443

Proceedings of the Specialty Conference on

ADVANCES IN IRRIGATION AND DRAINAGE: SURVIVING EXTERNAL PRESSURES

Sponsored by the Irrigation and Drainage Division
of the American Society of Civil Engineers

Co-Sponsors
American Society of Agricultural Engineers
National Association of Conservation Districts

Americana Snow King Resort
Jackson, Wyoming
July 20-22, 1983

John Borrelli, Victor R. Hasfurther, and Robert D. Burman
Co-Editors

Published by the
American Society of Civil Engineers
345 East 47th Street
New York, New York 10017

Experience with Curve Numbers in EPIC

J. R. Williams, M. ASCE and K. G. Renard, M. ASCE*

Abstract: Estimating the effect of soil erosion on future soil productivity is essential for agricultural decision making and resource utilization planning from individual fields to the national level. The U.S. Department of Agriculture is required to make periodic reports of the status of the soil and water resources in the U.S. as a result of the Soil and Water Resources Conservation Act (RCA, PL 95-192). In the process of these assessments, one of the most difficult tasks has involved assessing the effect of erosion on long-term soil productivity.

To assist with the assessment, a simulation model, EPIC (Erosion Productivity Impact Calculator), has been developed which considers physically-based components for simulating hydrology, erosion, plant growth and related processes and economic components for assessing the cost of erosion with optimal management strategies. The hydrology portion of the model includes the curve number runoff model of the Soil Conservation Service. The curve numbers are made dynamic in the model by considering soil moisture changes in the root zone of the soil. The paper discusses the model and shows the result of some comparisons for a rangeland area in southeastern Arizona and an upland cotton irrigated field in central Arizona.

Introduction

A mathematical model, called EPIC, has been developed to determine the relationship between soil erosion and soil productivity in the United States (10). The model was developed to assist USDA with the mandates of the Soil and Water Conservation Act of 1977, commonly referred to as RCA. The law directs the Secretary of Agriculture to make periodic appraisals of the soil, water and related resources of the agricultural lands in the nation and develop plans for their conservation. With the early plans to implement the RCA, it became obvious that there was no reliable method for estimating the cost of erosion or the benefits from erosion research and control. A noteworthy first attempt to develop a nationally-applicable crop yield-soil loss relationship was the empirical model developed by Hagen and Dyke (1). The recognized need to improve this early crop yield-soil loss relation led to the formation of a modeling team in the Agricultural Research Service (ARS) of USDA under the leadership of J. R. Williams. The model developed, EPIC, is: (1) physically based and capable of continuously simulating the processes affecting soil erosion and crop productivity using readily available inputs; (2) capable of simulating many years, when necessary,

*Research Hydraulic Engineers, USDA-ARS, Grassland, Soil and Water Research Laboratory, Temple, TX, and Southwest Rangeland Watershed Research Center, Tucson, AZ, respectively.

because the insidious nature of erosion may take decades before it is reflected in crop productivity; and (3) generally applicable, computationally efficient, convenient to use and capable of assessing the effects of management changes on soil erosion and productivity.

Model Description

An operational version of the EPIC model was needed by January, 1983 to meet the deadlines of RCA. During its development, the model was tested on more than 150 sites in the Continental U.S. and 13 in Hawaii. Although the model is operational, additional testing and modification for other uses, and for future RCA planning, will continue.

Weather: Precipitation, air temperature, solar radiation, and wind (for wind erosion computations) data are necessary on a daily basis for the EPIC model. The model can accomodate either actual data, or simulate the data. Precipitation is simulated (3) with a first-order Markov Chain model. The model user must provide input monthly probabilities of receiving precipitation if the previous day was dry, and similar probabilities if the previous day was wet. Given the wet-dry state, the model stochastically determines if precipitation occurs on each day. These monthly probabilities are available for EPIC users at a large number of locations.

When precipitation occurs, the depth is determined by generating randomly from a skewed normal daily precipitation distribution. Inputs necessary to describe the distribution for each month are the mean, standard deviation, and skew coefficient. Again, data for these parameters are available for a large number of locations in the country. The precipitation is partitioned between rainfall and snowfall using average daily air temperature.

