanagan et al. (2007). The writings of Miller (1946a, 1946b), Duley and Miller (1923), and Duley and Ackerman (1934) provide views of early soil erosion plot experiments.

2 Empirical soil erosion prediction in the United States

McDonald (1941) described efforts to understand and control soil erosion in the earliest time of settlement in the U. S. Wind and water erosion were significant problems in the U. S. and in Europe. Early U. S. conservationists blamed erosion problems on plowing, continuous cropping, a lack of crop rotations, and a plentiful land supply. Many farmers advocated various measures to reduce soil erosion based on their observations and those published in Europe, sharing and publishing their thoughts on soil erosion, the causal factors, and how erosion might be controlled. One of those was the second president of the United States, Thomas Jefferson, who in 1813 advocated "horizontal plowing". Jefferson's letter (Jefferson, 1813) demonstrates his awareness of the on-and off-site effects of soil erosion, the role of runoff in soil erosion, and the interaction of soil conservation, hydrology and crop production, important scientific topics today in understanding, predicting and modeling soil erosion, 200 years later.

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[1] Adjunct Professor, Iowa State U., Ames IA. Former USDA-ARS Agricultural Engineer. Corresponding author: E-mail: laflen@wctatel.net

[2] Research Agricultural Engineer, USDA – ARS National Soil Erosion Research Laboratory, West Lafayette, IN

2.1 *First measurements of soil erosion in the United States*

The earliest measurements of soil erosion in the U. S. were made in 1915 by the U. S. Forest Service in Utah (Forsling, 1931) and by Ray W. McClure, a Department of Soils undergraduate student at the University of Missouri (Miller, 1946a). A German scientist, Ewald Wollny, is credited with making the first scientific measurements of soil erosion in the late 19th century (Dotterweich, 2013).

McClure went to Professor M. F. Miller for a special problem. He was assigned a project to measure rainfall and runoff from a small bare plot over a 2 month period in the spring of 1915. Measurements were made after each rainfall event, and after the first runoff event he inquired of Miller how to handle sediment accumulated in the catch basin, an unexpected development. Miller advised him to measure the amount of sediment. He found that the soil lost contained more nutrients than would be applied to the soil in a year (Woodruff, 1987). The records from this work have apparently been lost.

The next year, a graduate student at the University of Missouri, R. M. Vifquain (Vifquain, 1917), followed McClure and collected runoff and soil loss data from a set of 4 plots, each 5.5 feet wide by 91 feet long, with a slope of 4% (Fig. 1). Details of the experiment as well as the runoff and soil loss data are available in Miller (1946b) and in Vifquain's thesis (Vifquain, 1917). The major focus of Vifquain's work was soil moisture rather than soil erosion, as was McClure's work. Vifquain's major professor was M. F. Miller.

In 1917, F. L. Duley developed a set of 7 erosion plots located on the campus of the University of Missouri in the same area used by Vifquain. This was the first study in the U. S. to focus on soil erosion on cropland. Duley and Miller (1923) were the first in the United States to report scientific measurements of soil erosion. Other scientific efforts related to soil erosion began to develop, and the U. S. Congress appropriated funds for soil erosion research. In 1928, the U. S. Dept. of Agriculture published a circular on "Soil Erosion—A National Menace" (Bennett and Chapline, 1928). Bennett (1939) indicated that the publication of this bulletin, plus the educational campaign by the USDA were critical elements in securing public and political attention to soil erosion.

