APEX: A NEW TOOL FOR PREDICTING THE EFFECTS OF CLIMATE AND CO_2 CHANGES ON EROSION AND WATER QUALITY

Jimmy R. Williams[1], Jeffrey G. Arnold[2], Raghavan Srinivasan[3], and Tharacad S. Ramanarayanan[4]

[1] *U.S. Department of Agriculture, Agricultural Research Service*
Grassland, Soil and Water Research Laboratory
808 East Blackland Road
Temple, TX 76502 U.S.A.

[2] *U.S. Department of Agriculture, Agricultural Research Service*
Grassland, Soil and Water Research Laboratory
808 East Blackland Road
Temple, TX 76502 U.S.A.

[3] *Texas Agricultural Experiment Station*
808 East Blackland Road
Temple, TX 76502 U.S.A.

[4] *Texas Agricultural Experiment Station*
808 East Blackland Road
Temple, TX 76502 U.S.A.

Abstract

Several field scale hydrologic/water quality models have been developed to study the impacts of agricultural management practices. EPIC (Environment Policy Integrated Climate - previously called as Erosion Productivity Impact Calculator) model is one of the popular models, which was widely applied in US and around the world. But the scope of these field scale models is limited to small field size areas, where the soil, management, crop, and topography are assumed to be homogeneous. To extend the capabilities of EPIC to simulate large complex farming systems (multiple fields, soils, rotations, management etc.), a model called APEX (Agricultural Policy/Environmental eXtender) was developed. In addition to the capabilities of EPIC, APEX has components for routing water, sediment, and chemicals (nutrients and pesticides) across complex landscapes and channel systems to the watershed outlet. The subsurface routing routine to APEX is more enhanced than EPIC and could be used to simulate subsurface processes even up to a depth of 30 m. In this paper we present an overview of EPIC and APEX and described in detail the newly added CO_2 component of the model.

Introduction

The CO_2 relationships and the erosion equations in EPIC and APEX are described here. Recently, most of the EPIC model development has been 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 SCS technology for estimating peak runoff rates, newly developed sediment yield equations, and mechanisms for simulating CO_2 effects on crop growth and water use. Stockle et al. (1992) modified EPIC to simulate the effects of CO_2 on plant growth and water use efficiency.

In this paper we have presented an overview of the EPIC (Environmental Policy Integrated Climate) model and described the newly added CO_2 component. Williams et al. (1984) developed EPIC to assess the effect of soil erosion on soil productivity. EPIC 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). To better address these changes the model name was changed from Erosion Productivity Impact Calculator to Environmental Policy Integrated Climate, but the acronym EPIC remains the same.

The runoff model simulates surface runoff volumes and peak runoff rates, given daily rainfall amounts. Runoff volume is estimated by using a modification of the Soil Conservation Service (SCS) curve number technique (USDA-SCS, 1972).

There are two options for estimating the peak runoff rate -- the modified Rational formula and the SCS 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, 1977). 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, faba beans, rapeseed, sugarcane, sorghum hay, range grass, rice, cassava, 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. Annual crops grow from planting date to harvest date or until the accumulated heat units equal the potential heat units for the crop.

Perennial crops maintain their root systems throughout the year, although they may become dormant after frost. They start growing when the average daily air temperature exceeds their base temperature. 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 include 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

(EI). 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.

Thus, the water erosion model uses an equation of the form

$$Y = \chi\,(K)\,(CE)\,(PE)\,(LS)\,(ROKF) \tag{1}$$

and

$$\begin{aligned}
\chi &= EI \quad \text{for USLE} \\
\chi &= 0.646\,EI + 0.45\,(Q\,.\,q_p)^{0.33} \quad \text{for Onstad - Foster} \\
\chi &= 1.586(Q\,q_p)^{0.56}\;A^{0.12} \quad \text{for MUSLE} \\
\chi &= 2.5\,(Q\,q_p)^{0.5} \quad \text{for MUST} \\
\chi &= 0.79\,(Q\,q_p)^{0.65}\;A^{0.009} \quad \text{for MUSS} \\
\chi &= by_1\;Q^{by_2}\;q_p^{by_3}\;A^{by_4} \quad \text{for MUSI}
\end{aligned} \tag{2}$$

where Y is the sediment yield in t ha^{-1}, K is the soil erodibility factor, CE is the crop management factor, PE is the erosion control practice factor, LS is the slope length and steepness factor, ROKF is the coarse fragment factor, Q is the runoff volume in mm, q_p is the peak runoff rate in mm h^{-1}, and A is the watershed area in ha. MUST is a new equation theoretically developed from sediment concentration bases, MUSS is a new equation developed by fitting small watershed data (no channel erosion), and MUSI allows user input of four coefficients (by_i).

