# Using soil erosion models for global change studies

*J. Williams, M. Nearing, A. Nicks, E. Skidmore, C. Valentin, K. King, and R. Savabi*

Future changes in climate and atmospheric $CO_2$ concentration will change the hydrologic cycle, affecting important soil-plant-water interactions, which in turn affect soil erosion rates. Climate and $CO_2$ changes can be estimated with global circulation models (GCMs). Mathematical models are also available for simulating soil erosion as affected by weather and soil-plant-water interactions.

Three major soil erosion models, including Environmental Policy Integrated Climate (EPIC) (formerly the Erosion-Productivity Impact Calculator); Water Erosion Prediction Project (WEPP); and Wind Erosion Prediction System (WEPS), are reviewed and briefly described here. The CLIGEN (Climate Generator) model, which has been refined to simulate changing climate, is also described here.

Stockle et al. (1992) modified EPIC to simulate the effects of $CO_2$ changes on plant growth and water-use efficiency. Recently, the Stockle relationships have been added to WEPP and to the basin scale model SWAT (Soil Water Assessment Tool) (Arnold et al. 1993). These relationships are also described in this paper.

## The EPIC model

The Erosion-Productivity Impact Calculator (EPIC) (Williams et al. 1984) model was originally developed to assess the effect of soil erosion on soil productivity. It was used for that purpose as part of the 1985 RCA (1977 Soil and Water Resources Conservation Act) analysis. Since the RCA application, the model has been expanded and refined to allow simulation of many processes important in agricultural management (Sharpley and Williams 1990; Williams 1995).

EPIC is a continuous simulation model that can be used to determine the effect of management strategies on agricultural production and soil and water resources. The drainage area considered by EPIC is generally field-sized, up to 100 ha (247 ac) (weather, soils, and management systems are assumed to be homogeneous). The major components in EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control.

Recently, most EPIC model development has focused on problems involving water quality and global climate/$CO_2$ change. Example additions include the GLEAMS (Leonard et al. 1987) pesticide fate component; nitrification and volatilization submodels; a new, more physically based wind erosion component; optional Natural Resources Conservation Service (NRCS) technology for estimating peak runoff rates; newly developed sediment yield equations; and mechanisms for simulating $CO_2$ effects on crop growth and water use. With these changes, the model has been renamed—Environmental Policy Integrated Climate.

The runoff addition to the EPIC model simulates surface runoff volumes and peak runoff rates, given daily rainfall amounts. Runoff volume is estimated by using a modification of the NRCS curve number technique (U.S. Department of Agriculture, Soil Conservation Service 1972).

There are two options for estimating the peak runoff rate—the modified Rational Formula and the NRCS TR-55 method (USDA-SCS 1986). A stochastic element is included in the Rational equation to allow realistic simulation of peak runoff rates, given only daily rainfall and monthly rainfall intensity.

The model offers four options for estimating potential evaporation—Hargreaves and Samani (1985), Penman (1948), Priestley-Taylor (1972), and Penman-Monteith (Monteith 1965). The Penman and Penman-Monteith methods require solar radiation, air temperature, wind speed, and relative humidity as input. If wind speed, relative humidity, and solar radiation data are not available, the Hargreaves or Priestley-Taylor methods provide options that give realistic results in most cases.

The weather variables necessary for driving the EPIC model are precipitation, air temperature, and solar radiation. If the Penman methods are used to estimate potential evaporation, wind speed and relative humidity are also required. Wind speed is also needed when wind-induced erosion is simulated. If daily precipitation, air temperature, and solar radiation data are available, they can be input directly into EPIC. Rainfall and temperature data are available for many areas of the United States, but solar radiation, relative humidity, and wind data are scarce. Even rainfall and temperature data are generally not adequate for the long-term EPIC simulation (100 years+). Thus, EPIC provides options for simulating various combinations of the five weather variables.

A single model is used in EPIC for simulating all the crops considered (corn, grain sorghum, wheat, barley, oats, sunflower, soybean, alfalfa, cotton, peanuts, potatoes, durham wheat, winter peas, fava beans, rapeseed, sugarcane, sorghum hay, range grass, rice, casava, lentils, and pine trees). Each crop has unique values for the model parameters. EPIC is capable of simulating growth for both annual and perennial crops.