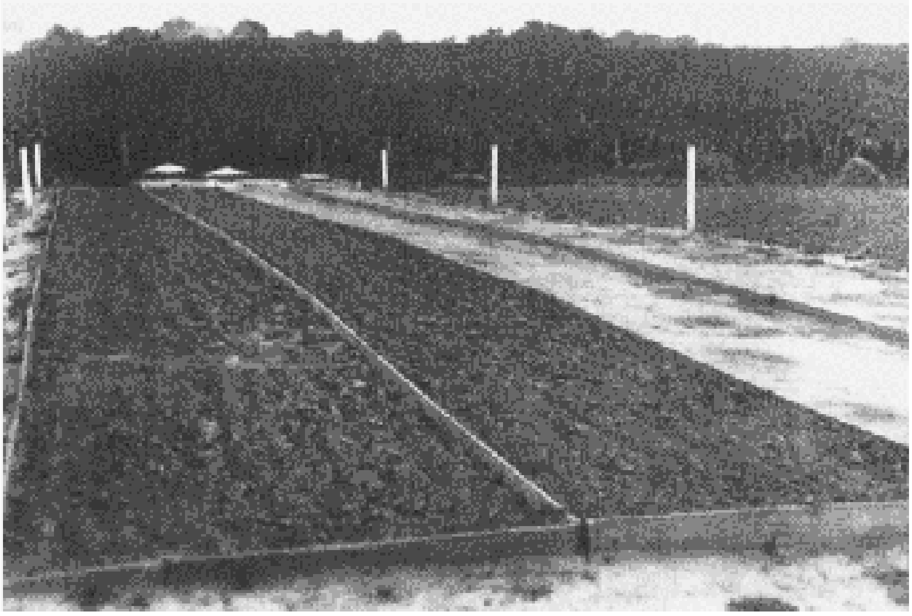


Fig. 1 Vifquain's plots in 1916, following McClure's plots in 1915

2.2 *Erosion research stations*

In the battle to control soil erosion, the first step was to develop a scientific basis for understanding soil erosion. Erosion research stations, also known as Soil Conservation Experiment Stations (SCES), were established representing ten major regions of the United States (Gilley and Flanagan, 2007). Plot design was based on the studies by Duley and Miller and associates at the University of Missouri (Meyer and Moldenhauer, 1985). The most common design was a plot 6 feet wide by 72.6 feet long, equal in area to1% of an acre. Slopes were usually those available at the site. Some sites had plot lengths much greater, and in some cases, much less than 72.6 feet. Eventually, the number of erosion research stations exceeded 30. The data collected provided a basis for the selection of conservation practices and for computing cropping and management effects on soil erosion. The SCES also served as a testing ground and a demonstration area for local and regional crops, managements and soils. The soils on many of these stations were part of a set of "benchmark" soils used to estimate the erosion impact of practices applied to other soils. The data from the SCES were used in developing empirical erosion prediction technologies of a regional nature, and in the analyses that led to the development of the USLE. Data from 20 of the erosion research stations were used in the evaluation of the WEPP model (Tiwari et al., 2000).

3 Development of the Universal Soil Loss Equation (USLE)

The development of the USLE followed an evolutionary pathway (Meyer, 1984) as shown in Table 1. While several had made measurements of soil erosion and of the factors that affected it (Duley and Ackerman, 1934), no one had published any mathematical relationships between these factors and soil erosion.

The first to do so was Austin W. Zingg in 1940. He evaluated data from field experiments under natural rainfall and from a rainfall simulation experiment on a Shelby loam soil in Missouri. Zingg's (1940) relationship (Eq. 1) was the first on the long path to expressing soil erosion in a model:

$$X = CS^m L^n \tag{1}$$

where X is total soil loss from a land slope of unit width (lbs), C was a constant of variation, S was land slope (%), L was horizontal length of land slope (ft), and m and n were exponents.

Zingg expressed average soil loss per unit area from a slope of unit width as

$$A = CS^m L^{n-1} \tag{2}$$

The values of m and n (derived from the simulated rainfall experiment) were 1.4, and 1.6.

The following year, Smith (1941) expanded Zingg's work to

$$A = CS^{1.4} L^{0.6} P \tag{3}$$

where P is the ratio of soil loss with a mechanical conservation practice to soil loss without the practice. Smith retained the m and n values on length and slope derived by Zingg. He used Eq. (3) with measured annual values of A, and values of S and L from individual plots on the Shelby loam soil to compute C values for various rotations and soil treatments. Smith's work also established the concept of an allowable soil loss—now known as the "T Value", (tolerable soil loss value) which he based on maintenance of soil fertility, which was about 4 tons/acre for the Shelby soil in Missouri.

Browning et al. (1947) presented a full soil erosion prediction technology based on Smith's work that included a soil erodibility factor. They developed soil erodibility factors and permissible soil loss limits for a suite of Iowa soils, and used Smith's equation to compute slope length limits for management of these soils.

