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Modeling Soil and Water Conservation

Dennis C. Flanagan, Larry E. Wagner, Richard M. Cruse, and Jeffrey G. Arnold

Great strides have been made over the past 75 years toward conserving the United States' precious soil and water resources. The earliest national soil conservation efforts began in the 1930s when the US Department of Agriculture Soil Conservation Service (USDA SCS) was created in response to severe wind erosion during the Great Plains' Dust Bowl. In addition to working with farmers and landowners to implement soil conservation practices on the land, SCS also conducted research at 35 soil conservation experiment stations located across the United States. These locations provided long-term natural rainfall/runoff plot data that were used in the development of the Universal Soil Loss Equation (USLE), the first widely used erosion prediction model. Modeling efforts after development of the USLE expanded into effects of erosion on soil productivity; runoff and water quality from agricultural lands; watershed-scale runoff, sediment, and pollutant losses; and systems for process-based predictions of water or wind erosion. Wind erosion research and modeling was a direct response to the Dust Bowl, with the empirical Wind Erosion Equation (WEQ) first published in 1965. This chapter looks back through history at soil and water conservation modeling efforts, describes current state-of-the-art models, and discusses future modeling needs.

Dennis C. Flanagan is a research agricultural engineer, USDA Agricultural Research Service (ARS), National Soil Erosion Research Laboratory, West Lafayette, Indiana. **Larry E. Wagner** is a research agricultural engineer, USDA ARS, Rangeland Resources and Systems Research Unit, Fort Collins, Colorado. **Richard M. Cruse** is a professor and director of the Iowa Water Center, Iowa State University, Ames, Iowa. **Jeffrey G. Arnold** is a research agricultural engineer, USDA ARS, Grassland Soil and Water Research Laboratory, Temple, Texas.

Early Water Erosion Research and Modeling Efforts

The first field research in the United States to focus on soil erosion by water was conducted by F.L. Duley in 1917 on seven erosion plots in Columbia, Missouri (Duley and Miller 1923). Soil Conservation Experiment Stations (SCES) were installed by the USDA beginning in 1930, initially at 10 locations (9 east of the Rocky Mountains and 1 in Pullman, Washington), and ultimately expanded to 35 sites (Gilley and Flanagan 2007). Plots were commonly 2 m wide by 22 m long (6 ft wide by 72.6 ft long; 1% of an acre). Slope gradients used were those available at each site, and some locations had plot lengths shorter or greater than 22 m. Experimental treatments usually included continuous tilled fallow for a baseline worst erosion case, as well as various cropping and management practices, with typical crops and crop rotations for each station's region of the country. Different soil conservation practices were also tested at these stations (e.g., contouring, strip-cropping, etc.) to gauge their effect on reducing erosion caused by water.

The first mathematical description of soil erosion, developed by Austin W. Zingg in 1940 using experimental data from natural and simulated erosion studies on a loam soil in Missouri, was

$$X = C \times S^{m} \times L^{n}, \qquad (1)$$

where X was total soil loss (kg [lb]) from a land slope of unit width, C was a constant, S was land slope (%), L was horizontal length of land slope (m [ft]), and m and n were exponents. Zingg calculated average soil loss per unit area from a unit width slope as

$$A = C \times S^{m} \times L^{n-1}, \qquad (2)$$

and the values of C, m, and n were 0.026, 1.4, and 1.6, respectively (Zingg 1940).

D.D. Smith (1941) expanded on Zingg's work, and expressed average soil loss as

$$A = C \times S^{1.4} \times L^{0.6} \times P, \qquad (3)$$

where P was the ratio of soil loss with a mechanical conservation practice to soil loss without the practice. He retained the m and n values derived by Zingg and used equation 3 with measured annual values of A, and values of S and L from individual plots on the loam soil in Missouri to compute C values for various soil treatments and crop rotations. Smith also established the concept of an allowable soil loss—now referred to as the tolerable soil loss "T" value—that he based on soil fertility maintenance, which was about 9 Mg ha^{-1} y^{-1} (4 tn ac^{-1} yr^{-1}) for the Shelby loam soil in Missouri. (T values across the United States range from 1.1 to 13.4 Mg ha^{-1} y^{-1} [0.5 to 6.0 tn ac^{-1} yr^{-1}] [Smith and Stamey 1965].)