Potential crop growth and yield are usually not achieved because of constraints imposed by the plant environment. The model estimates stresses caused by water, nutrients, temperature, aeration, and radiation.

The EPIC tillage component was designed to mix nutrients and crop residues within the plow depth, simulate the change in bulk density, and convert standing residue to flat residue. Other functions of the tillage component in-

*J. Williams is a research scientist at the Texas Ag Experiment Station in Temple, Texas; M. Nearing is an agricultural engineer at USDA/ARS, West Lafayette, Indiana; E. Skidmore is a soil scientist at USDA/ARS, Manhattan, Kansas; C. Valentin is with ORSTOM, Niamey, Niger; K. King is an agricultural engineer at the Texas Ag Experiment Station in Temple, Texas; and R. Savabi is a hydrologist at USDA/ARS, West Lafayette, Indiana.*

clude simulating ridge height and surface roughness.

The EPIC component for water-induced erosion simulates erosion caused by rainfall and runoff and by irrigation (sprinkler and furrow). To simulate rainfall/ runoff erosion, EPIC contains six equations—the USLE (Wischmeier and Smith 1978), the Onstad-Foster modification of the USLE (Onstad and Foster 1975), the MUSLE (Williams 1975), two recently developed variations of MUSLE, and a MUSLE structure that accepts input coefficients. Only one of the equations (user specified) interacts with other EPIC components. The six equations are identical except for their energy components. The USLE depends strictly upon rainfall as an indicator of erosive energy. The MUSLE and its variations use only runoff variables to simulate erosion and sediment yield. The Onstad-Foster equation contains a combination of the USLE and MUSLE energy factors.

The original EPIC wind erosion model (WEQ) required daily mean wind speed as a driving variable. The new EPIC wind erosion model, Wind Erosion Continuous Simulation (WECS), requires the daily distribution of wind speed to take advantage of the more mechanistic erosion equation. The new approach estimates potential wind erosion for a smooth bare soil by integrating the erosion equation through a day using the wind speed distribution. Potential erosion is adjusted using four factors based on soil properties, surface roughness, cover, and distance across the field in the wind direction.

The EPIC model with $CO_2$ capabilities has been used in several major studies in the United States, including Robertson et al. (1987; 1990), Easterling et al. (1993), and Lee (1995).

## The WEPP model

***Model description.*** WEPP is a new generation of soil erosion prediction technology for use in soil and water conservation planning and assessment (Flanagan and Nearing 1995). The WEPP model is based on physical descriptions of rill and interrill erosion processes and sediment transport mechanics. It does not use principles, parameters, or logic from the USLE for predicting erosion. Because it is to a large degree process-based, the model is well suited for studying the effects of environmental system changes on hydrologic and erosion processes, including interactions between climate change, hydrologic response, and sediment generation. WEPP is a continuous simulation model and works primarily on a daily time step in terms of updating system parameters that define the surface conditions for each rainfall. The model does not consider wind erosion. The appropriate scale of application ranges from 1 $m^2$ (1.2 $yd^2$) to small watersheds on the order of approximately 1 $km^2$ (0.4 $mi^2$).

The WEPP erosion model includes the following eight major components: climate, infiltration, water balance, plant growth and residue decomposition, tillage and consolidation, surface runoff, erosion, and winter processes.

The daily weather data for WEPP may be inserted by the user or created by the CLIGEN model (Nicks 1985). CLIGEN generates daily precipitation, daily maximum and minimum temperature, and daily solar radiation. Daily precipitation is described by four variables: rainfall depth, peak rainfall intensity, time to peak intensity within the event, and rain duration. WEPP disaggregates the CLIGEN or user rainfall input to generate time-rainfall intensity (break point) data. Given a rainfall amount and rainfall duration, the disaggregation model derives a rainfall intensity pattern with properties similar to those obtained from analysis of breakpoint data. The model will also use measured breakpoint rainfall data directly if available. The breakpoint rainfall data are required by the infiltration component to compute rainfall excess rates and thus runoff.

The infiltration component of WEPP is based on the Green and Ampt equation, as modified by Mein and Larson (1973), with the ponding time calculation for an unsteady rainfall (Chu 1978). Extensive research was conducted (Risse et al. 1994; 1995a; 1995b; Zhang et al. 1995a; 1995b) to develop time-variant infiltration parameters for WEPP.