Also in 1947, a diverse group of workers led by G. W. Musgrave (Browning and Smith were included in this group) met to evaluate the factors involved in soil erosion. They represented a very broad range of erosion, crop production, soils and climate experiences. From this work, an equation called the Musgrave equation (Musgrave, 1947) was developed. The result was the first complete equation for predicting soil erosion. The relationship is shown in Table 1.

There was considerable interest in the use of a single technology for predicting soil loss across the U. S., and the work in the late 1940's and early 1950's had produced very useful results for much of the country. But there was no consensus on a final form, particularly for the effect of rainfall. In 1954, the National Runoff and Soil Loss Data Center (NRSLDC) was established by the USDA-ARS at Purdue University in West Lafayette (Indiana). The NRSLDC was to be the central location for the soil erosion data that had been collected at the soil erosion research stations. The center was responsible for summarizing and analyzing this immense data set—eventually exceeding 10,000 plot years of soil erosion and runoff data.

From 1954 onward the focus was on analyzing the existing data sets, and developing an overall scheme for analyzing these data to support a broader prediction technology built on the previous work. Major works published related to the accomplishment of this goal included:

- Factors affecting sheet and rill erosion (Smith and Wischmeier, 1957).
- Rainfall energy and its relationship to soil loss (Wischmeier and Smith, 1958).
- A rainfall erosion index for a Universal Soil-Loss Equation (Wischmeier, 1959).
- Cropping-management factor evaluation for a Universal Soil-Loss Equation (Wischmeier, 1960).
- First publication of the USLE in an ARS Special Report. A universal equation for predicting rainfall-erosion losses—An aid to conservation farming in humid regions (Wischmeier and Smith, 1961).
- Soil-erodibility evaluations for soils on the runoff and erosion stations (Olson and Wischmeier, 1963).

- 1^{st} publication of the USLE in a USDA Agriculture Handbook. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains—Guide for selection of practices for soil and water conservation(Wischmeier and Smith, 1965).
- 2^{nd} publication of USLE in a USDA Agriculture Handbook. Predicting rainfall-erosion losses—A guide to conservation farming(Wischmeier and Smith, 1978).
- Publication of RUSLE in a USDA Agriculture Handbook. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation(RUSLE)(Renard et al., 1997).

Table 1 **Equations in the development of the Universal Soil Loss Equation**

Zingg, 1940	$A = C'L^{0.6}S^{1.4}$
Smith, 1941	$A = C''L^{0.6}S^{1.4}P$
Browning, 1947	$A = C'''L^{0.6}S^{1.4}P$
Musgrave, 1947	$A' = (P_{30}/1.25)^{1.75}K'(L/72)^{0.35}(S/10)^{1.35}C^*$
USLE, Wischmeier & Smith, 1965	$A = RK(L/72.6)^{0.5}(0.065+0.045S+0.0065S^2)CP$
USLE, Wischmeier & Smith, 1978	$A = RK(L/72.6)^{0.5}(65.4\sin 2\Theta+4.56\sin\Theta+0.065)CP$
RUSLE, Renard et al., 1997	$A = RK(L/72.6)^{M}(a\sin\Theta + b)CP$

A—Soil loss in tons/acre; A′—Soil loss in inches of depth
C′, C″, C‴—Coefficients, C^*—Vegetal cover factor
P_{30}—Maximum Precipitation amount(inches) falling in 30 minutes in a storm
R—Rainfall and runoff erosivity factor = $\sum EI_{30}$ in hundreds ft-tons inch/acre hr
E—Storm rainfall energy in hundreds of ft-tons per acre
I_{30}—Maximum rainfall intensity in a 30 minute period within a storm in inches/hour
K′—Musgrave equation soil erodibility factor(in/yr)
K—USLE soil erodibility factor in(0.01 ton acre hour / Acre ft-ton inch)
L—Slope length in feet, S—Slope gradient in percent
Θ—Slope angle in degrees, C—Cropping management factor
P—Conservation practice factor
M—Exponent on length term-values depend on slope or slope and rill/interrill ratio
a, b—Coefficients in function making up slope term-values depend on slope

3.1 *Unit plot concept*

The unit plot concept was widely used in establishing factor values for the USLE. The unit plot was defined as a plot 72.6 feet long with a uniform 9% slope, maintained in a continuous regularly tilled fallow condition with up-and-down hill tillage. The unit plot was used as a base condition to which all other topographic, cropping and management, and conservation practices were related. Data collected on plots that had different slopes and lengths could be adjusted to the unit plot slope and length, and then compared across locations to establish reliable factor values. The Unit Plot concept was extremely useful, but there is little evidence that there ever existed an actual "Unit Plot".

