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PREFACE

Wind erosion is a serious problem on agricultural lands throughout the United States as well as the world. The ability to accurately predict soil loss by wind is essential for, among other things, conservation planning, natural resource inventories, and reducing air pollution from wind blown sources.

The Wind Erosion Equation (WEQ) is currently the most widely used method for assessing average annual soil loss by wind from agricultural fields. The primary user of WEQ is the United States Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS). When WEQ was developed more than 30 years ago, it was necessary to make it a simple mathematical expression, readily solvable with the computational tools available. Since its inception, there have been a number of efforts to improve the accuracy, ease of application, and range of WEQ. Despite efforts to make such improvements, the structure of WEQ precludes adaptation to many problems.

The USDA appointed a team of scientists to take a leading role in combining the latest in wind erosion science and technology with databases and computers, to develop what should be a significant advancement in wind erosion prediction technology. The Wind Erosion Prediction System (WEPS) incorporates this new technology and is designed to be a replacement for WEQ.

Unlike WEQ (and RWEQ), WEPS is a process-based, continuous, daily time-step model that simulates weather, field conditions, and erosion. It is a user friendly program that has the capability of simulating spatial and temporal variability of field conditions and soil loss/deposition within a field. WEPS can also simulate complex field shapes, barriers not on the field boundaries, and complex topographies. The saltation, creep, suspension, and PM10 components of eroding material also can be reported separately by direction in WEPS. WEPS is designed to be used under a wide range of conditions in the U.S. and easily adapted to other parts of the world.

The objective of this release is to facilitate communication among potential users of WEPS and to allow for Beta testing of the model.

We anticipate future updates and enhancements to WEPS including extension to range and other non-cropped disturbed lands.

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Finally, acknowledgment is made of the many other individuals who have made this release of WEPS possible by reviewing this document and those who contributed through fundamental research on which many of the underlying concepts of WEPS are based.

Lawrence J. Hagen
WEPS Project Leader

WIND EROSION PREDICTION SYSTEM (WEPS)



WIND EROSION PREDICTION SYSTEM (WEPS)

L.J. Hagen, L.E. Wagner, and J. Tatarko

INTRODUCTION

The Wind Erosion Prediction System (WEPS) is a process-based, continuous, daily time-step model that simulates weather, field conditions, and erosion. It is intended to replace the predominately empirical Wind Erosion Equation (WEQ) (Woodruff and Siddoway, 1965) as a prediction tool for those who plan soil conservation systems or provide environmental planning and assessment. A listing of WEPS-related literature is given in Appendix AA.

OBJECTIVES

The objectives of this report are to summarize the structure of the WEPS model and to describe the design and modeling techniques.

THE SIMULATION REGION

In WEPS, the simulation region is a field or, at most, a few adjacent fields (Fig. I-1). Users must input the geometry of the simulation region and any subregions that have differing soil, management, or crop conditions. Users must also input initial conditions for the surface and four to ten layers. WEPS output is average soil loss/deposition over user-selected time intervals and accounting regions within the simulation region. Multiple and overlapping accounting regions can be selected by the user to obtain output averaged over various spatial scales in the simulation region. WEPS also has an option to provide users with individual soil loss components of creep-saltation and suspension soil-size fractions. The latter is particularly useful as an aid in estimating off-site impacts of wind erosion.

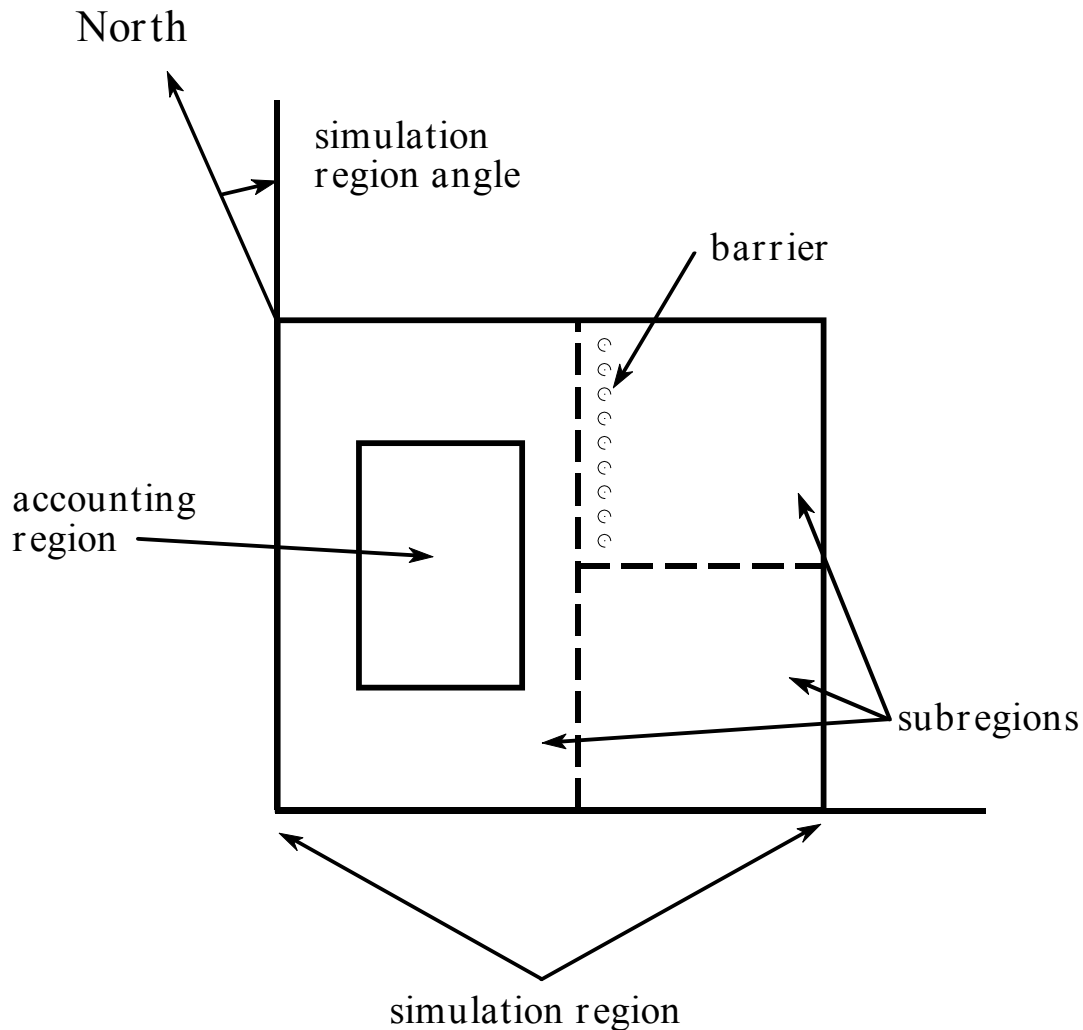


Figure I-1. WEPS simulation geometries.

SIMULATED PROCESSES

Soil erosion by wind is initiated when the wind speed exceeds the saltation threshold velocity for a given soil and biomass condition. After initiation, the duration and severity of an erosion event depends on the wind speed distribution and the evolution of the surface condition. Because WEPS is a continuous, daily, time-step model, it simulates not only the basic wind erosion processes, but also the processes that modify a soil's susceptibility to wind erosion.

The structure of WEPS is modular and consists of a user-interface, a MAIN (supervisory) routine, seven submodels, and four databases (Fig. I-2). The user-interface is used to create

"input run" files using information from the data bases and the weather generator. In practical application, new "run" files usually will be created by editing default "run" files within the user-interface.

Most of the submodels within WEPS use daily weather as the natural driving force for the physical processes that change field conditions. The HYDROLOGY submodel accounts for changes in the temperature and water status of the soil. Changes in the soil properties between management events are simulated in the SOIL submodel. The growth of crop plants is simulated in the CROP submodel, and their decomposition is accounted for in the DECOMPOSITION submodel. Finally, the power of the wind on a subhourly basis is used to drive the EROSION submodel.

Step changes in the soil and biomass conditions are generated from typical management practices such as tillage, planting, harvesting, and irrigation. These events and their influence on the "state" of the system are grouped together by function and modeled within the MANAGEMENT submodel of WEPS.

MODEL DESIGN CONCEPTS

WEPS has a modular design, and each subroutine in WEPS is contained in a separate file. This allows individual components of the WEPS submodels to be easily maintained, modified, or replaced if necessary. This modular concept also enhances the possibility of future simulation models borrowing specific components from individual submodels in WEPS with little code modification. It also eases the task of any potential recoding into another programming language, if needed. Other WEPS design concepts are listed below.

Discrete Time and Discrete Space.

The time step is controlled by the main program. To reduce computation time, a daily time step is used in WEPS, except for selected subroutines in the HYDROLOGY and EROSION submodels, which use hourly or subhourly time steps. Submodels are called by MAIN in the order shown in Fig. I-2. Individual submodels control the sequence of calculations within each submodel. However, in MANAGEMENT, actions are simulated sequentially according to the order in which they appear in the management plan. When the last action listed in a management plan is performed, the plan is repeated again. Currently, management plans must cover at least a single year and may cover multiple years. The management plan can be initiated on any given day of the year, however the WEPS model simulation must begin when there is no growing crop. Only management plans covering discrete yearly intervals are allowed.