Air temperature and solar radiation are simulated in EPIC (when actual data are not used) using a model developed by Richardson (5) that exhibits proper correlation among temperature, radiation, and precipitation. Residuals of daily maximum and minimum temperature and solar radiation are generated from a multivariate normal distribution. The dependence structure of daily maximum and minimum temperature and solar radiation was described by Richardson (6). Maps of parameter values for the distributions are available for the United States to assist EPIC users.

Because wind erosion may also dramatically affect soil productivity and, in some areas, may be greater than water erosion, average daily wind velocity is generated from a two-parameter gama distribution with wind direction, expressed as radians from north, generated from an empirical distribution specific to each location.

Hydrology: Surface runoff is predicted from daily rainfall using a procedure similar to that in the CREAMS model (2, 9). The runoff volume is estimated using a modification of the SCS curve number method (2) accommodating a variable soil layer thickness as well as a provision for runoff from frozen soil.

Peak runoff rate predictions are based on a modification of the Rational Formula. The runoff coefficient is calculated as the ratio of runoff volume to rainfall. Rainfall intensity, during the watershed time of concentration, is estimated for each storm as a function of total rainfall. A stochastic technique is used to estimate the fraction of the daily rainfall that occurs during the time of concentration. Watershed time of concentration is estimated using Manning's Formula considering overland and channel flow.

The percolation component uses a storage routing technique combined with a crack-flow model to predict flow through each soil layer in the root zone. Water percolating below the root zone is assumed to become groundwater or appear as base flow downstream. The storage routing technique assumes travel time is a function of hydraulic conductivity, and may be reduced by a saturated lower layer. The crack-flow model allows percolation, even though the soil water content is less than field capacity. When the soil is dry and cracked, the water can flow through the cracks of a layer without becoming part of that layer's soil moisture.

Percolation is also affected in the model by soil temperature. If the temperature in a particular layer is zero °C or less, no percolation is allowed from that layer. Water can percolate into the layer, however, if storage is available. EPIC operates on a daily time step, which is relatively long for routing soil water. Thus, the model divides the flow into each layer into 4 mm slugs and routes each slug individually. This adjustment is felt to be necessary because the flow rates in each layer are dependent upon soil water content, which is changing continuously.

Lateral subsurface flow is calculated simultaneously with percolation. Each 4 mm slug has the opportunity to percolate first, with the remainder subjected to the lateral flow computation. Thus, lateral flow can occur when the storage in any layer exceeds field capacity after percolation. Lateral flow is simulated with a travel time routing function like that used in percolation.

Evapotranspiration is computed using the Ritchie algorithm (7). EPIC computes potential evaporation as a function of solar radiation, air temperature and albedo (adjusted to reflect soil, cover, and snow pack). The model computes soil and plant evaporation separately. Potential soil evaporation is computed as a function of potential evaporation and leaf area index (area of plant leaves relative to the soil surface area). Actual soil evaporation is computed in two stages. In stage 1, soil evaporation is limited only by the energy available at the surface, and thus is equal to potential soil evaporation. When the accumulated soil evaporation exceeds the stage 1 upper limit (6 mm), the stage 2 process begins. Stage 2 soil evaporation is predicted with a square root function of time. Finally, plant evaporation is estimated as a linear function of potential evaporation and leaf area index.

Irrigation can be simulated in addition to the normal dryland agricultural operation. The EPIC user must specify the irrigation efficiency and a plant water stress for starting irrigation. The user must also specify whether sprinklers or furrow irrigation is to be used. When the specified stress level is reached, the model assumes water is applied to bring the root zone up to field capacity plus enough water to satisfy the irrigation application efficiency. Excess water, applied to satisfy the specified efficiency, becomes runoff and provides energy for erosion.

Erosion: Water erosion, in EPIC, is generated by the Universal Soil Loss Equation (USLE) (11), MUSLE (8), or the Onstad and Foster modification (4) of the USLE. In the Onstad-Foster equation, the USLE energy factor (R) is replaced by a term reflecting both rainfall and runoff energy, whereas the MUSLE equation uses only a runoff energy factor.

The EPIC hydrology component provides estimates of the runoff volume and peak discharge rate needed for both modifications of the USLE. To estimate the daily rainfall energy in the absence of time-distributed precipitation, it is assumed that the rainfall rate is exponentially distributed, which allows simple substitution of rainfall rates into the USLE R-factor. The fraction of 24-hour rainfall that occurs during 0.5-hour is simulated stochastically, using an approach similar to the one used to estimate peak runoff rate.