The water balance component of WEPP is similar to that used in EPIC. It includes percolation and evapotranspiration. The principal model used is based on the Penman equation, with an alternative being the Priestly-Taylor equation when wind and dewpoint temperature data are not available. The Penman-Monteith equation (Monteith 1965) is an option in an experimental version of the model designed for purposes of climate change studies. This version also has coded the equations of Stockle et al. (1992) for consideration of the $CO_2$ effects on plant growth and transpiration.

The plant growth component of the USDA/WEPP profile model simulates plant growth and residue decomposition for cropland and rangeland conditions. The purpose of this component is to simulate temporal changes in plant variables that influence the runoff and erosion processes. The plant growth model for cropland simulation is very similar to those found in EPIC. The range plant model is designed specifically for range conditions, and is not based on EPIC. The residue and root decomposition model simulates decomposition of surface residue (both standing and flat), buried residue, and roots. The biological models estimate daily values for canopy, surface residue, buried residue, stubble, leaf area index, live and dead roots, standing biomass, and crop yield.

Surface runoff is routed on hillslopes using a kinematic wave approach, or alternatively an approximate method based on the kinematic wave equation. Peak runoff rates in watersheds may be estimated using either a modified NRCS TR-55 method (USDA-SCS 1986), similar to that used in EPIC, or the empirical equation used in the CREAMS model.

The erosion component of the model uses a steady-state sediment continuity equation, which calculates net values of detachment or deposition rates along the hillslope profile (Nearing et al. 1989) and in watershed channels (Foster et al. 1981). The erosion process is divided into channel, rill, and interrill components where the interrill areas act as sediment feeds to the rills, or small channel flows. Hillslopes feed sediment to watershed channels. Within the rills and channels the sediment may be carried downslope or deposited. Scour by rill and channel flow is calculated for the case when flow shear exceeds critical shear of the soil and when sediment load is less than calculated sediment capacity.

***Using WEPP to study the impacts of climate change.*** WEPP is useful in studying the effects of changing temperature, humidity, rainfall amounts, rainfall intensities, and atmospheric $CO_2$ concentrations on hydrology and erosion, because the processes described by the model are highly interrelated and interactive. As an example, $CO_2$, temperature, and humidity influence transpiration and growth rates of plants. Temperature and humidity affect soil evaporation rates. When $CO_2$ and temperature increase, transpiration and evaporation effect a change in the soil water balance, which in turn increases the inherent rainfall infiltration capacity of the soil to reduce both runoff and erosion. Additionally, increased plant biomass production will also increase infiltration rates and reduce erosion. Changes in rainfall amounts, intensities, and distributional patterns directly influence runoff

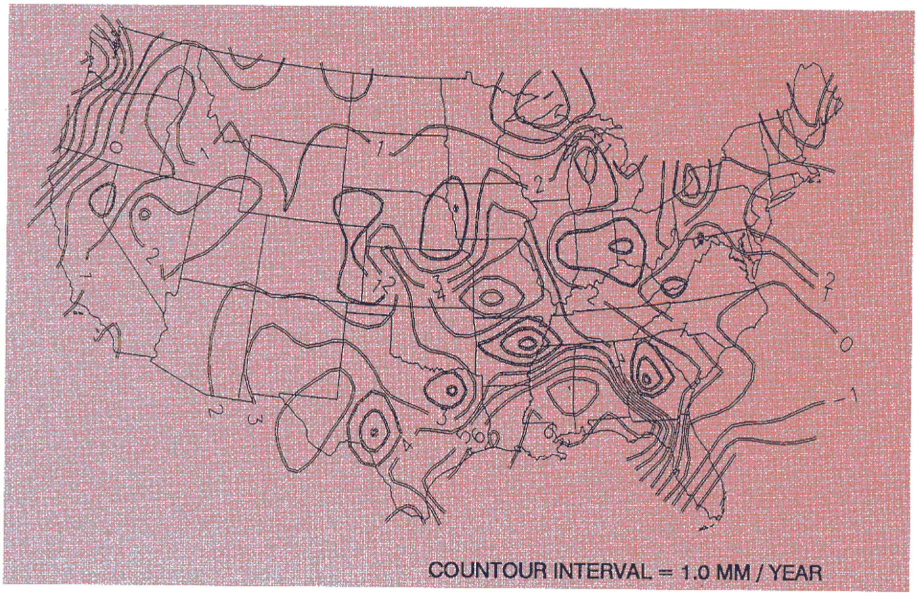

**Figure 1. Annual precipitation trends**

and erosion. Because WEPP uses a daily time-series of rainfall data, rather than a lumped term for rainfall erosivity as does the USLE, and because it is sensitive to rainfall pattern via the Green and Ampt infiltration, kinetic wave runoff routing, and sediment continuity equations, the model is suited to assess the effects of rainfall on hydrologic and erosional response to the system.