Wind Erosion Prediction System (WEPS)

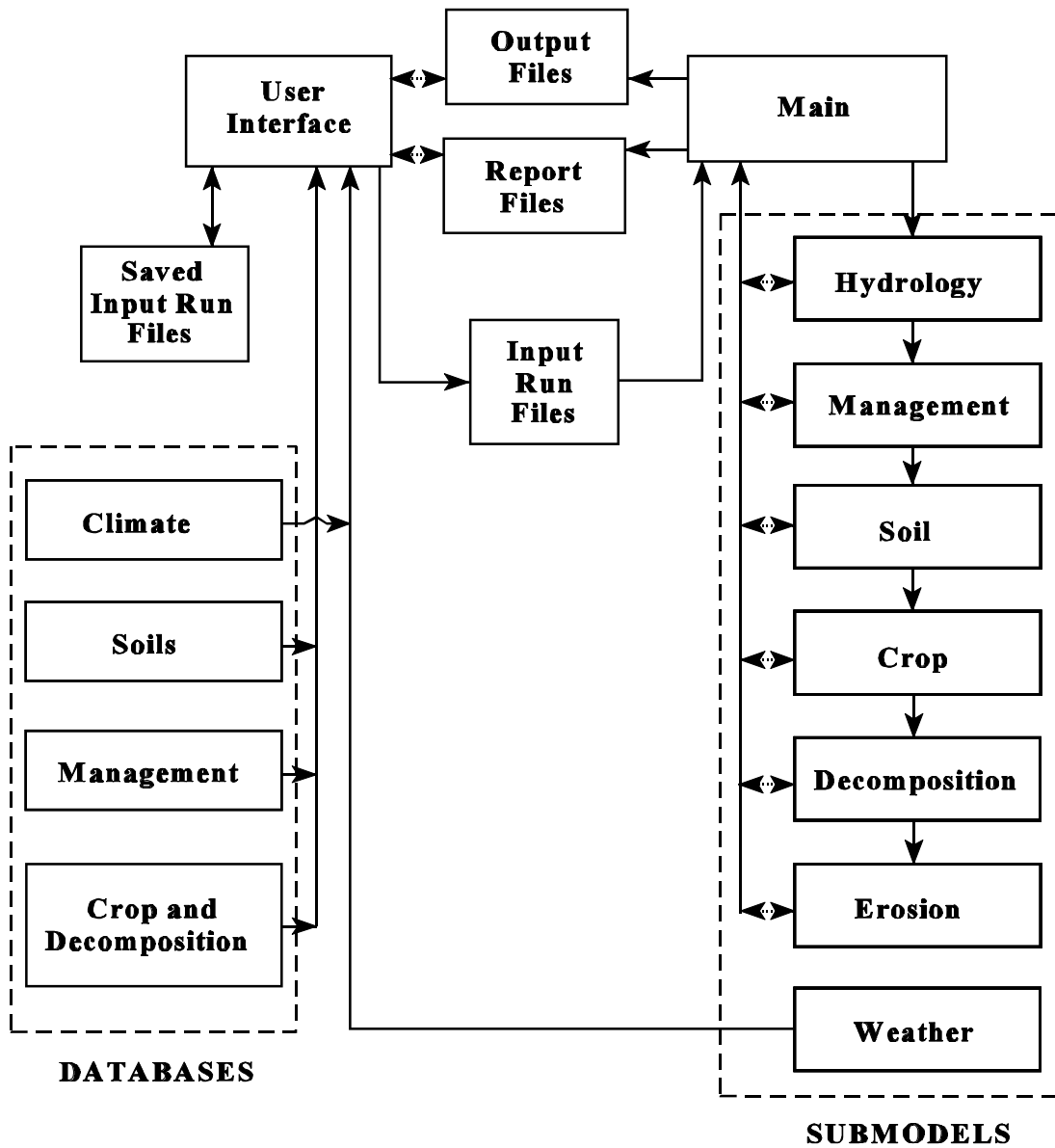


Figure I-2. Structure of the WEPS model.

The WEPS model simulates nonhomogeneous sites by partitioning them into homogeneous subregions and maintaining the individual subregion soil and biomass "states" independently.

"Homogeneous" means that the soil type, biomass, and management are similar over a subregion. Therefore, the basic WEPS submodels (except EROSION) were developed so that individual submodels do not require information on how MAIN internally handles nonhomogeneous sites.

MODELING TECHNIQUES: WEPS compared to WEQ

Users of wind erosion prediction technology encounter a wide range of challenging environmental problems that require solutions. WEQ was unable to meet some of these needs. After extensive consultations with users, the WEPS structure was designed with the capabilities to meet the needs that were identified. As such, WEPS represents new technology and is not merely an improvement and recoding of WEQ technology. Also, WEPS is not a "research model" and contains numerous simplifications in order to maintain reasonable computation times. Most users of wind erosion prediction technology are familiar with WEQ. To facilitate understanding of WEPS modeling techniques, a brief comparison of WEPS and WEQ follows.

WEQ predicts soil loss for a single, uniform, isolated field. In contrast, WEPS provides capability to handle nonuniform areas and also "look inside" the simulation region to obtain predictions for specific areas of interest. In WEPS, spatial variation of the surface is input by describing a simulation region as series of subregions including subregions that are merely sinks (i.e. deposition regions for saltation/creep) such as a water body or drainage ditch. This treatment of spatial variability allows one to determine deposition in critical areas. It also allows one to simulate the interaction of areas with varying erosion rates on soil loss/deposition. For example, a region simulated in isolation may be a soil loss area, but simulated as interacting with other region may actually be a deposition area.

WEQ predicts erosion along line-transects across the field, while WEPS treats the field as two-dimensional. The WEPS EROSION submodel simulates soil loss/deposition at grid points over the entire simulation region. This feature allows users to "look inside" by specifying arbitrary accounting regions within the simulation region, and thus, obtain results averaged over grid points within the accounting region.

WEQ predicts only long-term, average soil loss. WEPS calculates on a daily basis and allows users to specify the output intervals. Thus, users can obtain outputs ranging from single storms to multiple years. By simulating for multiple years, the probability of various levels of erosion during any period of the year also can be determined.

The largest contrast between WEQ and WEPS technology occurs, because WEPS simulates a wide range of processes to describe field surface conditions and wind erosion. The WEQ depends on users to input correct estimates of the field surface conditions. Unfortunately,

erosion does not vary linearly with residue cover and other temporal field conditions. Hence, simply specifying average field conditions as inputs will not likely yield the best estimates of long-term average erosion.

In WEQ there is no feedback loop which modifies the field in response to weather or erosion. In WEPS, the weather driving forces cause the field surface temporal properties to change. Thus, in a year with high rainfall, the field soil roughness may be reduced below average, while biomass production is above average. However, in a drought year biomass and aggregate size may be below average and erosion may fill ridges to reduce roughness.

The modeling techniques used to simulate processes in WEPS vary. The WEATHER submodel generates stochastic simulated weather variables. Mechanistic and statistical relations are generally used to represent processes in the other submodels. However, there was a structured design methodology. First, the major wind erosion processes such as emission, abrasion, trapping, etc. were identified. Next, the individual temporal soil and biomass properties that affect the wind erosion processes were selected. Then, WEPS submodels were designed to simulate the general processes that control both the surface temporal properties and the erosion processes. Finally, parameters from the databases were used to make the simulation of various processes unique for specific soil, crop, or management actions.

Where suitable simulation technology was already available in the literature, it was selected. Thus, the generalized crop growth simulation from EPIC was selected and modified for use in WEPS. Similarly, the stochastic weather generator used for WEPP is also used in WEPS, except for the simulation of winds.

IMPLEMENTATION

Implementation of the WEPS model has several requirements.

Software

The current WEPS model is coded in FORTRAN conforming to the ANSI FORTRAN 77 standard. All discussion of and reasons for this language choice are omitted here. The coding guidelines used are outlined in the "Water Erosion Prediction Project (WEPP) Fortran-77 Coding Convention" (Carey, et al., 1989). These guidelines contain a few minor modifications and additions for WEPS.

Hardware

The model can be run in both a DOS and Unix environment. Therefore, portability, size, and speed constraints are present in order for the model to work satisfactorily in both environments.

Operation

The operation of WEPS is fully documented in the WEPS Users Guide which is distributed with the WEPS program diskette set.

LIMITATIONS

The current version of WEPS is limited to fields growing a single crop at one time period. This limitation is imposed because the CROP submodel does not provide competition among different plant species. There are also limitations on the number of parameters available in the databases on soils, management operations, and crop species. The database parameters currently available are listed in the WEPS Users Guide.

At present, the climate database contains only statistics for 672 U.S. locations.

WEPS UPDATES

The WEPS model will be improved continually and updated periodically. The USDA-ARS Wind Erosion Research Unit (WERU) has established several means for others to obtain the latest release of the WEPS model, databases, documents, and other related information as they become available.

For users with Internet access, an anonymous FTP site is available for downloading the desired information. The FTP address is: <ftp.weru.ksu.edu> . Login is accomplished by entering "anonymous" at the "Name" prompt, and your E-mail address when asked for a "Password". This site contains readme files at each directory level which should help the user to locate the desired materials. WERU has also established a World Wide Web site. The WERU Home Page URL for this site is: <http://weru.ksu.edu> . This site contains all the information available by FTP as well as information about wind erosion research conducted at WERU. Specific WEPS information also can be obtained through E-Mail at office@weru.ksu.edu .

Users without Internet access can obtain WEPS update information by contacting:

USDA-ARS, NPA
Wind Erosion Research Unit
Throckmorton Hall
Kansas State University
Manhattan, KS 66506

Phone: (913) 532-6495
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MAIN PROGRAM



MAIN PROGRAM

John Tatarko

INTRODUCTION

The purpose of the MAIN program is to control the initialization and execution of the Wind Erosion Prediction System (WEPS). It calls subroutines that read the input data and outputs the general report. In addition, MAIN calls submodels on a daily timestep, which update the field conditions. If the maximum wind speed for the day exceeds a set value (i.e., 8 m/s), MAIN calculates subdaily (e.g., hourly) wind speed and then calls the EROSION submodel to simulate erosion processes. The current version of WEPS reads in the climate data produced by the WEATHER submodel; performs daily simulation of the hydrologic and soil conditions, crop growth, and residue decomposition; and accounts for management effects. Finally, the model determines soil erosion by wind for the desired simulation period.

PROGRAM DESCRIPTION

The current version of MAIN requires the following files for a WEPS simulation run: a) a simulation run file; b) initial field conditions file; d) a tillage/management file; and e) two climate files, one each in the CLIGEN and WINDGEN output formats, that provide climate data on a daily basis. The creation of these files for a WEPS simulation run and their contents are discussed in the WEPS Users Guide. A flowchart of the MAIN program operation is given in Fig. M-1.