A full soil erosion prediction model, based on Smith's work, which included a soil erodibility (K) factor, was presented by Browning et al. (1947). They developed K factors and allowable soil loss values for several soils in Iowa, and used Smith's equation for managing these soils with slope length limits, though the equation was still site specific. Musgrave (1947) presented an alternative equation to predict soil erosion, which included a rainfall term (maximum precipitation falling in 30 minutes within a storm) and was the first complete equation to predict erosion by water from individual rain storms.

A national effort began in the 1950s to incorporate the effect of rainfall on soil erosion by water, and assemble and analyze all of the existing runoff and soil loss data collected from the SCES. There was widespread interest in having a single technology for erosion by water calculation, to replace the multiple regional equations. The newly created (in 1953) USDA Agricultural Research Service (ARS) established the National Runoff and Soil Loss Data Center (NRSLDC) at Purdue University in West Lafayette, Indiana, in 1954. The NRSLDC became the central location for over 10,000 plot years of natural runoff plot data. The research leader, Walter H. Wischmeier, conducted extensive statistical analyses to isolate the major factors affecting soil erosion by water, which culminated in the development and publication of the USLE in Agriculture Handbook 262 (Wischmeier and Smith 1965). USLE is

$$A = R \times K \times L \times S \times C \times P \,, \tag{4}$$

where A is average annual soil loss in tonnes per hectare (tons per acre), R is the rainfall/runoff erosivity factor (MJ mm ha^{-1} h^{-1} y^{-1} [100 ft-tn in ac^{-1} hr^{-1} yr^{-1}]), K is the soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1} [0.01 tn ac hr ac^{-1} ft-tn^{-1} in^{-1}]), L is the slope length factor, S is the slope steepness factor, C is the cover and management factor, and P is the support practice factor. USLE has been extensively applied by SCS and others and was updated in Agriculture Handbook 537 (Wischmeier and Smith 1978).

Early Wind Erosion Research and Modeling Efforts

Wind erosion observations in the United States were first noted in the Midwest and West, beginning in the late 1800s (Tatarko et al. 2013). Severe wind erosion occurred in the Great Plains as a direct result of the combined effects of tilling of prairie soils to grow wheat, bare soil practices that left the land exposed, long stretches of landscape with little resistance to wind velocities, and consecutive years of drought and failed crops. This was especially the case during the 1930s in the Dust Bowl regions of Kansas, Oklahoma, Colorado, Texas, and New Mexico, where frequent huge dust storms detached and transported soil particles hundreds to thousands of miles away.

The extreme environmental and economic effects of the Dust Bowl resulted in the US government funding erosion control and research activities, and the establishment of the SCS in 1935, as part of the Soil Conservation Act. SCS continued research efforts at the SCES mentioned earlier, which focused mainly on water erosion research and control, while Congressional action to more fully address wind erosion research and control efforts was part of the Agricultural Marketing Act of 1946. This act established an SCS Wind Erosion Project and laboratory on the campus of the Kansas State Agricultural College in 1947, which later became part of ARS in 1953. Groundbreaking research was conducted there, first by mechanical engineer Austin W. Zingg and later by soil scientist William S. Chepil, on wind erosion measurement techniques (Zingg 1951a; Zingg and Woodruff 1951) and process mechanics (Zingg 1949, 1951b, 1953; Zingg and Chepil 1950; Zingg et al. 1952). This research group identified five main factors affecting wind erosion: climate, soil cloddiness, ridge roughness, field length, and vegetative material (Chepil and Woodruff 1954, 1959, 1963; Chepil 1960; Chepil et al. 1962). The group's initial wind erosion model was