Savabi et al. (1993) studied the response of WEPP to changes in rainfall and temperature. He found the model was sensitive to climatic variation over time, and the results were reasonable. His results, though preliminary, also showed to some degree the potential of using WEPP in terms of determining the inter-dependence of the processes, in that the relative degree of the changes in soil water content, runoff, and erosion were dependent on soil type.

## Wind erosion models

***Wind erosion equation (WEQ).*** A model proposed by Woodruff and Siddoway (1965), titled a wind erosion equation, has been used extensively with various modifications during the past quarter century. The model was developed as a result of investigations to understand the mechanics of wind erosion, to identify major factors influencing wind erosion, and to develop wind erosion control methods. Soil erodibility index and climatic factor were the two most important dependent variables.

Solving the functional relationships of the wind erosion equation as presented by Woodruff and Siddoway required the use of tables and figures. The awkwardness of the manual solution prompted a computer solution (Skidmore et al. 1970) (and later the development of a slide-rule calculator). The computer solution not only predicted average annual soil loss, but solved the equation to determine the field conditions necessary to reduce potential soil loss to a tolerable amount. It allowed the user to look at many combinations of wind erosion control practices for particular field and climatic conditions. Later Cole et al. (1983) adapted the model for simulating daily wind erosion as a submodel in the Erosion Productivity Impact Calculator (EPIC) developed by Williams et al. (1984) and later modified (Skidmore and Williams 1991).

***Wind erosion prediction system (WEPS).*** Although WEQ was used widely, it had many faults. Therefore the U.S. Department of Agriculture (Hagen 1991) initiated the Wind Erosion Prediction System (WEPS), a multidisciplinary project to develop improved technology to predict wind erosion. WEPS is designed to use a weather generator to drive other submodels that simulate soil, crop, and residue conditions of a field scale using a daily time step. On days with high wind speed, the erosion is calculated on a subhourly basis.

The structure of WEPS is modular, consisting of a main supervisory program; a user interface input section; an output control section; and seven submodels (WEATHER, SOIL, HYDROLOGY, CROP, DECOMPOSITION, MANAGEMENT, and EROSION) along with their associated databases.

***Revised wind erosion equation (RWEQ).*** Several issues regarding WEQ were identified as needing attention in order to support soil conservation programs until the Wind Erosion Prediction System (WEPS), now under development (Hagen 1991), is fully implemented. In order of significance these issues were identified as follows: 1) the climatic factor is unrealistically high in arid climates and is perceived to be too low in humid climates and does not account for irrigation. 2) The soil erodibility index does not account for temporal variation of aggregate status as influenced by management, weather, etc. 3) WEQ does not account for temporal variation in other model factors like climate, roughness, growing crop, and crop residue. 4) Small grain equivalent is difficult to communicate to the person in the field. 5) Random roughness is not presently recognized in WEQ. 6) Spatial variability is not presently recognized in WEQ. Persons were assigned to address each of the above listed issues and revise the associated factors of the wind erosion equation and deliver a revised wind erosion equation (RWEQ) for use until WEPS is implemented.

***Wind erosion and climate change.*** Research is proposed to evaluate the impact of predicted climate change on wind erosion and associated soil and environmental degradation in the Great Plains of the United States. Questions to be examined include how predicted climate change will affect the following: 1) wind erosion climatic erosivity, 2) wind erosion protection afforded by vegetation as influenced by growth of major agronomic crops in the region, 3) residue decomposition of main residue-producing crops, 4) soil properties that are related to susceptibility to wind erosion, and 5) the total field soil loss partitioned among saltation-creep and suspension components.