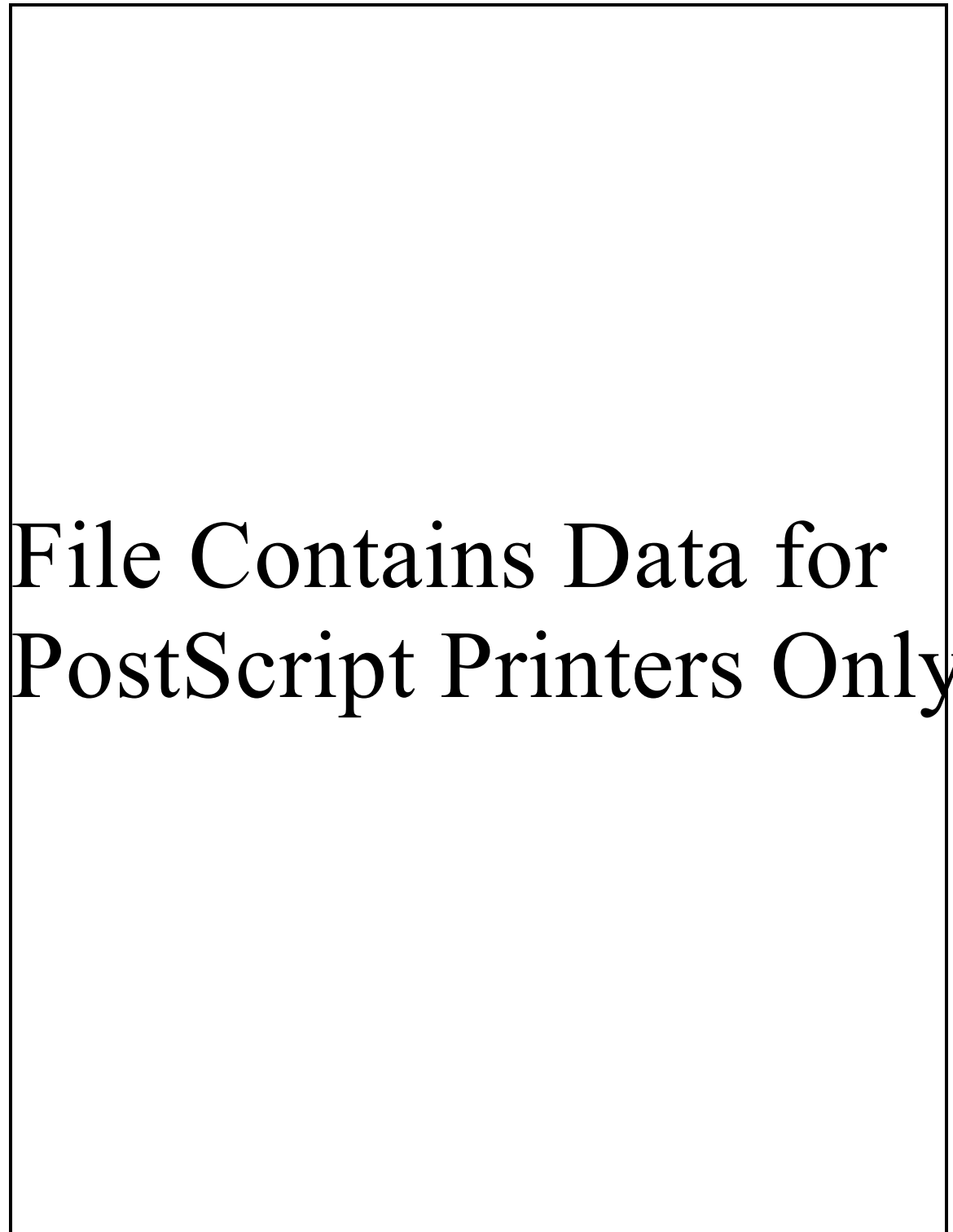


Figure M-1. Flowchart for MAIN program.

The MAIN program begins by initializing local variables and then calls the subroutine INPUT which reads the simulation run file and the initial field conditions file. The simulation then is executed as a daily loop that controls the counters for the current day and an embedded subregion loop. The model can perform any length of simulation on a daily time step and currently allows only one subregion (but up to four are anticipated). For each simulation day, the daily weather is read from the CLIGEN and WINDGEN data files. As some of the submodels are executed, summary information may be compiled for output. All submodels except EROSION are called within the subregion loop. Once field conditions are updated, if maximum wind speed for the day exceeds a set minimum (i.e., 8 m/s), a subdaily wind speed distribution is read or generated. The EROSION submodel then is called to determine threshold conditions and compute soil erosion. Finally, the MAIN program calls subroutine GENREP, which outputs a series of user-selected output forms with general information about the simulation run.

WEPS was developed using Microsoft¹ FORTRAN, which conforms to the ANSI FORTRAN 77 standard. One known Microsoft extension to the ANSI standard used in WEPS. This extension is the use of \$INCLUDE statements. Communication between submodels is accomplished primarily through COMMON blocks that are contained in include files (i.e., *.inc). Each submodel as well as MAIN contain one or more \$INCLUDE statements, which cause FORTRAN to insert the contents of the specified text file (i.e., common blocks) into the source code at that location during compilation. For those who must use only the ANSI standard with no extensions, the "include files" must be inserted into the appropriate subroutines at the location of the \$INCLUDE statements. A description of WEPS variable naming conventions is given in Appendix BB.

MAIN VARIABLE, SUBROUTINE, AND FUNCTION LISTS AND DEFINITIONS

Local Variables

am0*fl	These are switches for production of submodel output, where the asterisk represents the first letter of the submodel name.
am0eif	This variable is an initialization flag for the EROSION submodel.
am0ifl	This variable is an initialization flag that is set to .false. after the first simulation day.
ararea	This variable holds the accounting region area (m ²).

¹ Trade names are for information only and do not constitute endorsement by the USDA.

ccd	The current day of the CLIGEN file.
ccm	The current month of the CLIGEN file.
ccy	The current year of the CLIGEN file.
cflag	This logical variable controls output of warning messages for mismatch of CLIGEN and simulation dates.
cd	The current day of simulation month.
cm	The current month of simulation year.
cy	The current year of simulation run.
clifil	This variable holds the CLIGEN file name.
cwd	The current day of the WINDGEN file.
cwm	The current month of the WINDGEN file.
cwy	The current year of the WINDGEN file.
daysim	This variable holds the total current days of simulation.
diff	This variable holds the number of simulation days.
div	This variable holds the number of simulation days between screen output during execution.
header	Dummy variable to read in character values that are not used.
i	This variable is a counter for simulation loops.
id,im,iy	The initial day, month, and year of simulation.
ijday	This variable contains the initial Julian day of the simulation run.
isr	This variable holds the subregion index.
l	This variable is an index on soil layers.
lchar	This variable holds the character position in a string so as to ignore leading blanks in that string.
ld,lm,ly	The last day, month, and year of simulation.
line	This character variable is used to read the comment lines in the run files.
ljday	This variable contains the last Julian day of the simulation run.
nslay	The number of soil layers.
nsubr	This variable holds the total number of subregions.
runfil	This variable holds the simulation run input file name.
sarea	This variable holds the simulation region area.
series	This character variable holds the soil series name.
simout	This variable holds the simulation output file name.
sinfil	This character variable holds the initial field conditions file name.
srarea	This variable holds the subregion area.
subfil	This variable holds the subdaily wind information file name for use by subroutine 'calcwu'.
subflg	This logical variable is used to read header information in the subdaily wind file (if .true., read header).
usr id	This character variable is an identification string to aid the user in identifying the simulation run.

usrloc	This character variable holds a location description of the simulation site.
usrnam	This character variable holds the user's name.
winfil	This variable holds the WINDGEN input file name.
wflag	This logical variable controls output of a warning message for mismatch of WINDGEN and simulation dates.
wcflag	This logical variable controls output of a warning message for mismatch of CLIGEN and WINDGEN dates.

Subroutines Called

CALCWU	This subroutine generates a subdaily wind speed distributions for the EROSION submodel. If real subdaily wind speed data exists they are used; if not, they are generated.
CALDAT	This subroutine converts Julian day to day, month, and year.
CDEBUG	This subroutine prints selected global variables immediately before and after the call to CROP.
CROP	This is a modified version of the EPIC crop growth model and calculates potential growth of leaves, stems, yield, and root components.
DDEBUG	This subroutine prints selected global variables immediately before and after the call to DECOMP.
DECOMP	The purpose of this model is to account for the biomass residues in the standing, flat, and buried categories.
EROSION	This is a simulation model to compute soil loss/deposition and make new estimates of the surface erodibility parameters.
GENREP	This subroutine controls the output of the general report file.
HDEBUG	This subroutine prints selected global variables immediately before and after the call to HYDRO.
HYDRO	This is a simulation model of the soil water and energy balance.
INPUT	This subroutine controls the input of the various run files. It performs some interactive error checking on these files.

- MANAGE This is a model that assesses the effects of tillage on both temporal soil properties and surface configuration. It also simulates biomass manipulation resulting from tillage operations.
- MFINIT This subroutine initializes MANAGE. It searches the management data file, marking the start sections of each subregion, while storing the number of years in each subregion's management cycle.
- SDEBUG This subroutine prints selected global variables immediately before and after the call to SOIL.
- SOIL This is a model that modifies the temporal soil profile properties as well as surface configuration between erosion and tillage events.

Functions Called

- JULDAY This function determines the Julian date, given a day, month, and year.
- LSTDAY This function determines the last day of a given month for the given year.

WEATHER SUBMODEL



WEATHER SUBMODEL

John Tatarko, E.L. Skidmore, and L.E. Wagner

INTRODUCTION

The Wind Erosion Prediction System (WEPS) requires wind speed and direction in order to simulate the process of soil erosion by wind. These and other weather variables are also needed to drive temporal changes in hydrology, soil erodibility, crop growth, and residue decomposition in WEPS. The weather generator of WEPS consists of the programs WINDGEN and CLIGEN as well as a user interface and it is capable of simulating the needed weather variables on a daily basis and wind speed on a subdaily basis.

WINDGEN is the program that simulates wind speed and direction for WEPS (Skidmore and Tatarko, 1990; Wagner et al., 1992). It was developed specifically for use with WEPS and stochastically simulates wind direction and maximum and minimum wind speed on a daily basis. In addition, WINDGEN provides the hour at which the maximum wind speed occurs for each day based on historical records. Subdaily wind speeds are generated from within WEPS by the subroutine 'calcwu'.

CLIGEN is the weather generator developed for the Water Erosion Prediction Project (WEPP) family of erosion models (Nicks et al., 1987). It is used with WEPS to generate an average annual air temperature as well as daily precipitation, maximum and minimum temperature, solar radiation, and dew point temperature. Average daily air temperature and elevation for the site are used to calculate average daily air density within WEPS. CLIGEN will not be described in this document. However, those interested in CLIGEN and how it simulates these variables should consult the WEPP documentation (Nicks and Lane, 1989). Both CLIGEN and WINDGEN may be executed separately from the command line, or they may be executed together under a menu driven program called 'CLI_WIND'. This is a stand-alone program that allows the generation of weather output from CLIGEN and WINDGEN through a user-friendly menu-driven interface.