3.2 *Rainfall factor*

In 1958, Wischmeier and Smith used precipitation and soil loss data from fallow plots at Bethany, Missouri; Clarinda, Iowa; and LaCrosse, Wisconsin to determine the best characteristics of rainfall for estimating storm soil loss. The results indicated that the rainfall characteristic best for estimating single storm soil erosion was the product of the total kinetic energy(E) of a storm and the maximum rainfall intensity over a continuous 30 minute period during the rainstorm(I_{30})—this was known as the storm EI_{30} or commonly EI, and the summation of these EI values over a year was the R factor. Wischmeier(1959) evaluated the R factor's suitability at other locations, and for various cropping periods. In all cases, including management, crops, soils and climates far different than those in the 1958 analysis, the R value proved to be a good rainfall characteristic for estimating soil loss. Periods included seasonal and annual periods. By 1965 when Agriculture Handbook 282 was published, data showing the distribution of EI for half month periods for areas east of the Rocky Mountains, as well as a map giving average annual values for the same areas were available for use in predicting period or average annual soil loss. Additionally, statistics related to probabilities of occurrence of single-storms and single year R values were given for many locations in the United States.

3.3 *K—Soil erodibility factor*

The first step in soil erodibility (K) evaluations for the USLE was the publication of K values for the runoff and erosion stations. Olson and Wischmeier (1963) computed soil erodibility values based on the new rainfall factor. Wischmeier and Mannering (1969) used a rainfall simulator in a study to measure soil loss on 55 Corn Belt soils. They computed soil erodibilities from the data adjusted to the unit plot. Then, they related soil erodibility to a number of variables using multiple regression techniques. A major finding was that very fine sand behaves much more like silt than like sand. These data were further analyzed and used with the benchmark soils'erodibilities to develop a soil erodibility nomograph (Wischmeier et al., 1971) that has been proven as a good tool for estimating soil erodibility for most soils. This was a critical step for the widespread use of the USLE.

3.4 *LS—Length and steepness of slope factors*

Smith and Wischmeier (1957) evaluated the effect of slope and length on soil erosion for several locations. They defined slope length as the distance from the point of origin of overland flow to either where the slope decreases to the point that deposition begins, or to the point where runoff entered a well-defined channel. They expressed the effect of slope length as:

$$L = (\lambda/72.6)^{m} \tag{4}$$

where L is the slope length factor, λ is slope length (ft), and m is the slope length exponent.

The data evaluated to determine the relationship between slope steepness and soil loss included slope gradients ranging from about 1% to 25%. No single data set covered the entire range. The derived function was a quadratic relationship (with only positive coefficients on slope gradient):

$$S = (0.43 + 0.30s + 0.043s^{2})/6.613 \tag{5}$$

where S is the slope factor and s is slope gradient (%). There were no data used above a steepness of 25%, so relationships above that were extrapolated beyond the range of the experimental data. As shown in Table 1, the effect of slope on soil erosion has evolved, but there is little difference in the predicted effect of slope on soil erosion between the relationships up to slope gradients of about 20%. While severe soil erosion occurs on many slopes above 20%, most agricultural applications occur at lesser slopes, although there are significant exceptions. In the USLE the relationship between land slope gradient and the S value insured that the rate of increase of S would always increase. McCool et al. (1987) found this was not the case, and developed a new relationship between slope gradient and the slope factor that is used in the Revised Universal Soil Loss Equation (RUSLE, Renard et al., 1997).