The new advances in wind erosion prediction technology from WEPS will be used to quantify the impact of predicted climate change on the climatic, vegetative, and soil factors that control wind erosion. The HYDROLOGY submodel of WEPS will be used to evaluate soil wetness at the soil-atmosphere interface as influenced by modified climate. The CROP and DECOMPOSITION submodels will be used to quantify the effects of climate change on the growth of major agronomic crops and the decomposition of their residues. The SOIL submodel of WEPS will be used to evaluate the influence of climate change on soil erodibility by wind. Furthermore, the EROSION submodel will be used to predict field soil loss and deposition.

The proposed research will contribute

valuable knowledge for assessing wind erosion potential and associated soil and environmental degradation as a result of climate change. It will aid in developing sound conservation and environmental planning.

## CLIGEN

Several weather generators have been developed in the past decade to simulate inputs to various types of models (Nicks 1974), (Richardson 1981). Three hydrologic and erosion simulation models, including EPIC (Williams, et al. 1990), Simulator of Water Resources in Rural Basin (SWRRB) (Arnold, et al. 1990), and Simulator of Production and Utilization of Rangelands (SPUR) (Wight and Skiles 1987) use weather generators to simulate climate data. The SWRRB model contains an early version of CLIGEN based on the work of Nicks (1974). Outputs from these generators include occurrence and amount of daily precipitation, maximum and minimum air temperature, and solar radiation. In some cases wind speed and direction and relative humidity are also simulated.

CLIGEN (Nicks and Lane 1989) was enhanced to supply daily weather input to WEPP including the following: 1) precipitation amount, duration, maximum intensity, and time to peak; 2) maximum, minimum, and dew point temperature; 3) solar radiation; and 4) wind speed and direction. To provide the necessary parameters for the generator, a database with about 1,300 stations was developed for the United States, Puerto Rico, and nine U.S. Pacific islands.

***Generated climate change scenarios.*** The database associated with CLIGEN consists of about 1,100 stations in the 48 conterminous U.S. states. It is assumed that the time series of these values is stationary with respect to the time period used in calculating the moments of these distributions from the raw climate data. Therefore, no trend is attributed to the generated time series of these elements. However, monthly and annual trends for precipitation and temperature calculated from these data indicate patterns of increasing or decreasing precipitation and air temperature across the United States (Nicks, et al. 1993). An example of the precipitation trends for the U.S. during the period 1950 to 1990 is shown in Figure 1. CLIGEN was modified to simulate these trends in the observed data.

Modification of the generator to simulate trends that may be present in the data is accomplished by calculating the linear trend of the raw data for precipitation and air temperature elements using the following equation:

$$Y_i = a_i u_i + b_i$$

where Y is the yearly adjusted mean of the raw variate, u the year number from the beginning of the series, a the trend coefficient and b the intercept of the regression for i = 1,2,3, ... 12 monthly intervals. Weather files with and without trends are input to models to estimate trend effects on runoff, erosion and evaporation (Nicks and Williams 1994).

## Conclusions

Water and wind erosion are still studied by two rather distinct communities. Such a disconnection can be pernicious to erosion modeling in semi-arid systems where both erosion processes are intimately linked. Models that couple water and wind erosion processes are required to predict soil erosion under global change in semi-arid regions.

Global circulation models are available for estimating climate and $CO_2$ changes. Recently, mathematical models are being developed for simulating soil erosion as affected by changes in climate and $CO_2$. Stockle et al. (1992) provided equations for simulating the effects of $CO_2$ on plant growth and water use efficiency. Recently the Stockle relationships have been added to EPIC, WEPP, and SWAT. These models, along with the wind erosion models WEQ, RWEQ, and WEPS, provide tools for estimating changes in erosion rates if climatic changes occur. A companion weather simulation model, CLIGEN, is a convenient tool for projecting long term weather sequences with built in trends.