WINDGEN DEVELOPMENT

Prediction of wind speed and direction, like most meteorological variables, is extremely difficult. Even with advanced technology, such as sophisticated numerical models and super computers, using climatological means is only as accurate as predicting meteorological variables a few days in advance (Tribbia and Anthes, 1987). Therefore, we resort to historical statistical information about most meteorological variables and use stochastic techniques to determine likelihood of various levels of those variables.

Various models have been used to describe wind speed distribution. A glance at a frequency versus wind speed histogram shows that the distribution is not best described by the familiar normal distribution. Distributions that have been used to describe wind speed include the one-parameter Rayleigh (Hennessey, 1977; Corotis et al., 1978), the two parameter gamma (Nicks and Lane, 1989), and the two-parameter Weibull (Takle and Brown, 1978; Corotis et al., 1978). The Weibull is undoubtedly the most widely used model of common wind behavior representing wind speed distributions.

We developed a stochastic wind simulator to furnish wind direction and wind speed as needed by the Wind Erosion Prediction System described by Hagen (1991).

Compact Database

One important requirement of a wind simulator for wind erosion modeling is to develop a compact database. Although described elsewhere (Skidmore and Tatarko, 1990, 1991), we give here some of the details of creating the compact database. Our database was created from historical monthly summaries of wind speed and wind direction contained in the extensive Wind Energy Resource Information System (WERIS) database at the National Climatic Data Center, Asheville, North Carolina (NCC TD 9793). The WERIS database is described further in Appendix C of Elliot et al. (1986). Data were extracted from WERIS tables and, in some cases, analyzed further to create a database suitable for our needs.

We used data from WERIS Table 12 A-L, joint wind speed/direction frequency by month (e.g., Table W-1), to calculate scale and shape parameters of the Weibull distribution function for each of the 16 cardinal wind directions by month.

The cumulative Weibull distribution function $F(u)$ and the probability density function $f(u)$ are defined by:

$$F(u) = 1 - \exp[-(u/c)^k] \quad (1)$$

and

$$f(u) = dF(u)/du = (k/c)(u/c)^{k-1} \exp[-(u/c)^k] \quad (2)$$

where u is wind speed, c is scale parameter (units of velocity), and k is shape parameter (dimensionless) (Apt, 1976). Because anemometer heights varied from location to location, all wind speeds (e.g., Column 1, Table W-1) were adjusted to a 10 m reference height according to the following:

$$u_2 = u_1(z_2/z_1)^{1/7} \quad (3)$$

where u_1 and u_2 are wind speeds at heights z_1 and z_2 , respectively (Elliot, 1979).

Table W-1. Monthly joint wind speed/direction frequency values.

Wind Speed (m/s)	Wind Direction																Calm	Total	
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW			
Calm	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.7	1.7
1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
2	.3	.1	.1	.0	.1	.1	.2	.1	.3	.1	.5	.5	.6	.4	.5	.2	.0	.0	4.1
3	.7	.3	.5	.4	.9	.4	.6	.5	.9	.4	1.1	1.1	1.5	.8	.7	.3	.0	.0	11.1
4	1.0	.6	.8	.4	1.1	.9	1.0	.8	1.9	.6	.8	1.2	1.6	1.2	.7	.5	.0	.0	15.1
5	.9	.6	.8	.5	.9	.9	1.0	1.3	2.1	.9	1.2	1.2	1.6	.5	.4	.5	.0	.0	15.4
6	.7	.7	.6	.4	.6	.5	.9	.6	1.6	1.0	1.1	1.2	.7	.6	.3	.5	.0	.0	12.2
7	1.0	.6	.6	.4	.2	.5	.4	.5	1.6	1.0	1.4	.8	.7	.5	.3	.2	.0	.0	10.0
8	1.0	.6	.8	.2	.5	.3	.6	.3	1.4	1.2	1.0	.6	.7	.4	.4	.2	.0	.0	10.1
9	.8	.4	.6	.2	.3	.1	.2	.4	1.0	.8	.7	.6	.6	.4	.2	.3	.0	.0	7.6
10	.3	.4	.2	.2	.1	.0	.1	.2	.8	.4	.2	.3	.4	.3	.1	.1	.0	.0	4.3
11	.3	.4	.1	.1	.0	.0	.1	.1	.5	.2	.3	.3	.5	.1	.1	.1	.0	.0	3.1
12	.2	.1	.0	.0	.0	.0	.0	.1	.0	.1	.1	.2	.4	.1	.1	.0	.0	.0	1.6
13	.2	.1	.0	.0	.0	.0	.0	.0	.0	.8	.2	.1	.3	.2	.1	.1	.0	.0	1.3
14	.1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1	.1	.2	.1	.1	.0	.0	.0	.7
15	.1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1	.1	.0	.0	.0	.0	.0	.0	.5
16	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1	.1	.0	.0	.0	.0	.0	.2
17	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1	.0	.0	.0	.0	.1
18	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1
19	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1
20	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
21-25	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
26-30	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
31-35	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
36-40	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
41-up	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
Total	7.8	4.8	5.1	2.9	4.9	3.8	5.1	4.9	12.2	6.8	8.9	8.5	9.9	5.7	4.0	3.0	1.7	100.0	
Avg	6.9	7.0	6.1	6.0	5.1	5.2	5.5	5.9	6.2	6.7	6.4	6.2	6.4	6.2	5.6	6.3	.0	6.1	

Table 12c of WERIS for March, Lubbock, TX

The calm periods were eliminated, and the frequency of wind in each speed group was normalized to give a total of 1.0 for each of the 16 cardinal directions. Thus,

$$F_1(u) = [(F(u) - F_0)/(1 - F_0)] = 1 - \exp[-(u/c)^k] \quad (4)$$

where $F_1(u)$ is the cumulative distribution with the calm periods eliminated, and F_0 is the frequency of the calm periods. The scale and shape parameters were calculated by the method of least squares applied to the cumulative distribution function (Eqn. [W-4]). Equation [W-4] was rewritten as:

$$1 - F_1(u) = \exp[-(u/c)^k] \quad (5)$$

Then by taking the logarithm twice, this becomes:

$$\ln[-\ln(1 - F_1(u))] = -k \ln c + k \ln u \quad (6)$$

If we let $y = \ln[-\ln(1 - F_1(u))]$, $a = -k \ln c$, $b = k$, and $x = \ln u$, Equation [W-6] may be rewritten as:

$$y = a + bx \quad (7)$$

$F_1(u)$ was calculated from information in tables like Table W-1 for each wind speed group to determine y and x in Equation [W-7]. This gave the information needed to use a standard method of least squares to determine the Weibull scale and shape parameters. To recover the real distribution, we can rewrite Equation [W-4] as:

$$F_1(u) = F_0 + (1 - F_0)(1 - \exp[-(u/c)^k]) \quad (8)$$

Wind direction distribution for each location was summarized by month from the "TOTAL" row near the bottom of Table W-1 for each location.

Other pertinent data, obtained from the Wind Energy Resource Atlas of the United States (Elliot et al., 1986), included latitude, longitude, city, state, location name, Weather Bureau Army Navy (WBAN) number, agency responsible for the weather station, period of record, anemometer height and location, and number of observations per 24-hour period.

We eliminated WERIS sites from our database if they represented less than 5 years of data, the anemometer height was not known, or fewer than 8 observations were taken per day. Where more than one satisfactory observation period/site remained in a metropolis, we picked the site with the best combination of the following: (1) maximum number of hours per day observations were taken, (2) longest period of record, (3) 1 hourly versus 3 hourly observations, and (4) best location of anemometer (ground mast > beacon tower > roof top > unknown location). The WINDGEN database currently consists of statistical parameters for 672 locations in the United States.

From WERIS Table 5, we obtained a ratio of maximum/minimum mean hourly wind speed and hour of maximum wind speed by month (e.g., Table W-2). Tables W-2, W-3, W-4, and W-5 give examples of wind information we compiled into a compact database.

Table W-2. Ratio of maximum to minimum hourly wind speed (max/min) and hour of maximum wind speed.

	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
max/min	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.7	1.5	1.6	1.6	1.5
hour max	15	12	15	15	18	18	18	15	15	15	12	15

Values from WERIS Table 5 for Lubbock, TX (Skidmore and Tatarko, 1991) where Month 1 = January.

Table W-3. Wind direction distribution by month in percent.

Wind Direction	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1	8.2	9.7	7.8	5.5	5.3	3.1	2.3	2.9	5.9	6.3	8.8	9.0
2	5.0	4.9	4.8	3.6	3.7	2.2	1.5	2.6	4.8	5.0	4.4	4.8
3	5.0	5.9	5.1	4.1	4.1	3.2	3.9	4.2	6.3	5.3	4.8	4.7
4	3.8	4.2	2.9	4.5	4.8	4.1	3.8	4.7	4.9	4.1	3.1	3.1
5	4.0	4.3	4.9	5.3	5.9	5.0	5.9	6.7	6.3	4.3	4.4	2.2
6	3.1	3.8	3.8	4.7	6.6	6.1	5.7	6.3	5.7	3.0	3.2	1.9
7	3.3	3.8	5.1	6.5	10.5	10.4	10.0	9.7	7.5	4.2	3.4	2.1
8	2.9	3.3	4.9	4.9	8.3	9.5	11.6	14.9	13.6	9.0	5.4	3.7
9	9.8	8.7	12.2	16.4	16.4	26.8	27.4	24.1	18.6	19.7	11.7	9.4
10	6.0	5.7	6.8	6.5	6.9	9.2	8.8	7.2	7.9	9.6	7.5	7.4
11	9.6	8.5	8.9	7.7	7.3	5.9	5.9	5.1	6.2	8.2	9.9	10.1
12	9.6	9.3	8.5	7.9	4.7	3.4	2.4	2.8	3.5	6.0	9.0	9.8
13	12.3	10.8	9.9	6.7	5.1	3.3	2.0	1.7	3.5	6.1	9.0	11.8
14	6.3	6.2	5.7	4.6	3.0	1.5	1.0	1.1	1.7	3.2	5.1	7.7
15	4.7	4.9	4.0	3.4	2.6	1.6	0.8	1.1	2.0	3.0	4.3	5.3
16	3.8	3.4	3.0	3.0	1.8	1.1	0.6	1.1	2.1	2.9	3.0	4.0
17	2.7	2.7	1.7	1.4	1.8	1.5	3.1	5.0	4.0	3.6	4.8	4.3

Directions are clockwise with 1 = north and Month 1 = January. Direction 17 represents calm periods. Values for Lubbock, TX (Skidmore and Tatarko, 1991).

Table W-4. Weibull shape parameters by month and direction.