$$E = I \times R \times K \times F \times B \times W \times D \,, \tag{5}$$

where E was the quantity of soil eroded (t ha^{-1} y^{-1} [tn ac^{-1} yr^{-1}]), I was a factor for soil cloddiness, R was a factor for residue, K was a factor for roughness, F was a factor for soil abradability, B was a factor for wind barrier, W was the width of the field (m [ft]), and D was the wind direction (Chepil 1959). I, R, K, F, and B were all dimensionless and were determined from soil and field properties and use of nomographs and charts. However, wind velocities at different locations were not addressed by this equation. In 1965, the WEQ, based on Chepil's and his coworkers' previous work, was published by Woodruff and Siddoway (1965). WEQ has the form of

$$E = f\,(I \times K \times C \times L \times V) \,, \tag{6}$$

where E is average annual soil loss in tonnes per hectare (tons per acre), f indicates functional relationships that are not direct mathematical calculations, I is a soil erodibility index (t ha^{-1} y^{-1} [tn ac^{-1} yr^{-1}]), K is the soil surface roughness factor, C is the climatic factor, L is the unsheltered distance (field length in m [ft]), and V is a vegetative factor. K, C, and V were dimensionless. WEQ was initially applied on an average annual basis, but was later also applied by the SCS (and USDA Natural Resources Conservation Service [NRCS]) for conservation planning using the Critical Period Method (WEQ Management Period Procedure) that estimated wind erosion during times of the year when fields were most susceptible to soil loss, and when erosion control practices and land management changes would be most effective. This method was later computerized (Skidmore et al. 1970) and eventually implemented as a Microsoft Excel Spreadsheet application by NRCS.

Model Developments to 2000

The 1970s were a time of growing awareness and concern over environmental issues and pollution, with landmark legislation including the Clean Air Act, Clean Water Act, and Endangered Species Act. Modeling efforts during that time expanded from solely soil erosion by water or wind into additional considerations, especially water pollution as well as air and water quality. Where USLE and WEQ were empirical statistical models, new efforts on spatially distributed, process-based and/or hybrid natural resource models began to be developed. Many new models were developed to assess land management practice and chemical application effects on watershed-scale responses (runoff, sediment loss, pollutant losses), in order to meet new water quality goals or target pollutant limits that came about from new environmental regulations. Some of the models developed after USLE and WEQ are listed here.

MUSLE—Modified Universal Soil Loss Equation. This modification of the USLE substituted a runoff factor in place of the *R* factor, allowing prediction of sediment yield from small watersheds for individual storm events (Williams 1975). MUSLE was used for watershed sediment yield predictions and was incorporated as an option into larger catchment models (e.g., SWAT).

ANSWERS—Areal Nonpoint Source Watershed Environment Response Simulation. This was one of the first gridded distributed parameter watershed models and was developed at Purdue University by Beasley et al. (1980) as part of the Black Creek Watershed Project in northeastern Indiana in the 1970s.

CREAMS—Chemicals, Runoff, and Erosion from Agricultural Management Systems. This was a major USDA effort to comprehensively simulate hydrology, sediment detachment and transport, and chemical loss and transport from agricultural fields (Knisel 1980) that included both empirical and process-based components for hydrology, erosion by water, and chemical transport. It evolved into the GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) model (Leonard et al. 1987). Improvements were made in GLEAMS to better represent soil layering, crop rotations, irrigation, soil water routing, and chemical movement (Knisel and Douglas-Mankin 2012). Many of the components, especially the water quality logic and equations, were adapted and used in other subsequent models.

EPIC—Erosion Productivity Impact Calculator. This tool was developed by USDA ARS to estimate the effect of soil erosion on soil productivity (Williams et al. 1984) and effects of management decisions. It simulated hydrology, weather, erosion, nutrients, soil temperature, plant growth, tillage effects, plant environmental controls, and economics. EPIC has evolved into the Environmental Policy Integrated Climate model, as its functionality was expanded to include irrigation, pesticide losses, carbon dynamics, and climate change effects (Izaurralde et al. 2006).