## $CO_2$ relationships

The $CO_2$ developments of Stockle et al. (1992) were added to the EPIC potential evaporation and crop growth components. The Penman-Monteith method (Monteith 1965) is one of four potential ET equations available for use in EPIC. The Penman-Monteith equation is expressed as

$$E_p = \frac{\delta\,(h_0 - G) + 86.7\,AD\,(e_a\, e_d)\,/AR}{HV\left(\delta + \gamma\ \ (1. + CR/AR)\right)} \quad (1)$$

where Ep is the potential evaporation in mm, $\delta$ is the slope of the saturation vapor pressure curve in kPa° $C^{-1}$ is a psychrometer constant in kPa° $C^{-1}$, $h_0$ is the net radiation in MJ $m^{-2}$, $G$ is the soil heat flux in MJ $m^{-2}$, $HV$ is the latent heat of vaporization in MJ $kg^{-1}$, $e_a$ is the saturation vapor pressure at mean air temperature in kPa, $e_d$ is the vapor pressure at mean air temperature in kPa, $AD$ is the air density in g $m^{-3}$, $AR$ is the aerodynamic resistance for heat and vapor transfer in s $m^{-1}$, and $CR$ is the canopy resistance for vapor transfer in s $m^{-1}$.

The $CO_2$ effect on canopy resistance is computed with the equation

$$CR = \frac{P_1}{(LAI)\,(g_o{}^*)\,(1.4 - 0.00121\,CO_2)} \quad (2)$$

where $P_1$ is a parameter ranging from 1.0 to 2.0, $LAI$ is the leaf-area-index of the crop, $g_o{}^*$ is the leaf conductance in m s–1, and $CO_2$ is the carbon dioxide level in the atmosphere in ppm. Leaf conductance is estimated from the crop input rate adjusted for vapor pressure deficit (VPD).

$$g_o{}^*\,(g_o)\,(FV) \quad (3)$$

where $g_o$ is the crop's leaf resistance when VPD is less than the crops threshold VPD and $FV$ is the VPD correction factor.

$$FV = 1. - b_v\,(VPD - VPD_t) \geq 0.1 \quad (4)$$

where $b_v$ is a crop coefficient and $VPD_t$ is threshold VPD for the crop.

In addition to these changes affecting PET, Stockle modified the plant growth model to include $CO_2$ sensitivity. The EPIC plant growth model estimates intercepted solar radiation using Beer's law equation (Monsi and Saeki 1953)

$$PAR_i = 0.5\,(RA)_i\,[1. - \exp(-0.65\,LAI_i)] \quad (5)$$

where $PAR$ is intercepted photosynthetic active radiation in MJ $m^{-2}$, $RA$ is solar radiation in MJ $m^{-2}$, and subscript i is the day of the year. Using Monteith's approach (Monteith 1977), potential increase in biomass for a day can be estimated with the equation

$$\Delta B_{p,i} = 0.001\,(BE)_j\,(PAR)_i \quad (6)$$

where $\Delta B_p$ is the daily potential increase in biomass in t $ha^{-1}$ and $BE$ is the crop parameter for converting energy to biomass in kg $ha^{-1}$ $MJ^{-1}$ $m^2$.

Biomass energy conversion is affected by vapor pressure deficit (VPD) and by atmospheric $CO_2$ level. The biomass conversion factor BE is adjusted using the equations of Stockle et al. (1992).

$$BE^* = \frac{100.\ CO_2}{CO_2 + \exp\left(bc_1 - bc_2\left(CO_2\right)\right)} \quad (7)$$

where $bc_1$ and $bc_2$ are crop parameters. The VPD correction is accomplished in the equation

$$BE' = BE^* - bc_3\left(VPD - 1.\right)\ VPD > 0.5 \quad (8)$$

where $bc_3$ is a crop parameter.

## REFERENCES CITED

Arnold, J.G., B.A. Engel, and R. Srinivasan. 1993. A continuous time grid cell model. In: Application of Advanced Information Technologies for Management of Natural Resources. Sponsored by ASAE, June 17-19, Spokane, Washington.

Arnold, J.G., J.R. Williams, A.D. Nicks, and N.B. Sammons. 1990. SWRRB: A basin scale simulation model for soil and water management. Texas A&M University Press, College Station. 142 pp.

Chu, S.T. 1978. Infiltration during an unsteady rain. Water Resources Research, 14(3): 461-466.

Cole, G.W., L. Lyles, and L.J. Hagen. 1983. A simulation of daily wind erosion loss. Trans. ASAE 26:1754-1765.

Easterling, W.E., P.R. Crosson, N.J. Rosenberg, M.S. McKenney, L. Katz, and K. Lemon. 1993. Agricultural impacts of and responses to climate change in the Missouri-Iowa-Nebraska-Kansas (MINK) Region. Climatic Change 24(1-2):23-62.