Wind Direction	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1	2.5	2.5	2.7	2.6	2.8	2.3	2.2	2.6	2.3	2.5	2.7	2.7
2	2.8	2.4	3.2	2.9	2.8	2.7	3.2	2.3	3.1	2.8	2.7	2.6
3	2.8	3.1	3.3	2.8	2.7	2.9	2.8	3.3	3.2	3.3	3.0	3.2
4	3.9	3.4	3.0	3.5	3.0	2.6	2.8	2.9	3.2	3.1	2.7	3.2
5	3.1	3.2	3.3	2.9	3.0	3.4	3.1	3.2	3.3	3.0	3.6	2.8
6	3.4	3.6	3.9	3.3	3.6	4.4	3.7	3.9	3.3	3.5	3.6	5.1
7	3.7	3.3	3.3	3.3	3.4	3.6	3.5	3.5	3.9	4.1	3.6	5.4
8	3.2	4.1	3.3	3.5	3.3	3.5	3.8	3.7	3.5	2.9	3.0	4.5
9	2.9	3.2	3.6	3.3	3.3	3.7	3.7	3.7	3.4	3.3	3.3	3.2
10	3.1	3.5	3.7	3.7	3.2	3.5	3.9	3.6	4.0	3.2	3.5	3.2
11	3.4	3.2	2.7	3.2	3.2	3.0	3.5	3.0	3.4	3.0	3.2	3.2
12	2.5	2.6	2.5	2.4	2.5	2.9	3.4	3.6	3.0	2.7	2.6	2.6
13	2.1	2.4	2.2	2.5	2.6	2.2	3.3	3.1	3.0	2.4	2.2	2.2
14	2.1	2.2	2.3	2.5	2.4	3.6	4.1	3.5	2.6	2.4	1.8	2.0
15	2.4	2.6	2.2	2.5	2.5	3.1	3.3	2.9	2.9	2.0	2.2	2.3
16	2.2	2.6	2.7	2.3	2.8	3.3	2.6	3.5	2.5	2.1	2.4	2.4
17	2.6	2.6	2.7	2.9	3.0	3.1	3.3	3.2	3.0	2.7	2.6	2.6

The directions are clockwise starting with 1=north. Direction 17 is for total wind. Values are for Lubbock, TX (Skidmore and Tatarko, 1991).

Table W-5. Weibull scale parameters by month and direction in m/s.

Wind Direction	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1	8.0	8.2	8.8	8.3	8.0	7.6	5.8	5.0	6.4	7.5	7.5	7.9
2	8.2	9.2	9.0	8.6	8.3	7.6	6.0	5.7	7.3	7.5	6.7	8.1
3	6.6	7.8	8.0	8.3	7.9	7.2	5.8	5.8	5.9	7.0	6.5	6.8
4	6.5	6.5	7.8	6.9	7.3	6.3	5.9	5.2	5.3	6.2	5.7	6.3
5	6.0	6.3	6.7	6.4	6.6	6.3	5.2	4.8	4.6	5.2	5.0	5.0
6	5.3	6.4	6.8	7.1	7.1	6.2	5.3	5.0	5.2	5.1	5.1	4.2
7	5.5	6.4	7.2	7.2	7.4	6.8	6.0	5.5	5.5	5.3	4.8	5.2
8	5.9	6.1	7.5	8.5	8.0	7.5	6.3	5.8	5.9	6.2	5.8	5.2
9	6.2	7.0	7.9	8.5	8.1	8.0	6.8	6.5	6.5	6.6	6.2	6.5
10	7.2	7.2	8.7	8.5	8.1	7.7	6.9	6.5	6.9	6.9	6.9	7.4
11	7.3	7.6	8.2	8.4	7.6	6.9	6.1	5.9	6.1	6.2	6.5	6.9
12	6.5	7.0	8.0	8.6	7.8	7.0	5.4	5.0	5.2	5.9	6.4	6.0
13	6.7	6.8	8.3	8.8	7.2	6.4	4.9	4.4	5.3	5.1	6.3	6.4
14	7.1	7.2	7.8	8.1	7.0	5.6	4.3	4.2	4.6	5.1	6.0	6.9
15	6.1	6.1	7.2	7.2	7.1	5.3	4.6	4.5	4.4	4.9	6.4	6.5
16	7.1	7.7	7.7	8.3	6.6	5.7	4.8	3.9	4.9	6.4	7.1	7.2
17	6.8	7.3	8.1	8.2	7.7	7.3	6.3	5.8	5.9	6.3	6.4	6.7

Directions are clockwise starting with 1=north. Direction 17 is for total wind. Values for Lubbock, TX. Wind speed adjusted to height of 10 meters (Skidmore and Tatarko, 1991).

The following few paragraphs outline procedures to access the compact database and how it is used to simulate wind direction and wind speed. The actual implementation of these

procedures is accomplished through either a user-friendly interface or command line implemented computer programs (see WEPS Users Guide).

Determination of Wind Direction

Read the wind direction distribution array for the specified month (Table W-3). Calculate the cumulative wind direction distribution so that it ranges from 0.0 to 1.0. Draw a random number, RN, where $0.0 < RN < 1.0$, and compare it with the cumulative wind direction distribution. If the random number is equal to or less than the probability of the wind being from the north (i.e., direction = 1, Table W-3), then the simulated wind direction is north. If the random number is greater than the cumulative probability of the wind being from the north and equal to or less than the probability of the wind being from the north northeast, then the simulated wind direction is north northeast and so on. If the random number is greater than the cumulative probability of the wind being from all of the 16 cardinal directions, then the simulated wind is calm.

Determination of Wind Speed

Once wind direction is simulated, access the database to determine the Weibull scale, c (Table W-4), and shape, k (Table W-5), parameters for that direction and the month under consideration in preparation for the next step.

Rearrange Equation [W-8] to make wind speed, u , the dependent variable:

$$u = c \{-\ln[1 - (F(u) - F_0)/(1 - F_0)]\}^{1/k} \quad (9)$$

Draw a random number, $0.0 < RN < 1.0$, assign its value to $F(u)$, and subtract from it the frequency of calm periods, F_0 . If $F(u) < F_0$, then u is calm. In the rare case that $F(u) = 1.0$, the argument of \ln in Equation [W-9] is zero and does not compute. Therefore, if $F(u) > 0.999$, let $F(u) = 0.999$. Otherwise, calculate u from Equation [W-9] for $F_0 < F(u) < 0.999$ to determine a period simulated wind speed. If the period is 1 day, then u represents simulated daily mean wind speed.

Subdaily wind speeds in WEPS will be calculated whenever the maximum wind speed for the day exceeds a set erosion threshold (i.e., default is 8 m/s). To compute subdaily wind speeds, consider a diurnal variation. We present an example of hourly wind speeds, but shorter or longer periods are permitted in WEPS.

Read from the wind database the ratio of maximum to minimum mean hourly wind speed and the hour of maximum wind speed for the location and month under consideration. Calculate the maximum and minimum wind speed for the day based on the representative wind speed as calculated above and given the ratio of maximum to minimum wind speed:

$$urep = (umax + umin) / 2 \quad (10)$$

$$uratio = umax / umin \quad (11)$$

where urep is the daily mean representative wind speed as calculated from Equation [W-9], uratio is the ratio of daily maximum, umax, to daily minimum, umin, wind speed. Solving Equations [W-10] and [W-11] for umax and umin gives:

$$umax = 2 uratio urep / (1 + uratio) \quad (12)$$

$$umin = umax / uratio \quad (13)$$

therefore, wind speed for any hour of the day u(I) can be simulated from:

$$u(I) = urep + 0.5(umax - umin) \cos[2 \pi (24 - hrmax + I) / 24] \quad (14)$$

where hrmax is the hour of the day when wind speed is maximum; I is index for hour of day, and the other variables are as previously defined.

SUBROUTINE CALCWU

When daily maximum wind speed is above the erosion threshold, WEPS must be capable of simulating wind speeds on a subdaily basis. This threshold depends on surface conditions of the simulated field. The MAIN program tests for a maximum daily wind speed in excess of a set speed (i.e., 8 m/s). If winds are less than or equal to this value, subdaily wind speeds are not generated. If the maximum wind speed is greater than 8 m/s, subroutine 'calcwu' is called to provide the subdaily wind speed distribution using Equation W-14. If real subdaily wind speeds are available, they may be read from a file by subroutine 'calcwu' as described in the WEPS Users Guide. Once sub-daily wind speeds are generated or read, the EROSION submodel then will determine if threshold conditions are suitable for erosion to occur. A flow chart for subroutine 'calcwu' is shown in Fig. W-1.



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Figure W-1. Flowchart for subdaily wind subroutine 'calcwu'.

Subroutine calcwu is also capable of using observed weather files of subdaily data so that validation and other studies can be performed. An example of such a file is given in Fig. W-2. The user must specify a file name in the simulation run file for the 'real' data to be used (see WEPS Users Guide). The subroutine searches for the specified real data file. If the file name is not found, it is assumed that all data are to be generated. The daily wind file created by WINDGEN also must be altered so that maximum and minimum wind speeds match those in the subdaily file when maximum wind is greater than 8 m/s.

```

#-----
#      subdaily wind information
#
#      validation site: XXXXX
#
#
#day mo year
#      dir      wind      speeds
#-----
2 1  1985
      315.0  9.87 10.06 10.37 10.77 11.25 11.75 12.25 12.72
13.13 13.44 13.63 13.70 13.63 13.44 13.13 12.73 12.25 11.75
11.25 10.78 10.37 10.06  9.87  9.80
24 1  1985
      315.0  6.85  6.98  7.20  7.47  7.80  8.15  8.50  8.82
9.10  9.32  9.45  9.50  9.45  9.32  9.10  8.83  8.50  8.15
7.80  7.48  7.20  6.98  6.85  6.80
25 1  1985
      .0  8.05  8.21  8.45  8.77  9.15  9.55  9.95 10.32
10.65 10.89 11.05 11.10 11.05 10.89 10.65 10.33  9.95  9.55
9.15  8.78  8.45  8.21  8.05  8.00
30 1  1985
      292.5  8.36  8.52  8.78  9.12  9.52  9.95 10.38 10.77
11.12 11.38 11.54 11.60 11.54 11.38 11.12 10.78 10.38  9.95
9.52  9.13  8.78  8.52  8.36  8.30
10 2  1985
      315.0  8.86  9.03  9.31  9.67 10.10 10.55 11.00 11.42
11.79 12.07 12.24 12.30 12.24 12.07 11.79 11.43 11.00 10.55
10.10  9.68  9.31  9.03  8.86  8.80

. . .
. . .
. . .
. . .