3.5 *C—Cropping and management factor*

The Cropping and Management Factor (C) for the USLE is the ratio of soil loss from a particular cropping and management to soil loss from a continuously tilled fallow area. With the R value valid for seasonal periods, crop stage periods could be used rather than annual values in determining seasonal cropping and management factor values (Wischmeier, 1960). This was a major difference between the USLE and the preceding erosion prediction technologies. It was also the beginning of much greater flexibility in applying the USLE to new situations—including construction and forest applications. Eventually, this led to a subfactor approach to computing cropping and management factors (Wischmeier, 1975). A subfactor approach was followed in development of RUSLE (Laflen et al., 1985, Renard et al., 1997, Laflen and Moldenhauer, 2003).

3.6 *P—Conservation practices factor*

The Conservation Practices Factor (P)—later called the Erosion-Control Practice Factor (Wischmeier and Smith, 1965) and Support Practice Factor (Wischmeier and Smith, 1978)—is the ratio of soil loss for a specific practice to the soil loss with up-and-down hill culture. P values are available for most practices, and include slope length limits, and values that vary by land slope. RUSLE has major improvements in estimation of the effect of conservation practices.

3.7 *Universal Soil Loss Equation impact*

The USLE is one of the most significant advances in soil and water conservation in the 20th Century. Its influence extends to every continent on earth (except Antarctica), and it is an important part of many models (Table 2).

Table 2 Models developed that include USLE technology as part of the model

SWAT	Soil and Water Assessment Tool(Arnold et al. ,1998)
EPIC	Erosion Productivity Impact Calculator(Sharpley and Williams,1990)
RUSLE	Revised Universal Soil Loss Equation(Renard et al. ,1997)
AnnAGNPS	A Gricultural NonPoint Source pollution model(Bingner et al. ,2011)
SLEMSA	Soil Loss Estimation Model for Southern Africa(Elwell,1978)
MUSLE	Modified Universal Soil Loss Equation(Williams,1975)
SOILOSS	Similar to RUSLE,developed in Australia(Rosewell and Edwards,1988)

4 WEPP(Water Erosion Prediction Project)

During the late 1970s, the successful development of a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems—CREAMS(Knisel, 1980), and the increasing use of computers demonstrated that a new generation of erosion prediction technology built upon fundamental processes, and operated via computer, was a distinct possibility. At that time, technology was being delivered by central computer systems, and it seemed that it would be possible soon to deliver via a personal computer a sophisticated erosion prediction system that employed a fundamental process model. In 1983, Foster, Laflen and Alonso(Foster et al. , 1985) made the case for replacing the USLE, expressed the requirements for a USLE replacement, discussed the theory that might be used and explored the experimental challenges that might be encountered and the experimental approaches that might be followed in replacing the USLE.

There were well known shortcomings in the USLE that limited its applicability to many problems. It did a very poor job in estimating short term soil erosion. It did not consider deposition. The rainfall factor in the USLE expressed detachment as a function of rainfall energy, a major weakness when erosion was due to snowmelt or irrigation(This had been worked around when the MUSLE was developed by Williams et al. [1971]).

In April 1985, two workshops were held in Lafayette, Indiana, one to arrive at a consensus regarding a revision of the USLE(eventually named the Revised Universal Soil Loss Equation—RUSLE) and the other to begin planning for a technology(which eventually became the Water Erosion Prediction Project—WEPP model) to replace the empirical USLE for erosion prediction. G. R. Foster was designated to lead both efforts beginning in 1985.

By 1986, WEPP planning was well advanced. Foster, working with a project management consultant, and with a selected Core Team of scientists and federal user agency representatives, prepared a research and development plan that was to deliver a working model by August 31, 1989.

The WEPP hillslope model components planned included plant growth, residue management and decomposition, water balance, weather generation, soil disturbance by tillage, rill and interrill soil detachment, sediment transport and deposition, and sediment particle size distributions. The user agencies(Soil Conservation Service [SCS], Forest Service [FS], Bureau of Land Management [BLM]) were very interested in a model that mimicked what took place on the land that impacted soil erosion. Later, the individual hillslopes were to be structured together with channels and impoundments into small watersheds, with soil detachment, sediment transport and deposition simulated.

There was considerable debate on what kind of plant growth submodel was needed. It was felt by the user agencies that their experience was that plant growth and residue production varied from year to year, and within a season due to weather, and this impact needed to be reflected in WEPP so that realistic estimates of erosion and its variability could be computed. On the basis of that discussion, the plant growth model in EPIC was selected.