RUSLE/RUSLE2—Revised Universal Soil Loss Equation (Versions 1 and 2). RUSLE (Renard et al. 1997) and RUSLE2 (USDA ARS 2013) were developed by USDA ARS and built upon the empirical USLE technology with updated factors and the addition of some process-based science to allow for simulation of erosion and deposition on complex slopes and management systems where sediment deposition may occur (slope concavities, filter strips). NRCS databases allow application to over 20,000 land management scenarios. While RUSLE functioned on a 15-day time interval, RUSLE2 operates on a 1-day time step, with time-varying erodibilities and crop residue decay.

AGNPS—AGricultural NonPoint Source Pollution Model. This was an event-based model developed by USDA ARS to simulate runoff, sediment, and nutrient losses from agricultural watersheds (Young et al. 1989). In a cooperative project with NRCS, the tool was converted into a continuous simulation model, which allows for detailed evaluations of cropping/management and conservation practice effects on runoff, sediment, and pollutant losses from hillslopes, channels, and streams. AnnAGNPS (Annualized AGNPS) includes updated routines for stream network processes, ephemeral gully erosion prediction, a stream corridor model, an instream temperature model, and several salmonid models (Cronshey and Theurer 1998; Yuan et al. 2001).

APEX—Agricultural Policy/Environmental eXtender Model. This extends the capability of the EPIC model to application to fields and small watersheds and farms with spatially varying soils, cropping, and land management practices (Williams et al. 1995; Wang et al. 2012). The impacts of soil conservation practices on control of water and wind erosion, as well as losses of nutrients and pesticides from agricultural systems, can be evaluated. APEX has been used in nationwide Conservation Effects Assessment Project (CEAP) evaluations, to examine the effects that use of conservation practices on private lands have had on soil erosion and water quality.

SWAT—Soil and Water Assessment Tool. SWAT (Arnold et al. 1998, 2012) is a continuous simulation, basin-scale, distributed parameter model that allows for analysis of the effects of land and water management practices on flow discharge, sediment losses, and various pollutant losses (nutrients, pesticides, bacteria, pathogens, etc.). SWAT was developed by USDA ARS in Temple, Texas, in cooperation with Texas A&M University, and incorporates many of the components from other modeling efforts (MUSLE, EPIC, APEX, etc.). SWAT and APEX have been used extensively in recent national Conservation Effects Assessments by NRCS and ARS, and SWAT has an immense group of users worldwide (Gassman et al. 2014).

WEPP—Water Erosion Prediction Project. This is a process-based, continuous simulation, distributed parameter soil erosion prediction tool for application to hillslope profiles and small field-sized watersheds. It was developed in a national project by USDA (ARS, NRCS, and Forest Service [FS]) and US Department of the Interior (Bureau of Land Management) from 1985 to 1995, and ongoing maintenance, updates, and applications continue (Flanagan and Nearing 1995; Flanagan et al. 2007). WEPP simulates the important processes controlling upland soil erosion by water, including hydrology (infiltration, runoff, lateral subsurface flow, percolation, etc.), flow hydraulics, detachment by raindrops and flow, sediment transport, sediment deposition, tillage disturbance and soil consolidation, plant growth, residue decomposition, etc. A variety of interface programs have been developed for standalone use within Windows, within a geographic information system (GIS) framework (GeoWEPP), or via web browsers. The hillslope erosion model (HEM) from WEPP has been extracted and utilized in other models for erosion by water predictions. WEPP has been extensively used by the USDA FS for erosion predictions on forested lands and effects of wildfires and forest management practices (Elliot 2013).

WEPS—Wind Erosion Prediction System. This is a process-based, continuous simulation wind erosion modeling system developed by USDA (ARS, NRCS) to replace WEQ (Hagen 1991; Wagner 2013). In addition to greatly improved science describing the detachment, transport (by saltation, suspension, creep modes), and deposition of wind-blown sediments, WEPS also allows for extensive soil conservation practice simulations, including use of windbreaks of varying size and density, conservation tillage practices, and emergency tillage to roughen the soil surface to impede detachment. NRCS has been using WEPS in their field offices since 2010 as a replacement for WEQ.