The crop-management factor (C) is evaluated as a function of above-ground biomass, crop residue on the surface, and the minimum factor for the crop. Other factors are evaluated as described by Wischmeier and Smith (11).

Because wind erosion is not considered in this paper, its simulation is not detailed, except to say that the wind erosion equation, developed by Woodruff and Siddoway (12), is used.

Nutrients: The two plant nutrients simulated in EPIC are nitrogen and phosphorus. The nitrogen processes simulated include runoff of NO_3, organic N transport by sediment, leaching, upward NO_3 movement by soil evaporation, denitrification, immobilization, mineralization, crop uptake, input with rainfall, fertilizer addition, and fixation. Phosphorus processes simulated include the loss of soluble P with runoff, mineral and organic P losses with sediment, immobilization, mineralization, sorption-desorption, crop uptake, and fertilizer addition.

Plant Growth: A general plant growth model is used to simulate above-ground biomass, seed or lint yield, and root biomass for the most common agricultural crops (corn, grain sorghum, wheat, barley, oats, peanuts, soybeans, sunflowers, alfalfa, cotton, and pasture grasses). The plant growth model simulates energy interception, energy conversion to roots, above-ground biomass, grain and fiber production, and water and nutrient uptake. Plant growth is constrained by stresses associated with water, nutrients, and/or air temperature. Soil temperature, simulated for the nutrient cycling and plant root growth, is predicted at the center of each soil layer as a function of the previous day's soil temperature and the present day's air temperature and solar radiation.

Tillage: The tillage component of EPIC considers row height, soil surface roughness, change in bulk density, transition from standing to flat residue, and mixing of soil layers, nutrients, and plant residue for any tillage operation. The EPIC user must specify the tillage operations.

The EPIC user must also specify a number of soil physical and chemical properties for each soil horizon described in a typical pedon description (percentage of sand, silt, and clay, moisture at 1/3- and 15-bar tensions, hydraulic conductivity, pH, Aℓ, $CaCO_3$, labile P, NO_3, organic C, etc.).

Although EPIC is a comprehensive model, it was developed specifically to assess the erosion-productivity problem. Thus, user convenience was an important consideration in the model design. The computer program contains 53 subroutines (with the wind erosion and economic components), although there are only 2700 FORTRAN statements. The model can be run on a variety of computers, since storage requirements are only 210K.

Application of EPIC

Rangeland: EPIC has been tested quite extensively, where data was available, throughout the United States, and in other instances, the simulations appear to provide reasonable output of such things as crop yield, sediment yield, runoff, etc., using simulated inputs.

In southeastern Arizona, some hydrologic data were available for a small watershed (1.8 ha) on the Walnut Gulch Experimental Watershed operated by the Agricultural Research Service, USDA. The Hathaway soil (loamy-skeletal, mixed, thermic Aridic Calciustoll) is a deep, well-drained gravelly medium and moderately coarse-textured material of moderate depth. The soils data were input as 7 layers to the EPIC model, with a total depth of 1190 mm. Sideoats grama and blue grama grasses dominate the vegetation in the area and account for about 90 percent of the 2 percent basal area of vegetation. Crown cover, which is highly variable in response to grazing, varies from a minimum of about 20 percent to over 50 percent.

The EPIC user, among other things, must specify a CN_2 curve number for the hydrologic routine in the model. This number is then used with a polynomial to specify the minimum curve number (CN_1). The model computes an actual curve number for each storm event considering the available soil moisture reservoir. Thus, during wet periods, the curve number for a storm will be greater than the minimum value.

Figure 1 shows a comparison of the distribution of annual precipitation and runoff measured and simulated with EPIC for two different CN_2 values specified for the small watershed. Also shown in the figure is the percentage of the simulated soil loss by month, using the MUSLE simulation. Of greatest significance is that the hydrologic model predicts runoff during the months (Dec - May) when runoff was not measured.

Because the curve number model is a simple one-parameter model, it isn't capable of reflecting differences in precipitation rates within daily totals which occur in most climatic provinces. In areas where thunderstorms of relatively short duration dominate, the soil moisture reservoir for reflecting the curve number should be reduced during such periods. Thus, in Fig. 1, the lower CN_2 might be used to reflect low winter runoff, whereas a shallow depth would be used to compute the CN during the summer. In essence, the effective soil reservoir for infiltration storage should be proportional to the expected storm duration within a 24-hour period.