In development of the plan, several meetings were held with the federal agencies that would be the major users of the technology to establish the criteria the WEPP model must meet. These were published as the WEPP User Requirements(Foster and Lane, 1987), and were approved by each of the Federal user agencies(SCS, FS, and BLM) and by the Agricultural Research Service(ARS) charged with developing the technology.

Work was underway in 1986 in developing field research projects to collect data for soil erodibility, hydraulic conductivity, and rill characteristics. In 1987 – 1988, the field experiments were conducted(Simanton et al. , 1987; Elliot et al. , 1989; Gilley et al. , 1990; Laflen et al. , 1991). Regular meetings were held of those working on WEPP to coordinate efforts, to review progress, and to resolve scientific and modeling issues. A major effort was made to evaluate overall progress toward meeting the project timelines that had been established. Additionally, these meetings provided opportunities for user agencies to insure that the model would meet their needs.

In August 1989, the first prototype of the WEPP hillslope erosion model was delivered to the federal agencies. In 1995, the complete documented and validated WEPP model (Flanagan and Nearing, 1995), including both hillslope and watershed versions with a text-based DOS interface was delivered to the user agencies and publicly released. It was clear that computer technology was changing rapidly, and users soon indicated that the text-based interface would not meet their needs. Major efforts to develop graphical user interfaces for WEPP began in 1996 (Flanagan et al., 1998), and these efforts continue today to make WEPP usable in a wide array of applications.

Flanagan et al. (2007) provide a more complete description of WEPP model development history and future directions through 2007. Considerable recent efforts have been related to improvement of selected model components and development of geo-spatial interfaces. WEPP model science improvements have included adapting the model to better simulate forested regions that are dominated by subsurface flows (Dun et al., 2009), and improvement of modeling of frost and thaw development in a soil under winter conditions, and subsequent snow melting and runoff erosion (Dun et al., 2010). Geo-spatial interfaces to apply WEPP include an ArcView/ArcGIS extension (GeoWEPP), and WWW-based GIS software to simulate small watersheds and their runoff and erosion potential (Flanagan et al., 2013). Targeted development of tailored WWW-based watershed GIS interfaces for Great Lakes forested watersheds and the Lake Tahoe basin are in progress.

Some areas in WEPP which may be changed and enhanced in the future include effects of soil hydrology on erodibility and sediment transport capacity, freeze/thaw effects on soil erodibility, wind-driven rain effects on interrill detachment, and ephemeral gully erosion predictions. Ongoing research at the USDA-ARS National Soil Erosion Research Laboratory (NSERL), the descendent of the NRSLDC on the campus of Purdue University, has documented significant effects of soil drainage and seepage conditions on subsequent soil erosion, with soil loss observed under seepage conditions being up to twice as great as when a surface is drained (Nouwakpo and Huang, 2012). McCool et al. (2013) recently evaluated WEPP erosion predictions from fallow plots subjected to freeze/thaw conditions in the Palouse region of Washington State, and found that current WEPP model adjustments for rill erodibility and critical shear stress may be inadequate to describe the observed changes in these values for the soil at the experiment station in Pullman, WA. Wind that occurs within a rain storm event can change the trajectory and velocity of raindrops, producing significant changes in interrill erosion (Erpul et al., 2013a, 2013b). Changes to WEPP model interrill detachment functions to account for wind effects could improve erosion predictions, particularly for hillslopes in which interrill processes dominate and in areas in which rain is often accompanied by strong winds. Improvement of prediction of the location and amount of ephemeral gully erosion has been identified as a major research need by NRCS.

5 Applications

The Forest Service and the Bureau of Land Management have adopted the WEPP model for use in erosion prediction and in management of their land resources. The Forest Service has an extensive WWW presence where the user can develop the information needed to make reliable estimates for forest conditions using WEPP (http://forest.moscowfsl.wsu.edu/fswepp/). The Bureau of Land Management has developed training modules for online WEPP training of BLM personnel (http://lesami.geog.buffalo.edu/blm_modules/BLM_Modules.htm). Very recently the Natural Resources Conservation Service (NRCS, formerly SCS), has provided grant funding to ARS to assist them with WEPP model implementation over the next two years (2013 – 2015).