SWEEP—Single-event Wind Erosion Evaluation Program. This is the wind erosion submodel in WEPS, which is a standalone subdaily timestep program containing its own graphical user interface. If the surface friction velocity threshold is exceeded by the actual surface friction velocity generated by the wind on the specified surface, SWEEP will predict soil loss by wind for a single day given the surface (soil and plant/residue) and wind conditions provided.

Conservation Modeling and Recent Developments

Modeling of soil and water conservation practices today is considerably advanced from the early applications of USLE and WEQ. Continuous simulation models allow updating of soil, plant, and residue conditions for every simulation day, potentially within a long period (100+ years). Thus, climate effects (rainfall, temperatures, wind) combined with land management (tillage, conservation practices), plant growth responses (canopy development, biomass production, yield), and their interactions affect the ultimate response in terms of soil loss, runoff, sediment transport, and pollutant losses. Also, modern models allow for evaluation of conservation effects from hillslopes to channels and streams. For example, a no-till cropping system may adequately control sheet and rill erosion, but could increase surface and/or subsurface water flows that can end up initiating or increasing ephemeral gully or channel erosion. With today's models, the potential for ephemeral gully erosion can be assessed, as well as the effects of conservation practices, such as installation of a grassed waterway. It is also easy to simulate many conservation practices, including no-till, buffer strips, residue/mulch additions, cover crops, contour planting, and strip-cropping.

During the past 10 years, efforts in soil and water conservation modeling have shifted to more process-based modeling efforts, and web-based interfaces and databases served to users via "the cloud." Specifically related to NRCS field-based conservation planning activities, extensive development on these types of erosion prediction tools have been underway as part of cooperative projects between NRCS, ARS, FS, and several universities. These tools provide substantially more output information than just average annual soil loss; simulate numerous environmental and crop/management interactions; and are extremely easy to use, maintain, and update. Some of the most current developments are described below.

RHEM—Rangeland Hydrology and Erosion Model. This is a process-based tool to predict runoff and erosion specifically from rangelands and is based on fundamentals of infiltration, plant science, hydrology, and erosion science (Nearing et al. 2011). It has been recently updated (Hernandez et al. 2017) with improved detachment and sediment transport functions, parameterization equations, and an improved user-friendly web-based interface.

DEP—Daily Erosion Project. This web-based tool was initially the Iowa Daily Erosion Project (IDEP). IDEP utilized NexRad radar precipitation data in Iowa, WEPP, and National Resource Inventory (NRI) data for soils, slope, and cropping to provide near real-time estimates of runoff and soil erosion on a township basis for all of Iowa (Cruse et al. 2006). DEP is an updated version that estimates on a daily basis and publicly reports WEPP-predicted runoff and hillslope sheet/rill erosion at the hydrologic unit code 12 (HUC-12) watershed scale. It uses remotely sensed data and electronic database inputs for precipitation; slope profile identification; and slope, soil, and land management input parameterization (Gelder et al. 2018). DEP is being extended to neighboring states and has a state-of-the-art web interface (figure 1).

IET—Integrated Erosion Tool. Developed by the NRCS Information Technology Center in cooperation with Colorado State University and ARS, IET2 is a common interface program designed for conservation field office users allowing wind and water erosion simulations using WEPS and WEPP, with a single set of common input screens and utilizing web-based climate, soils, and cropping/management databases. An initial version of IET utilized WEPS and RUSLE2.

WEPP—Water Erosion Prediction Project. This is an updated version of WEPP, with changes made specifically targeted for NRCS field office users and better capabilities to simulate conservation practices including contouring, strip-cropping, buffers, etc. (Flanagan et al. 2017, 2018). A new web-based interface for hillslope profile simulations is available (figure 2), and a companion one for field and small watershed simulations is under development. Updated climate (Srivastava et al. 2019), cropping, and operation databases have been extensively tested by NRCS and ARS. The same new web-based services developed as part of this implementation project are also being used in IET2.