Flanagan, D.C., and M.A. Nearing. 1995. USDA-Water Erosion Prediction Project: Hillslope profile and watershed model documentation. NSERL Report No. 10. USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana 47097-1196.

Foster, G.R., L.J. Lane, J.D. Nowlin, J.M. Laflen, and R.A. Young. 1981. Estimating erosion and sediment yield on field-sized areas. Trans. ASAE 24:1253-1262.

Hagen, L.J. 1991. A wind erosion prediction system to meet user needs. J. Soil and Water Cons. 46:106-111.

Hargreaves, G.H., and Z.A. Samani. 1985. Reference crop evapotranspiration from temperature. Applied Engr. Agric. 1:96-99.

Lane, L.J., and M.A. Nearing. 1989. USDA-Water Erosion Prediction Project: Profile model documentation. NSERL Report No. 2, USDA-ARS National Soil Erosion Laboratory, W. Lafayette, Indiana 47907. 263 pp.

Lee, J.J. 1995. The potential effects of afforestation on the carbon budget of the south central United States. In press.

Leonard, R.A., W.G. Knisel, and D.A. Still. 1987. GLEAMS: Groundwater loading effects on agricultural management systems. Trans. ASAE 30(5):1403-1428.

Mein, R.G., and C.L. Larson. 1973. Modeling infiltration during a steady rain. Water Resources Research 9(2):384-394.

Monsi, M., and T. Saeki. 1953. Uber den Lichtfaktor in den Pflanzengesellschaften und sein Bedeutung fur die Stoffproduktion. Japan J. Bot. 14:22-52.

Monteith, J.L. 1965. Evaporation and environment. Symp. Soc. Exp. Biol. 19:205-234.

Monteith, J.L. 1977. Climate and the efficiency of crop production in Britain. Phil. Trans. Res. Soc. London Ser. B. 281:277-329.

Nearing, M.A., G.R. Foster, L.J. Lane, S.C. Finkner. 1989. A process-based soil erosion model for USDA-Water Erosion Prediction Project technology. Trans. ASAE 32:1587-1593.

Nicks, A.D. 1985. Generation of climate data. In: D.G. DeCoursey (ed), Proc. of the Natural Resources Modeling Symp. Pingree Park, Colorado, October 16-21 1983, USDA-ARS-30.

Nicks, A.D., and L.J. Lane. 1989. Weather generator. In: L.J. Lane and M.A. Nearing (eds.), USDA-Water Erosion Prediction Project: Profile model documentation. NSERL No. 2. USDA-ARS National Soil Erosion Research Laboratory, W. Lafayette, Indiana 47907. pp. 2.1-19.

Nicks, A.D., L.J. Lane, G.A. Gander, and C. Manetsch. 1993. Regional analysis of precipitation and temperature trends using gridded climate station data. In: S.S.Y. Wang (ed.), Advances of Hydro-Science & Engineering. The University of Mississippi. Vol. 1, Part A. pp. 497-502.

Nicks, A.D., and R.D. Williams. 1994. Estimating the impacts of global change on erosion with stochastically generated climate data and erosion models. In: Olive et al. (eds), Variability in Stream Erosion and Sediment Transport. IASH Pub. No. 224. pp. 473-478.

Onstad, C.A., and G.R. Foster. 1975. Erosion modeling on a watershed. Trans. ASAE 18(2):288-292.

Penman, H.L. 1948. Natural evaporation from open, bare soil and grass. Proc. Soc. London Ser. A193:120-145.

Priestley, C.H.B., and R.J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100:81-92.

Risse, L.M., M.A. Nearing, and M.R. Savabi. 1994. Determining the Green and Ampt effective hydraulic conductivity from rainfall-runoff data for the WEPP model. Trans. ASAE 37:411-418.

Risse, L.M., M.A. Nearing, and X. Zhang. 1995a. Variability in Green-Ampt effective conductivity under fallow conditions. J. Hydrology 169:1-24.

Risse, L.M., B. Y. Liu, and M.A. Nearing. 1995b. Using curve numbers to determine baseline values of Green-Ampt effective hydraulic conductivity. Water Resources Bulletin 31(1):147-158.