Figure 2 illustrates the sensitivity of the simulations of soil loss by using MUSLE. The lines labeled 1st and 2nd try reflect the sensitivity of the model to various curve numbers. Comparison of the simulated with actual runoff data verify that the CN_2 is actually greater than the 89 value, but slightly less than the 92 value. Unfortunately, the use of the $CN_2 = 92$ value results in an appreciable amount of winter runoff, which is not verified by the prototype data.

The line labeled 3rd try reflects adjustments to the cover-management factor to reflect the reduction in soil loss due to erosion pavement (the gravel material > 2 mm on the soil surface following erosion). Finally, the simulations are appreciably different from the actual data. Unfortunately, the actual data (7 years) contain 3 years of essentially zero sediment yield. Thus, the actual data for the 50 percent probability (lowest point shown) has three values lower, which is not felt to be typical of what might be expected for a longer sample. The 3 years were actually the lowest years in a 17-year runoff record.

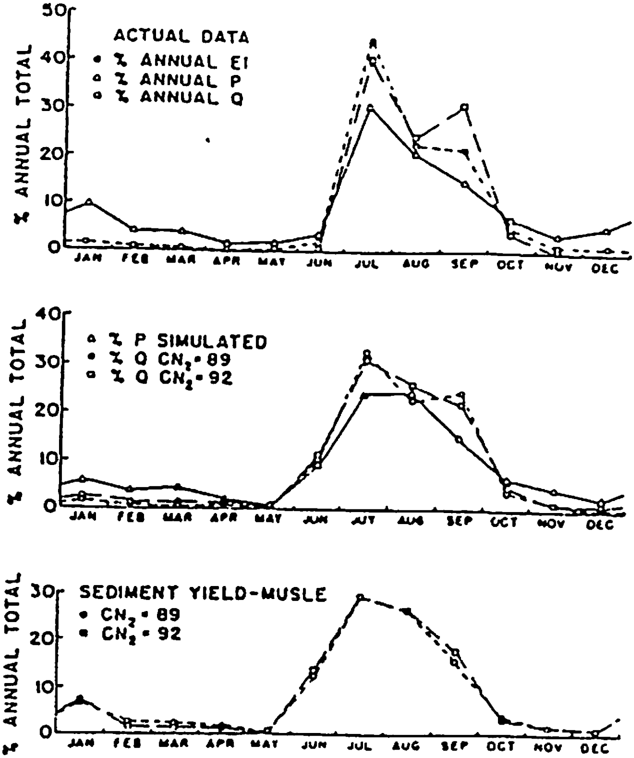

Fig. 1. Comparison of monthly actual (upper) and predicted (middle) precipitation (P), runoff (Q), rainfall erosivity (EI), and sediment yield (bottom) for two different assumed curve numbers.

Irrigation: EPIC can also be used to simulate the erosion-productivity problem from irrigated agriculture. The model was used to simulate cotton production on a Gilman loam soil (coarse-loamy, mixed hyperthermic Typic Torrifluvent) near Phoenix, AZ. The 1780 mm soil profile was divided into 7 segments, and the irrigation was assumed to occur when the soil moisture is 0.50 of field capacity. The irrigation scheme included furrow irrigation on 1 percent slopes. Little of the erosion from the field was simulated to occur due to rainfall and runoff (Fig. 3). When erosion due to water in the furrows was included, simulated erosion increased from an average of 0.56 to 5.01 t/ha, a ninefold increase. This value agrees quite well with measurements from C. Pachek[2] for one such field.