Figure 1

Screen capture showing estimated 24-hour precipitation and hillslope soil loss for May 24, 2019, from the Daily Erosion Project (Gelder et al. 2018).

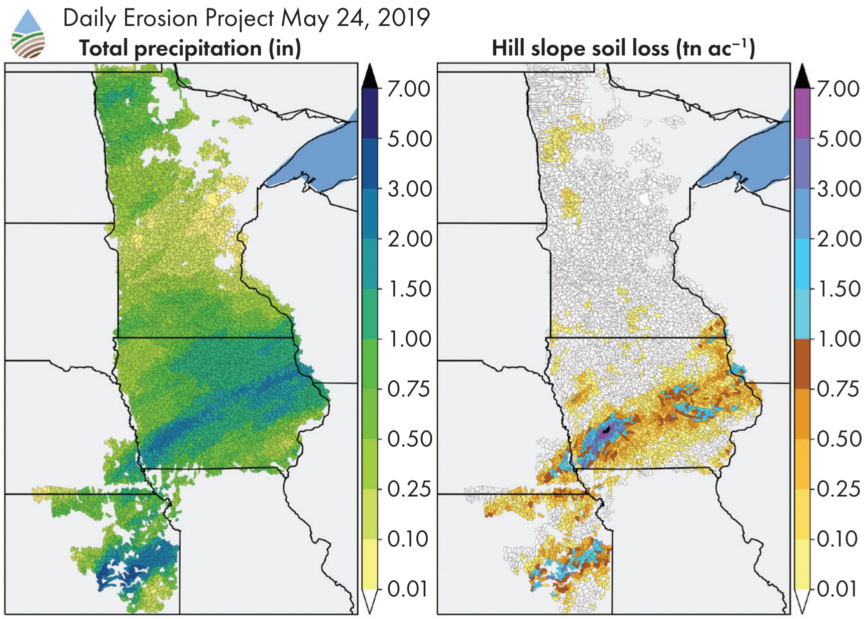
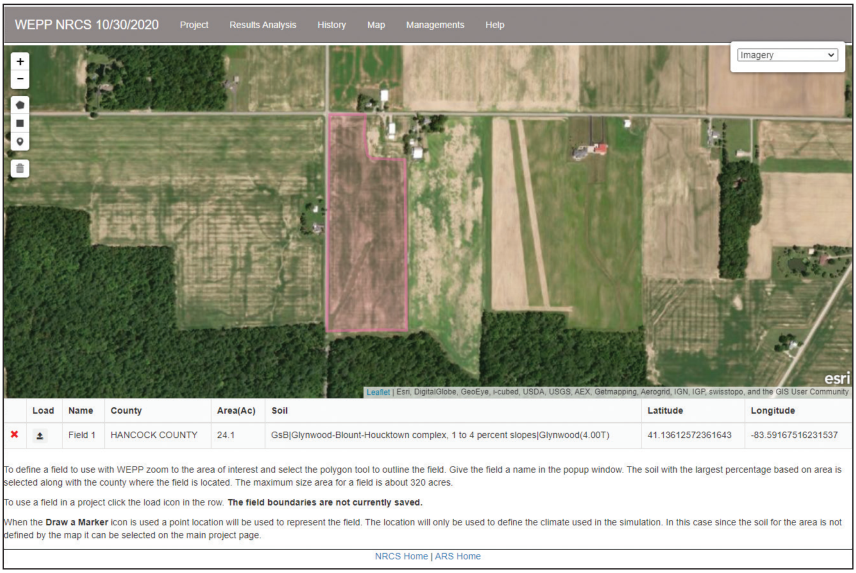


Figure 2

Screen capture of a part of the new Water Erosion Prediction Project (WEPP) web-based interface developed for USDA Natural Resources Conservation Service field office use. A field polygon drawn here provides the geographic coordinates to automatically identify soils, climate, and cropping/management zone inputs available for use in the erosion prediction simulations.