Robertson, T., V.W. Benson, J.R. Williams, C.A. Jones, and J.R. Kiniry. 1987. The impact of climate change on yields and erosion for selected crops in the southern United States. pp. 89-134. In: Proc. of the symposium on climate change in the Southern United States: future impacts and present policy issues. New Orleans, Louisiana: Science and Public Policy Program.

Robertson, T., C. Rosenzweig, V. Benson, and J.R. Williams. 1990. Projected impacts of carbon dioxide and climate change on agriculture in the Great Plains. pp. 675-677. In: P.W. Unger, T.V. Sneed, W.R. Jordan, and R. Jenson (eds.). Proc. Intl. Conf. on Dryland Farming, Challenges in Dryland Agriculture—A Global Perspective, August 1988, Amarillo/Bushland, Texas. Texas Agric. Exp. Stn., 965 pp.

Savabi, M.R., J.G. Arnold, and A.D. Nicks. 1993. Impact of global climate changes on hydrology and soil erosion: A modeling approach. In: Y. Eckstein and A. Zaporozec (eds.), Industrial and Agricultural Impacts on the Hydrologic Environment. Proc. 2nd USA/CIS Joint Conference on Environmental Hydrology and Hydrogeology. Washington, D.C. May 1993.

Sharpley, A.N., C.A. Jones, and J.R. Williams. 1990. The nutrient component of EPIC. Chapter 7, pp. 152-166. In: A.N. Sharpley and J.R. Williams (eds), EPIC—Erosion/Productivity Impact Calculator: 1. Model Documentation. U.S. Dept. Agric. Tech. Bull. No. 1768.

Skidmore, E.L., P.S. Fisher, and N.P. Woodruff. 1970. Wind erosion equation: computer solution and application. Soil Sci. Soc. Am. Proc. 34:931-935.

Skidmore, E.L., and J.R. Williams. 1991. In: J. Hanks and J.T. Ritchie (eds), Modeling Plant and Soil Systems. Agronomy 31:457-469. Madison, Wisconsin.

Stockle, C.O., J.R. Williams, N.J. Rosenberg, and C.A. Jones. 1992. A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part I—Modification of the EPIC model for climate change analysis. Agric. Systems 38:225-238.

U.S. Department of Agriculture, Soil Conservation Service. 1972. National Engineering Handbook, Hydrology Section 4, Chapters 4-10.

U.S. Department of Agriculture, Soil Conservation Service. 1986. Urban hydrology for small watersheds. Tech. Release 55.

Wight, J.R., and J.W. Skiles (eds). 1987. SPUR: Simulation of Production and Utilization of Rangelands. Documentation and user guide. U.S. Department of Agriculture, Agricultural Research Service, ARS 63. 372 pp.

Williams, J.R. 1975. Sediment yield prediction with universal equation using runoff energy factor. U.S. Dept. Agric., Agric. Res. Serv., ARS-S-40.

Williams, J.R. 1995. The EPIC Model. Chapter 25, pp. 909-1000 In: V.P. Singh (ed), Computer Models of Watershed Hydrology. Water Resources Publications, Littleton, Colorado.

Williams, J.R., C.A. Jones, and P.T. Dyke. 1984. The EPIC model and its application. pp. 111-121. In: Proc. Intl. Symp. on Minimum Data Sets for Agrotechnology Transfer, March 21-26 1983, ICRISAT Center, India. 1984.

Williams, J.R., C.A. Jones, and P.T. Dyke. 1990. The EPIC model. In: A.N. Sharpley and J.R. Williams (eds), EPIC—Erosion/Productivity Impact Calculator: 1. Model documentation. U.S. Department of Agriculture Technical Bulletin No. 1768. 235 pp.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall erosion losses, a guide to conservation planning. U.S. Dept. Agric., Agric. Handbook No. 537.

Woodruff, N.P., and F.H. Siddoway. 1965. A wind erosion equation. Soil Sci. Soc. Am. Proc. 29:602-608.

Zhang, X., L.M. Risse, and M.A. Nearing. 1995a. Estimation of Green-Ampt conductivity parameters: Part I. Row crops. Trans. ASAE (in press).

Zhang, X., L.M. Risse, and M.A. Nearing. 1995b. Estimation of Green-Ampt conductivity parameters: Part II. Perennial crops. Trans. ASAE (in press).