The original EPIC wind erosion model (WEQ) required daily mean wind speed as a driving variable. The new EPIC wind erosion model, WECS (Wind Erosion Continuous Simulation) 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 basic WECS wind erosion equation is

$$YW = (FI)(FR)(FV)(FD) \int_{0}^{DW} YWR dt \qquad (3)$$

where YW is the wind erosion in kg m^{-1}, FI is the soil erodibility factor, FR is the surface roughness factor, FV is the vegetative cover factor, FD is the mean unsheltered travel distance of wind across the field, YWR is the wind erosion rate in kg m^{-1} s^{-1} at time t, and DW is the duration of wind greater than threshold velocity in s.

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

$$E_p = \frac{\delta (h_o - G) + 86.7 AD(e_a - e_d) / AR}{HV(\delta + \gamma (1. + CR / AR))} \qquad (4)$$

where E_p is the potential evaporation in mm, δ is the slope of the saturation vapor pressure curve 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

$$CR = \frac{p_1}{(LAI)(g_o^*)(1.4 - 0.00121 CO_2)} \qquad (5)$$

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).

$$g_o^* = (g_o)(FV) \qquad (6)$$

where g_o is the crops leaf resistance when VPD is less than the crops threshold VPD and FV is the VPD correction factor given by

$$FV = 1. - b_v(VPD - VPD_t) \geq 0.1 \qquad (7)$$

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

In addition to these changes effecting 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)

$$PAR_i = 0.5\,(RA)_i\,[1. - \exp(-0.65\,LAI_i)] \qquad (8)$$

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

$$\Delta B_{p,i} = 0.001\,(BE)_j\,(PAR)_i \qquad (9)$$

where ΔB_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)

$$BE^{*} = \frac{100.\ CO_2}{CO_2 + \exp(bc_1 - bc_2(CO_2))} \qquad (10)$$

where CO_2 is the atmospheric CO_2 level in ppm and bc_1 and bc_2 are crop parameters. The VPD correction is accomplished in the equation

$$BE' = BE^{*} - bc_3\,(VPD - 1.) \quad VPD > 0.5 \qquad (11)$$

where VPD is the vapor pressure deficit in kPa and bc_3 is a crop parameter.

The EPIC model with CO_2 capabilities has been used in several major studies in the U.S. (Robertson et al., 1987 and 1990; Easterling et al., 1993).

The SWAT Model

SWAT (Soil Water Assessment Tool) (Arnold et al., 1993) was developed to predict the effect of alternative management decisions on water, sediment, and chemical yields with reasonable accuracy for ungaged rural basins. The model was developed by modifying the SWRRB model (Arnold et al., 1990) for application to large complex basins. SWAT offers; (i) distributed parameter and continuous time simulation, (ii) flexible watershed configuration , (iii) irrigation and water transfer, (iv) lateral flow, (v) ground water, and (vi) detailed lake water quality components. The distributed parameter, continuous time feature is achieved by the reach routing structure, where the flow is being routed and added down through the river reaches and reservoirs allowing flexible basin configurations. In general the a large complex basin is divided into several subbasins by natural flow paths, boundaries, and channels required for realistic routing of water sediment and chemicals, thus preserving the natural watershed configuration.

The SWAT model has been integrated with a raster-based GIS, GRASS (Shapiro et al., 1992). The input interface (Srinivasan and Arnold, 1994) uses a variety of hydrologic tools to derive SWAT input information from GRASS raster/site map layers such as basin boundary map with subbasin delineation, digital elevation map (DEM), soils map, land use/land cover map, weather station/generator location map. There is an output interface to view the results of the simulations by SWAT. The details of the SWAT-GRASS interface can be referred from Srinivasan and Arnold (1994).

The APEX Model

A model called APEX (Agricultural Policy/Environmental eXtender) was developed for use in whole farm management to extend the EPIC capabilities for simulation of large complex farming systems (many fields, soils, rotations, etc.). In addition, APEX has components for routing water, sediment, nutrients, and pesticides across complex landscapes and channel systems to the watershed outlet. The routing mechanisms provide for evaluation of interactions between subareas (fields) involving surface run-on, and sediment deposition and channel degradation, nutrient transport, and lateral subsurface flow. The routing component of APEX is similar to that of SWAT. APEX also allows convenient assessment of various systems including terraces, grass waterways, strip cropping, buffer strips, feed yards, dairies, etc.