```

Figure W-2. Example of a 'real data' subdaily wind speed file, where day mo year are the day , month, and year of the wind data, dir is the wind direction in degrees from North, and wind speeds are the 24 subdaily wind speeds.

The number of time steps used for subdaily wind speeds is user specified (default is 24 one hour steps) within the simulation run file as described in the WEPS Users Guide.

CLI_WIND PROGRAM

CLI_WIND is a stand-alone, menu-driven computer program to generate weather output. The program's main menu allows the user to select for CLIGEN or WINDGEN or both, enter the site selection menu, generate the desired data, modify CLI_WIND configurations, or exit the program. Within the site-selection menu, the user is allowed to change default settings for the database and output file names as well as a random seed number. The user must then select the site for the simulated weather. This site must be within a user-specified distance range from the WEPS simulation site. If no sites within the given distance range are present in the database, the user is prompted for an expanded search range. The user also has the option of selecting output header information, the starting year, as well as the number of years of simulation.

OUTPUT FILE

We illustrate the output of a simulation from WINDGEN in Fig. W-3. These simulations were generated by accessing data from the WEPS database (i.e., Tables W-2, W-3, W-4, and W-5) and performing the operations described previously.

SUMMARY

The weather generator for WEPS consists of statistical databases derived from historical weather records and computer programs to simulate wind direction and speed as well as other climatic variables on a daily basis. It also has the capability of simulating subdaily wind speeds. This weather generator was developed by the US Department of Agriculture-Agricultural Research Service and is suitable for simulating daily data as required by WEPS.

WINDGEN \$Revision: 1.1 \$						
day	mo	year	dir	umax	umin	hrmax
1	1	1985	225.0	5.8	4.1	12.0
2	1	1985	315.0	11.3	8.1	12.0
3	1	1985	112.5	7.5	5.3	12.0
4	1	1985	337.5	2.0	1.4	12.0
5	1	1985	180.0	3.4	2.4	12.0
.
.
.
30	1	1985	292.5	9.8	7.0	12.0
31	1	1985	247.5	5.2	3.7	12.0
1	2	1985	157.5	7.4	5.3	12.0
2	2	1985	270.0	7.2	5.2	12.0
3	2	1985	247.5	5.3	3.8	12.0
.
.
.

Figure W-3. Example of WINDGEN output where day, mo, and year are the day, month, and year of simulation; dir is the wind direction in degrees from North; umax and umin are maximum and minimum wind speed for the day; and hrmax is the hour at which the wind speed is maximum.

LIST OF SYMBOLS

<u>Symbol</u>	<u>Description</u>	<u>Unit</u>
a	represents $(-k \ln c)$ in regression equation (Eqn. [W-7])	$m s^{-1}$
b	represents (k) in regression equation (Eqn. [W-7])	-
c	Weibull distribution scale parameter	$m s^{-1}$
f(u)	probability density function	-
F(u)	cumulative Weibull distribution function	-
F ₁ (u)	cumulative distribution of winds with calm eliminated	-
F ₀	frequency of the calm periods	-
hrmax	hour of the day when wind speed is at maximum	-
k	Weibull distribution shape parameter	-
u	wind speed	$m s^{-1}$
u ₁	wind speed at height z ₁ used in Eqn. [W-3]	$m s^{-1}$
u ₂	wind speed at height z ₂ used in Eqn. [W-3]	$m s^{-1}$
u(I)	wind speed at time I	$m s^{-1}$
umax	daily maximum wind speed	$m s^{-1}$
umin	daily minimum wind speed	$m s^{-1}$
uratio	ratio of daily maximum to daily minimum wind speed	-
urep	daily mean representative wind speed	$m s^{-1}$
x	represents $(\ln u)$ in regression equation (Eqn. [W-7])	$m s^{-1}$
y	represents $(\ln [-\ln(1-F_1(u))])$ in regression equation (Eqn. [W-7])	$m s^{-1}$
z ₁	height associated with u ₁ in Eqn. [W-3]	m
z ₂	height associated with u ₂ in Eqn. [W-3]	m

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EROSION SUBMODEL



EROSION SUBMODEL

L.J. Hagen

INTRODUCTION

The Wind Erosion Prediction System (WEPS) is a process-based, computer model that predicts wind erosion for a rectangular simulation region on a daily time-step basis (Hagen, 1991a). The WEPS is composed of a user-interface, databases, a supervisory program and seven submodels.

The EROSION submodel uses parameters supplied by other submodels that describe the soil surface, flat biomass cover, standing biomass leaf and stem areas, and weather to decide if wind erosion can occur in a simulation region. If erosion can occur, then the submodel simulates the process of soil movement. Finally, the submodel periodically updates any changes in the soil surface caused by soil movement. At the completion of user-selected simulation intervals, the submodel outputs estimates of soil loss/deposition from the simulation region.

The EROSION submodel consists of several subroutines written in FORTRAN 77. Submodel input data are stored in arrays of variable size that usually represent either global subregion variables or local variables for points on a grid of the simulation region. The number of grid points, grid size, output frequency, output type, etc. are selected external to the submodel and passed to the submodel by program control. Thus, it is necessary to specify elsewhere the number of dimensions in arrays that will contain the inputs and outputs from the submodel before running this submodel.

The EROSION submodel considers the simulation region to be rectangular and composed of one or more rectangular subregions (fields) with differing surface conditions (Fig. E-1). The surface conditions considered are combinations of the following:

1. Surface roughness - random and/or oriented measured below the standing biomass canopy (Fig. E-2);

2. Covers - flat, random, biomass cover; crust with loose, erodible soil on crust; aggregated soil with a size distribution; and rock cover (> 2.0 mm dia.) (Fig. E-3);
3. Surface soil moisture; and
4. Standing biomass (Fig. E-4).

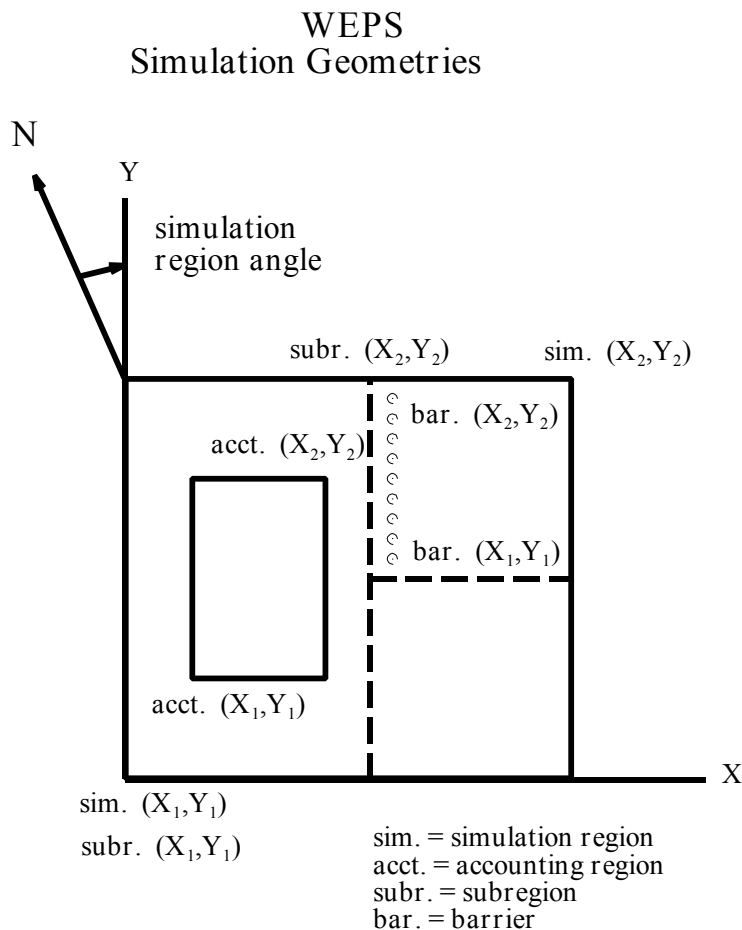


Figure E-1. Simulation region geometry. End points of barriers and opposite corners of rectangular simulation region, subregions, and accounting regions must be input by user.

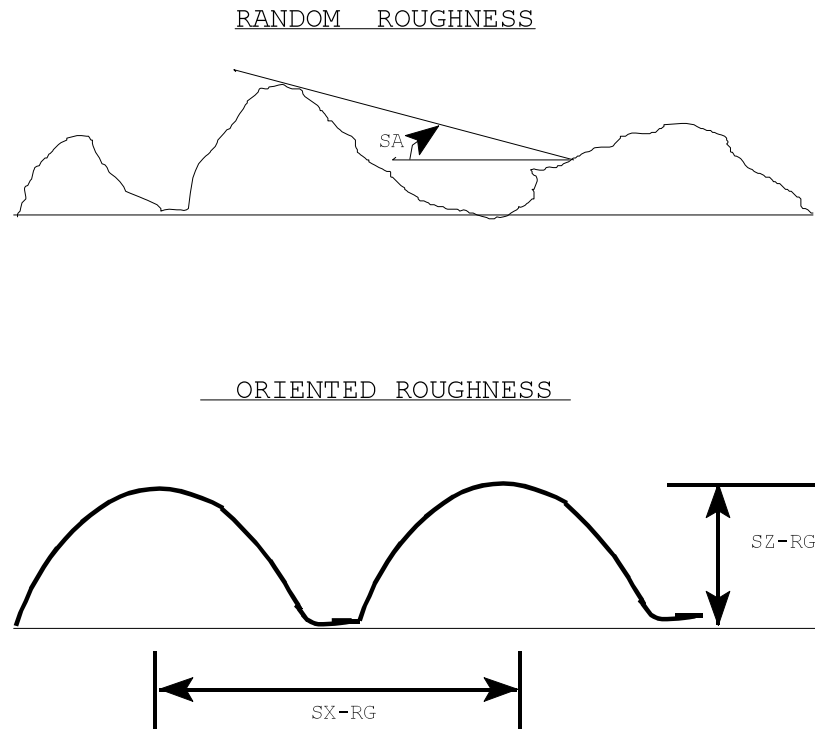


Figure E-2. Illustration of random roughness shelter angles (SA) and oriented roughness spacing (SX-RG) and height (SZ-RG) used in EROSION.