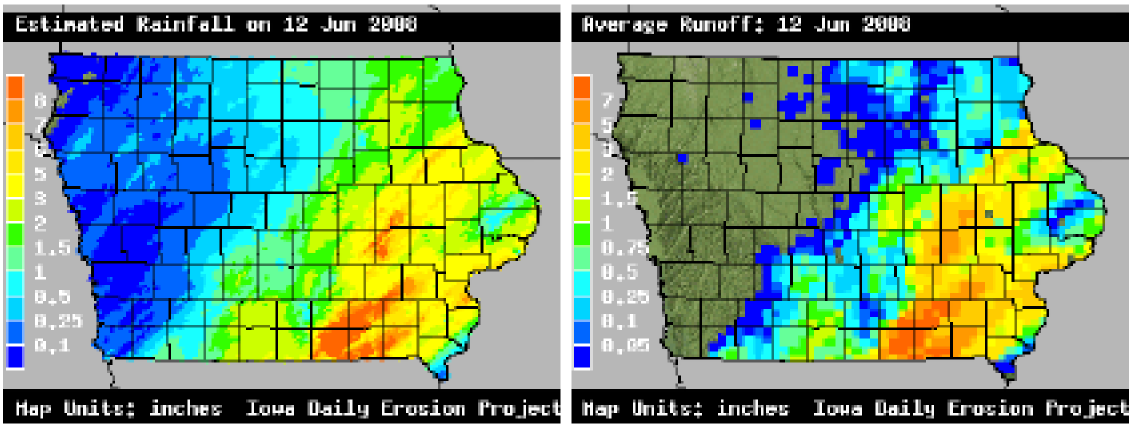
The FS has used WEPP to identify burned areas (from wildfires) with the greatest potential for soil erosion and most value for remediation. By mid-2012, the model had been used to target over $25 million in federal funds for placement of wildfire burned area remediation practices (personal communication – W. J. Elliot). WEPP is also used to evaluate the effects of timber harvesting operations, road placement and road design on erosion and off-site sediment losses. The BLM uses WEPP in a similar way to evaluate remediation of damaged lands for the public lands that they manage, mostly rangelands in the western part of the United States. Often BLM will utilize the FS interfaces and conduct joint training sessions.

WEPP was a significant part of the successful cleanup of a superfund site, the Rocky Flats Nuclear weapons plant, about 24 km from Denver, Colorado, USA (Clark et al., 2006). About 2.5 million people live within 80 km of the site. Various radioactive materials were stored and processed there for nearly 40 years, with some high losses to the environment. Research studies at the site found that most of the radioactive materials moved adsorbed to small soil particles. WEPP was chosen as the modeling tool to assist in estimating sediment (and contaminant)

movement, and designing appropriate remediation efforts. Because of the science based approach—which included the WEPP model, the Rocky Flats cleanup proceeded much faster and at a far less cost than had been estimated. The cleanup had initially been estimated to cost more than $37 billion and take 70 years to complete. The final total cost was $7 billion, and the time required to complete the project was only 9 years.

An important application of WEPP that gives a view of the potential of the model is the near real-time daily prediction of soil erosion for the state of Iowa (Cruse et al., 2006) (http://wepp.mesonet.agron.iastate.edu/). The database that supports the soil, cropping, management, and topography needed for WEPP operations is the 1997 NRCS National Resources Inventory (NRI; USDA, 1997), which provides the cropping sequence for a 4 year period, the USLE *C* value, the slope and length of the area, and the soil type. Precipitation is determined as the amount of rainfall by 15 minute periods within a day and is measured by Doppler radar. The expected geographic coverage for an individual Doppler measurement was about 6.25 square miles (at the beginning of the project). Other climate data (solar radiation, wind velocity, temperatures, and relative humidity) are obtained on a regional basis, with each region averaging about 11% of the area of Iowa. Runoff, soil erosion, and soil moisture estimates are averaged on a township basis, using all NRI point information within each township. An example daily map output is shown in Fig. 2 for an extreme event that occurred on June 12, 2008. Major flooding occurred in two Eastern Iowa Cities on that day. In addition, the Iowa Daily Erosion Project (IDEP) web pages allow the user to map rainfall, runoff, soil erosion and soil moisture for every day since the spring of 2002, and to aggregate the daily values into any continuous desired time periods.