Equally as important as the expanded spatial scale is the extension into the vadose zone. EPIC allows up to 10 soil layers and operates only in the root zone. APEX allows up to 30 soil layers thus extending water and chemical transport and fate computations into the vadose zone. With this additional capacity, APEX should simulate important processes and interactions to a depth of about 30 m.

APEX's ability to simulate the effects of nutrient distribution in the soil profile on runoff and leaching losses makes it an ideal tool to identify best management practices for particular soil-climate- topography-management combinations. APEX's ability to simulate soil fertility in response to organic and inorganic nutrient sources, soil types, and cropping systems, makes it a valuable tool for long-term fertility management. For example, though manure may be rich in phosphorus, inorganic sources of nitrogen may be needed to provide the nutrients needed for maximum crop production. APEX can be used to also evaluate their effects on nutrient movement to surface and ground waters.

APEX is currently operational and is being used to evaluate alternative animal waste management strategies in the Upper North Bosque watershed of Texas. It is also undergoing rapid development, testing, and improvement. One of the more useful improvements expected in the next year is integration of the model with a user interface utilizing a geographic information system (GIS) to facilitate input and visualize model output. This interface will be similar to that currently used by the SWAT.

Conclusion

APEX is an operational model and decision tool designed to simulate the behavior of complex farming systems at the whole-farm or small watershed scale. Its treatment of individual fields or areas of homogeneous soils, topography, management, etc. is taken from the EPIC model. Like the SWAT model, movements of water, sediment, nutrients, and pesticides are used to link fields within the farm or watershed. Future improvements are expected to include integration of APEX with a GIS and user interface like that used by the SWAT watershed hydrology model.

References

Arnold, J.G., Williams, J. R., Nicks, A.D., and Sammons, N.B. (1990). SWRRB - A basin scale simulation model for soil and water resource management. *Texas A&M Press,* College Station, Texas.

Arnold, J.G., Allen, P.M., and Bernhardt, G. (1993). A comprehensive surface-groundwater flow model. *J. Hydrol.* **142**, 47-69.

Easterling, W.E., Rosenberg, N.J., McKenney, M.S., Jones, C.A., Dyke, P.T., and Williams, J.R. (1992). Preparing the Erosion Productivity Impact Calculator (EPIC) model to simulate crop response to climate change and the direct effects of CO_2. *Agriculture and Forest Meteorology* **59**, 17-34.

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

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

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

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

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

Penman, H.L. (1948). Natural evaporation from open, bare soil and grass. *Proc. Soc. London Ser.* A**193**, 120-145

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

Robertson, T., Benson, V.W., Williams, J.R., Jones, C.A., and Kiniry, J.R. (1987). The impact of climate changes on yields and erosion for selected crops in the southern United State. In *Proceedings of the Symposium on ClimateChange in the United States: Future Impacts and Present Policy Issues*, New Orleans, Louisiana. pp 89-134.

Robertson, T., Rosenzweig, C., Benson, V., and Williams, J.R. (1990). Projected impacts of carbon dioxide and climate change on agriculture in the Great Plains. In Unger, P.W., Sneed, T.V., Jordan, W.R. and Jensen, R. (eds) *Proc. Intl. Conf. on dryland farming, Challenges in Dryland Agriculture - A Global Perspective*, Amarillo/Bushland, Texas. pp 675-677.

Shapiro, M., Westervelt, J., Gerdes, D., Larson, M., and Brownfield. (1992). GRASS 4.0 Reference Manual. *USA CERL*, Champaign, IL.

Sharpley, A.N., Williams, J.R, eds. (1990). EPIC-Erosion/Productivity Impact Calculator: Z 1. Model Documentation. *U.S. Dept. Agric. Tech. Bull.* No. **1768**.

Stockle, C.O., Williams, J.R., Rosenberg, N.J., Jones, C.A. (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

USDA-SCS. (1972). National Engineering Handbook, Hydrology Section **4**, Chapters 4-10.

USDA-SCS. (1986). Urban hydrology for small watersheds. *U.S. Dept. Agric. Technical Release No.* 55.

Williams, J.R. (1975). Sediment routing for agricultural watersheds. *Water Resources Bulletin* **11**, 965-974.

Williams, J.R., Jones, C.A., and Dyke, P.T. (1984). A modeling approach to determining the relationship between erosion and productivity. *Trans. ASAE* **27**, 129-144.

Williams, J.R. (1995). The EPIC model. In Singh, V.P. (ed*) Computer Models of Watershed Hydrology*, Water Resources Publication, Highlands Ranch, Colorado. pp 909-1000.

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