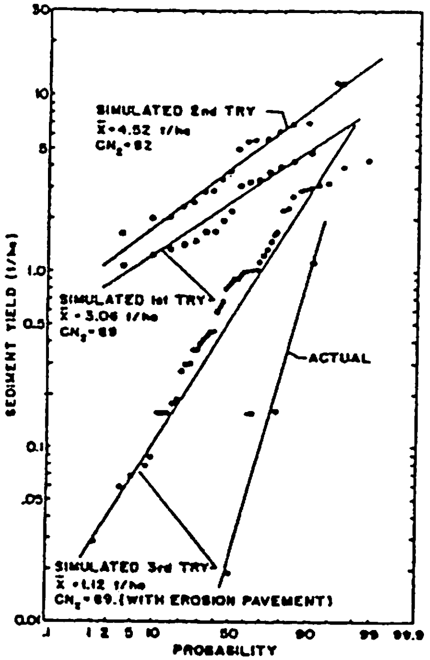

Fig. 2. Simulated and actual sediment yield for a small rangeland watershed in southeastern Arizona. Simulations labeled "1st and 2nd try" represent differences due to assumed different curve numbers, whereas "3rd try" represents consideration of the erosion pavement in the area.

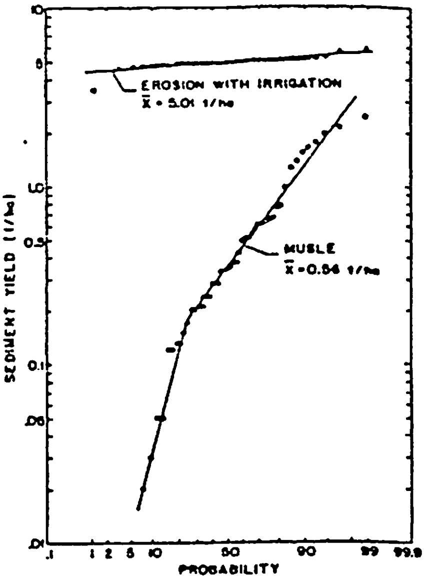

Fig. 3. Simulated erosion in a cotton field near Phoenix, AZ. The lower line represents the simulated erosion occurring from natural storms only, whereas the upper line represents the storm erosion plus that due to furrow irrigation.

Summary

The EPIC model has been tested on a fairly wide variety of climatic conditions, soil characteristics, and management practices. The model has also been observed to be sensitive to the minimum curve number, which in turn affects erosion and, for long term simulation, reduces forage production.

[2]Unpublished data from C. Pachek, State Agronomist, SCS, Phoenix AZ.

Testing in the rangeland areas and irrigated areas of southern Arizona indicate the model is sensitive to initial curve number which, in turn, greatly affects soil loss.

Appendix - References

1. Hagen, L. L., and P. T. Dyke. 1980. Merging resource data from disparate sources. Agr. Econ. Res. 32(4):45-49.

2. Knisel, W. G. 1980. A field scale model for chemicals, runoff, and erosion from agricultural management systems. USDA Conservation Research Report No. 26, 643 pp.

3. Nicks, A. D. 1974. Stochastic generation of the occurrence, pattern, and location of maximum amount of daily rainfall. Proc. Symp. Statis. Hydro., Tucson, AZ, Aug-Sept, 1971. USDA Misc. Pub. No. 1275, pp. 154-171.

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

5. Richardson, C. W. 1981. Stochastic simulation of daily precipitation, temperature, and solar radiation. Water Resources Res. 17-(1):182-190.

6. Richardson, C. W. 1982. Dependence structure of daily temperature and solar radiation. Trans. ASAE 25(3):735-739

7. Ritchie, J. T. 1972. A model for predicting evaporation from a row crop with incomplete cover. Water Resources Res. 8(5):1204-1213.

8. Williams, J. R. 1975. Sediment yield prediction with universal equation using runoff energy factor. USDA, ARS-S-40, pp. 244-252.

9. Williams, J. R. and A. D. Nicks. 1982. CREAMS hydrology model -- option one. Proc. Int'l Symp. Rainfall-Runoff Modeling, May 18-21, 1981, Mississippi State Univ., V.P. Singh, Editor, pp. 69-86.

10. Williams, J. R., P. T. Dyke and C. A. Jones. 1983. EPIC--a model for assessing the effects of erosion on soil productivity. Proc. Third Int'l Conf., State-of-the-Art in Ecological Modeling, Colorado State Univ., May 24-28, 1982.

11. Wischmeier, W. H. and D. D. Smith. 1978. Predicting rainfall erosion losses, a guide to conservation planning. USDA Agricultural Handbook No. 537, 58 pp.

12. Woodruff, N. P. and F. H. Siddoway. 1965. A wind erosion equation. Proc. Soil Sci. Soc. Amer. 29(5)602-608.