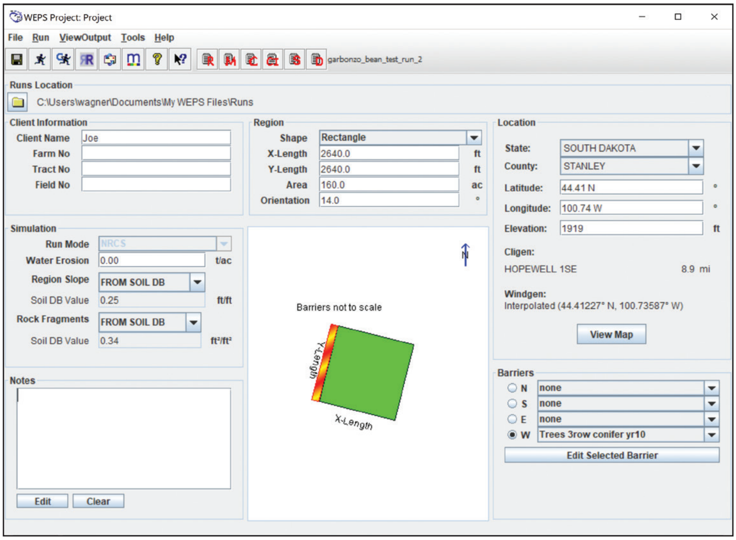


WEPS—Wind Erosion Prediction System. WebStart WEPS is an updated version of WEPS using Java WebStart (figure 3) to install and automatically update WEPS on a client's computer via a web link. It incorporates the use of CSIP (Cloud Service Integration Platform) services (David et al. 2014) for remote access to databases and execution of climate generators, as well as the WEPS science model. This updated version can work with multiple sub-regions, so it can handle fields with multiple soil types and multiple spatial cropping/management practices applied, e.g., strip cropping, cropped/pasture areas, cropped/forested windbreaks. A new interface is being created to allow users to specify the spatially explicit inputs for multi-subregion WEPS and SWEEP simulations. The WEPS science model is also currently incorporating UPGM (Unified Plant Growth Model) to enhance plant growth simulations.

SWAT+—Soil and Water Assessment Tool. SWAT+ is a completely restructured modular version of SWAT (Bieger et al. 2016). This update improves code development and maintenance; supports data availability, analysis, and

Figure 3

Screen capture of the main WebStart Wind Erosion Prediction System (WEPS) user interface window with the five required inputs populated: (1) field location (auto selects climate and wind inputs); (2) field geometry; (3) management/crop rotation; (4) soil component; and (5) field boundary wind barriers (if any).



visualization; and enhances the model's capabilities in terms of the spatial representation of elements and processes within watersheds. The most important changes are (1) spatial object modules allowing more flexible channel and landscape routing, and (2) a relational data input file structure. Also, SWAT+ offers more flexibility than SWAT in defining management schedules, routing sediment and constituents, and connecting managed flow systems to the natural stream network. In addition to use in the USDA CEAP project for national conservation planning (White et al. 2014), a web-based interface was developed for the US Environmental Protection Agency for national environmental assessment (Yen et al. 2016).

Looking to the Future

Natural resources modeling and applications for soil and water conservation will continue to evolve while attempting to adapt to very rapidly changing information technologies and smaller and faster personal electronic devices. Conventional personal computers are being replaced with multifunctional cell phones or tablets, using "apps" (applications) downloaded from the cloud!

The challenge for scientists and modelers is how to adequately simulate the important physical processes controlling hydrology, soil erosion, sediment transport, and pollutant transport for users desiring very minimal data input requirements and summarizing and displaying the most important model output information. With increasingly complex and data-driven models there is also a need for improved input data (e.g., finer spatial and temporal resolution soil data). Runoff, erosion, and pollutant loss forecasting under changing climate and economic analyses of conservation practice costs/benefits are also becoming increasingly important. Evolutionary changes and improvements are underway and expected in many of the current models, but potentially revolutionary changes in interfaces and information delivery may be here soon. Better optimized models are also required for interdisciplinary applications in a constantly changing world.

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