Efforts in IDEP are underway to update the methodology used to populate the soils, management, and topography databases using remotely sensed information to enable finer resolution and more current model management inputs than the 16-year old township level NRI allows. Methods for determining crop rotations and tillage practices and for processing the state LiDAR data to accurately determine profile slope and length have been developed. These methods could also extend the Daily Erosion Project beyond the boundaries of Iowa.



Soil Erosion Soil Moisture

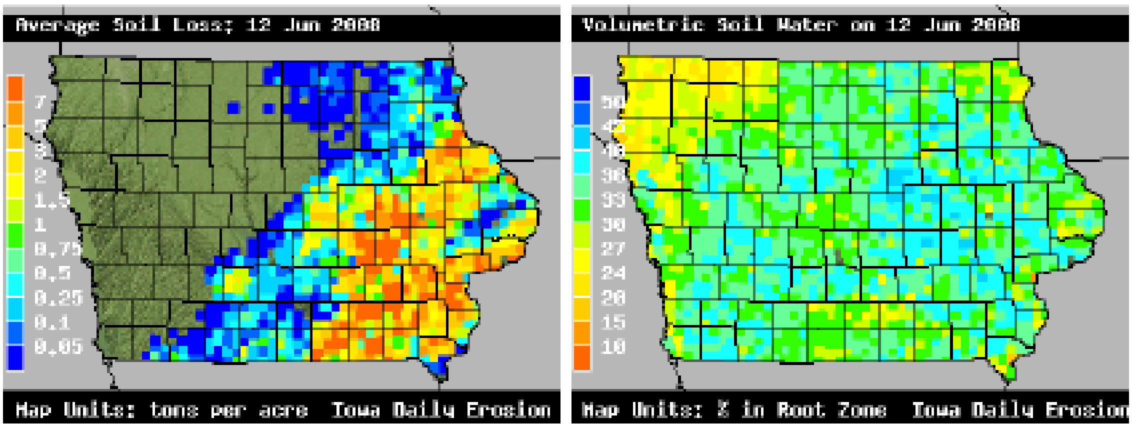


Fig. 2 Iowa Daily Erosion Project output for June 12, 2008

6 Future developments in soil erosion modeling

Meyer(1984)expressed clearly that the development of soil erosion modeling had proceeded along an evolutionary path. This is particularly evident in the development of the USLE and technologies later developed that use considerable portions of the USLE(RUSLE,MUSLE,EPIC,SWAT,AGNPS,and others).

The experience with CREAMS showed that an erosion-sediment yield model incorporating fundamental erosion-sediment transport relationships could be developed to evaluate best management practices,and that the estimates would be improved over that of the USLE and a modified form of the USLE(Foster et al. ,1981). This finding gave confidence to the selection of the rill-interrill and other concepts used in WEPP. What new findings will give us confidence to move ahead another large step?

A large step was taken when remote sensing began to be used in erosion and sediment transport modeling. Software that allows the determination of flow paths has been critical in modeling watersheds. But,the remote sensing of topography that might be suitable in modeling flow in channels has only recently been used,and the coverage of these data needs to be extended. Additionally,while it may be possible to locate the positions of channels, and the area that channels drain,are the dimensions of these channels measured well enough to compute the flow characteristics accurately that will determine the estimates of channel erosion,sediment transport and sediment delivery and deposition? Additionally,do we have the science needed to suitably estimate both classical and ephemeral gully erosion? Likely,the way to proceed ahead is to make our best estimates of channel dimensions,creatively model ephemeral and classical gully erosion,and move ahead while conducting evaluations. After all,we have used the USLE for over a half century,and it wasn't until Nearing et al. (1999)published the results of statistical analyses and Tiwari et al. (2000)published a comparison of USLE measured and predicted soil erosion that we had any idea of the reliability of USLE estimates for prediction of single storm soil erosion or average annual soil erosion.

But,the improvement in the models always requires improvement in the sciences and very significant steps in expansion of the technologies that support the applications. Many of these will be powerful,but totally unexpected. Many of them will require long term development to apply them.

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