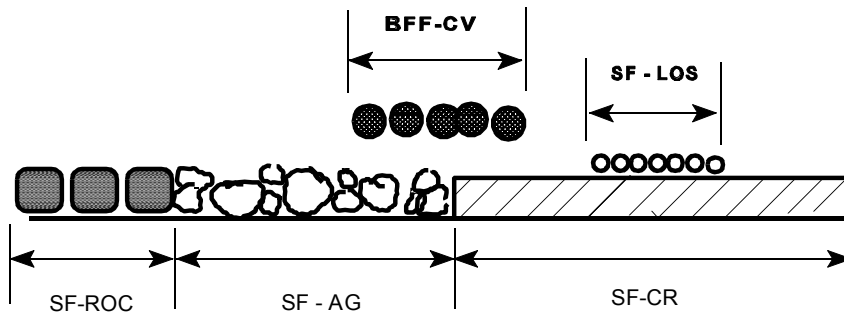


Figure E-3. Illustration of surface cover fraction descriptions used in EROSION. The rock > 2.0 mm (SF-ROC), aggregated (SF-AG), and crusted (SF-CR) soil constitute the lowest layer, and their fractions sum to 1. The second layer is cover fraction loose soil on the crust (SF-LOS), and it cannot exceed crust fraction. The third layer is the biomass flat fraction of cover (BFF-CV), which is assumed to have random distribution over the entire surface.

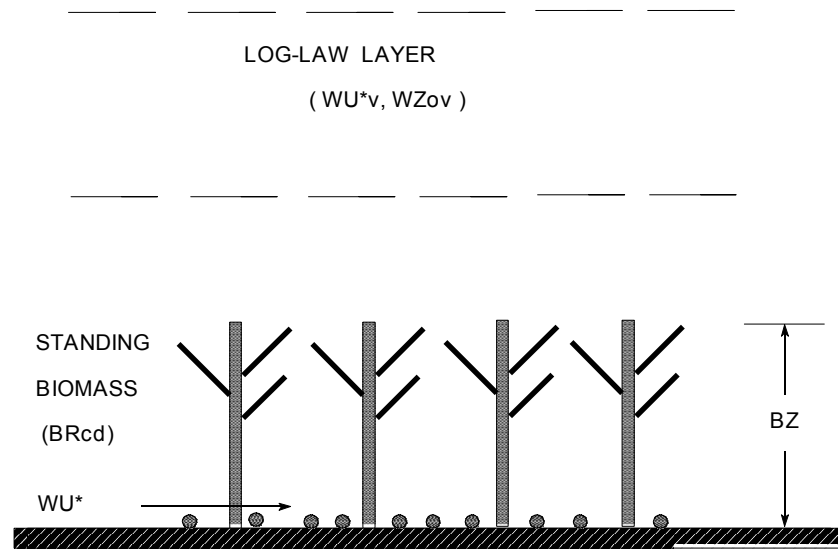


Figure E-4. Diagram illustrating above-canopy friction velocity (WU^*v), which is reduced by drag of the biomass ($BRcd$) to the below-canopy friction velocity (WU^*). The latter is used to drive EROSION.

The EROSION submodel is not called unless maximum daily wind speed at 10 m height reaches 8 m/s. Then, the maximum daily wind speed is used to determine if erosion can occur in any subregion. If snow depth exceeds 20 mm, no erosion occurs in a subregion. If erosion can occur, then generated weather data of subhourly wind speeds and a single wind direction (Skidmore and Tatarko, 1990) for each daily time-step are used to drive the EROSION submodel.

OBJECTIVES

The EROSION submodel is divided into several major functional sections to accomplish the following simulation objectives:

1. Calculate friction velocities in each subregion;
2. Calculate threshold friction velocities in each subregion;
3. Generate the simulation region grid points;
4. Initialize values on simulation region grid points;
5. Compute soil loss/deposition;
6. Update surface variables changed by erosion;
7. Update changed global subregion variables; and
8. Output selected information to files.

EROSION SUBMODEL CONTROL SECTIONS

The subroutine "sberos" serves as the control subroutine for the EROSION submodel (Figs. E-5, E-14, E-16, and E-22) and calls other subroutines which execute the calculations necessary to simulate wind erosion.

DETERMINE FRICTION VELOCITY

In order to determine friction velocity, the aerodynamic roughness term of the log-law wind speed profile must be determined first. For each subregion in the simulation region, the surface aerodynamic roughness as affected by microrelief of the soil and flat biomass cover

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Figure E-5. Partial flowchart of subroutine "Sberos" illustrating testing of subregions to determine if daily maximum friction velocity exceeds threshold friction velocity.

is calculated. In EROSION, tillage ridges are characterized by their height, spacing, orientation, and top bed width. For ridge heights greater than zero, the aerodynamic roughness is (Fig. E-6) (Hagen and Armbrust, 1992):

$$\frac{WZ0_{rg}}{SZ_{rg}} = \frac{1}{-64.1 + 135.5 \frac{SZ_{rg}}{SXP_{rg}} + \frac{20.84}{\sqrt{\frac{SZ_{rg}}{SXP_{rg}}}}}, \quad SZ_{rg} > 0 \quad (1)$$

where

$WZ0_{rg}$ = aerodynamic roughness of the ridges (mm),
 SZ_{rg} = ridge height (mm), and
 SXP_{rg} = ridge spacing parallel the wind direction (mm).

The ridge spacing parallel to the wind direction is:

$$SXP_{rg} = \frac{SX_{rg}}{\text{abs}[\sin(\frac{3.1416}{180}(AWA_{dir} - SA_{rg}))]}; \text{denominator} > 0.2 \quad (2)$$

where

SX_{rg} = ridge spacing (mm),
 AWA_{dir} = daily wind direction (degrees), and
 SA_{rg} = ridge orientation, clockwise from north and parallel to the ridge (degrees).

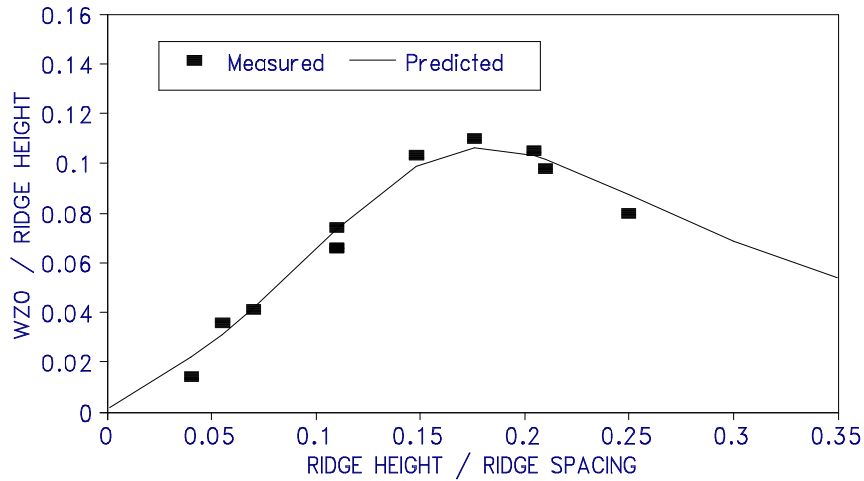


Figure E-6. Ratio of aerodynamic roughness to ridge height as a function of the ridge height to spacing ratio; predicted is equation E-1. (Hagen and Armbrust, 1992).

To describe the fraction of surface sheltered from saltation impacts, the random roughness in EROSION is characterized by shelter angles (Fig. E-2). A shelter angle at a point is defined as the largest angle above horizontal to the top of any upwind point. The shelter angle distribution is described by a two parameter Weibull distribution; the two parameters are a scale factor and a shape factor (Potter, Zobeck, and Hagen, 1990). The average shape factor measured over a range of random roughness was about 0.77 (Potter and Zobeck, 1990). The scale factor was related to the random roughness measurement described by Allmaras et al. (1966) as

$$SAC = 2.3 \sqrt{SZ_{tr}} \quad (3)$$

where

SAC = Weibull scale factor for shelter angle (degrees), and
 SZ_{tr} = random roughness (mm)

Aerodynamic roughness increases with the scale factor and for random roughness (Fig. E-7)(Hagen, 1991b).

$$WZ0_{rr} = \exp\left(2.1546 - \frac{14.44}{SAC_{rr}}\right); \quad SAC_{rr} > 2 \quad (4)$$

where

$WZ0_{rr}$ = aerodynamic roughness of random roughness including any flat biomass cover (mm), and
 SAC_{rr} = Weibull scale parameter of the shelter angle distribution (degrees).

The aerodynamic roughness for the surface, $WZ0$, then is calculated as the maximum of the ridge or random aerodynamic roughness.

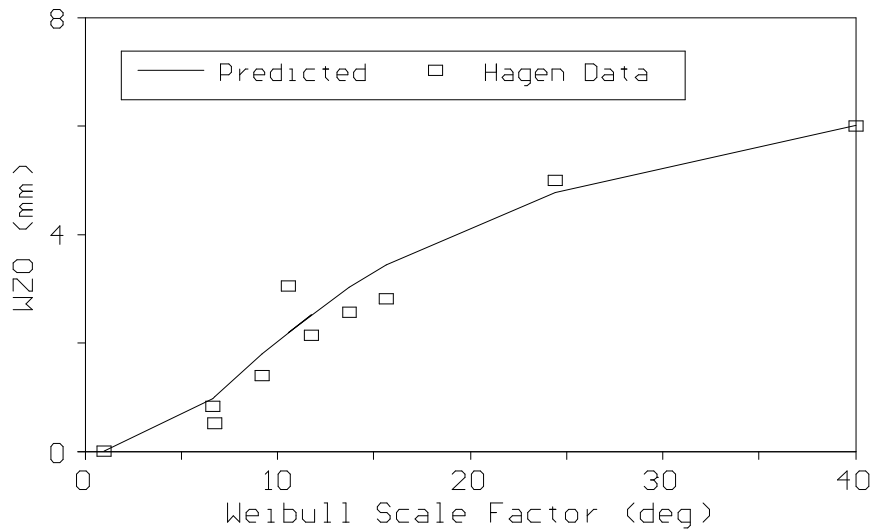


Figure E-7. Aerodynamic roughness of random rough surfaces as a function of the Weibull scale factor of the shelter angle distribution of the random rough surfaces; predicted is equation E-4.

If standing plant biomass is present, the aerodynamic roughness length of the canopy is calculated using the following procedure. First, an effective biomass drag coefficient is calculated as for all crops as (Armbrust and Bilbro, 1995):

$$BR_{cd} = BR_{lai} (0.2 - (0.15)EXP(-8 * BR_{lai})) + BR_{sai} \quad (5)$$

where

- BR_{cd} = effective biomass drag coefficient,
- BR_{lai} = biomass leaf area index (m^2/m^2), and
- BR_{sai} = stem area index, i.e., stem silhouette area per unit horizontal soil surface area (m^2/m^2).

Next, the standing biomass aerodynamic roughness is calculated using an average stem diameter of 20 mm as (Fig. E-8) (Hagen and Armbrust, 1994):

$$WZ0_v = \frac{BZ}{17.27 - \frac{1.254 \ln(BR_{cd})}{BR_{cd}} - \frac{3.714}{BR_{cd}}} \quad (6)$$

Minimum aerodynamic roughness is that of the below-canopy surface. While aerodynamic roughness may decrease slightly with stem diameter of residue, a constant value was assumed in this study.

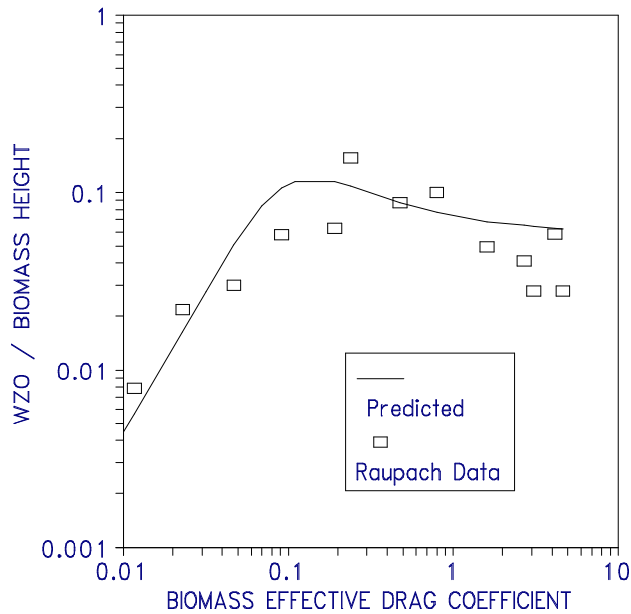


Figure E-8. Biomass aerodynamic roughness as a function of effective drag coefficient of the biomass; predicted is equation E-6.

Friction velocity at the subregion is calculated in two steps. First, the friction velocity at the weather station, where wind speeds are measured, is calculated for strong winds with neutral stability using the log-law profile (Panofsky and Dutton, 1984):

$$WUF = \frac{(0.4)WU}{\ln\left(\frac{WZ}{WZZ0}\right)} \quad (7)$$

where

- WUF = friction velocity at the weather station (m/s),
- WU = wind speed at weather station (m/s),
- WZ = anemometer height at the weather station (mm); (wind speeds were adjusted to 10 m height in WEPS data base), and
- WZZ0 = aerodynamic roughness at weather station, assumed to be 25 mm in WEPS.

Second, the maximum subregion friction velocity is calculated using the daily maximum wind speed. The calculation is based on the ratio of aerodynamic roughness at the subregion to that at the wind speed measurement station. This equation is an approximation of a

procedure suggested by Letteau (Panofsky and Dutton, 1984). If there is no standing biomass, then

$$WU_* = WUF \left(\frac{WZO}{WZZO} \right)^{0.067} \quad (8)$$

where

WU^* = friction velocity used to drive the erosion simulation (m/s).

However, if there is standing biomass, then

$$WU_{*v} = WUF \left(\frac{WZO_v}{WZZO} \right)^{0.067} \quad (9)$$

where

WU_{*v} = friction velocity above the standing biomass (m/s), and
 WZO_v = as defined by equation E-6.

Next, the subregion friction velocity below the standing biomass is calculated (Fig. E-9) (Hagen and Armbrust, 1994).

$$WU_* = WU_{*v} \left[0.86 \exp\left(\frac{-BR_{cd}}{0.0298}\right) + 0.025 \exp\left(-\frac{BR_{cd}}{0.356}\right) \right] \quad (10)$$

where

WU_* = friction velocity below the standing biomass at the surface that is used to drive the erosion simulation (m/s).

At this point in the calculations, the influence of barriers or hills on friction velocity are still neglected

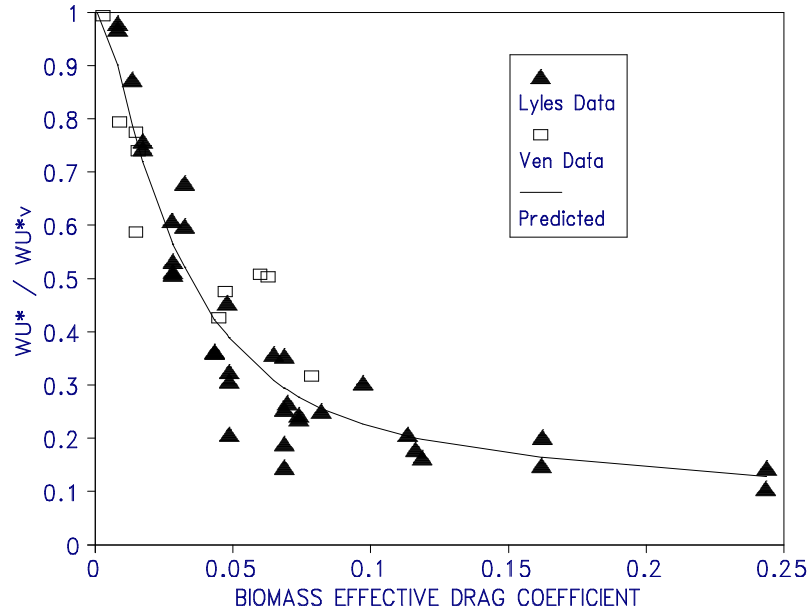


Figure E-9. Reduction in friction velocity through biomass canopy as a function of biomass drag coefficient; predicted is equation E-10 (Lyles and Allison, 1976; van de Ven, Fryrear, and Spaan, 1989).

DETERMINE STATIC THRESHOLD FRICTION VELOCITY

The velocity at which numerous aggregates begin to saltate is defined as the static threshold friction velocity. Static threshold friction velocity is calculated in each subregion as influenced by aggregate size and density, clod/crust cover, surface roughness, flat biomass cover, and surface soil wetness at noon.

Soil scientists generally report the sum of the soil mass fractions less than 2 mm diameter as 1.0 and then report volume of rocks as a separate value in their databases. In WEPS, we have followed this precedent and let the surface fractions of crusted and aggregated soil sum to 1.0. However, to calculate the true fraction of bare surface that does not emit, one must correct for the rock fraction, if it is present. Hence, the fraction of bare surface that does not emit loose soil is :

$$SF_{cv} = [(1 - SF_{cr})(1 - SF_{84}) + SF_{cr} - SF_{los}] [1 - SV_{roc}] + SV_{roc} \quad (11)$$

where

- SF_{cv} = soil fraction covered by clod/crust and rock so it does not emit,
- SF_{cr} = soil fraction covered by crust, but excluding the fraction of rock-covered area,
- SF_{los} = soil fraction covered with loose, erodible soil on the crusted area,
- SV_{roc} = soil volume rock > 2.0 mm. (m^3/m^3), and
- SF_{84} = soil fraction covered with aggregates < 0.84 mm in diameter on the noncrusted area, but excluding the fraction of rock-covered area.

The latter term is calculated from the modified lognormal aggregate size distribution as (Wagner and Ding, 1994):

$$SLT = \frac{(0.84 - SL_{agn})(SL_{agx} - SL_{agn})}{(SL_{agx} - 0.84)SL_{agm}} \quad (12)$$

$$SF_{84} = 0.5 \left[1 + \operatorname{erf} \left[\frac{\ln(SLT)}{\sqrt{2} \ln(SO_{ags})} \right] \right] \quad (13)$$

where

- SL_{agn} = lower limit of size distribution (mm),
- SL_{agx} = upper limit of size distribution (mm),
- SL_{agm} = geometric mean of size distribution (mm), and
- SO_{ags} = geometric standard deviation of size distribution.

To determine threshold friction velocities for bare soil surface, estimating equations were fitted to wind tunnel data (Hagen, 1991b; Chepil and Woodruff, 1963) to give (Figs. E-10 and E-11):

$$WUB_{*ts} = 1.7 - (1.35)\exp[-(b2)SF_{cv}] \quad (14)$$

$$b2 = \frac{1}{-0.076 + \frac{1.111}{\sqrt{WZO}}} \quad (15)$$

where

WUB_{*ts} = static threshold friction velocity of bare surface (m/s).

The minimum static threshold friction velocity for field surfaces was selected to be 0.35 m/s.

If random flat biomass cover is present, the increase in soil surface area protected from emission is (Fig. E-3):

$$SFC_{cv} = (1 - SF_{cv})BFF_{cv} \quad (16)$$

where

- SFC_{cv} = fraction change in soil surface area protected from emission, and
- BFF_{cv} = biomass fraction of flat cover.

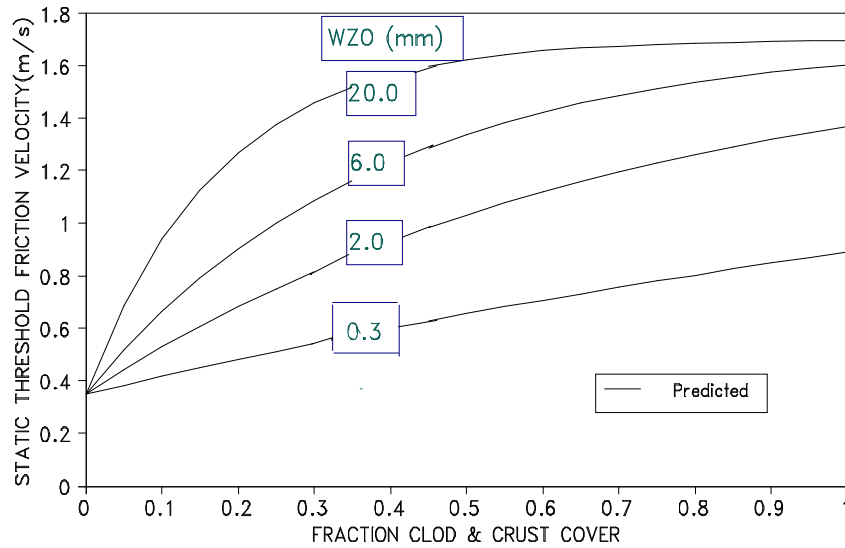


Figure E-10. Predicted threshold friction velocities for various levels of aerodynamic roughness and surface cover; predicted is equations E-14 and E-15.

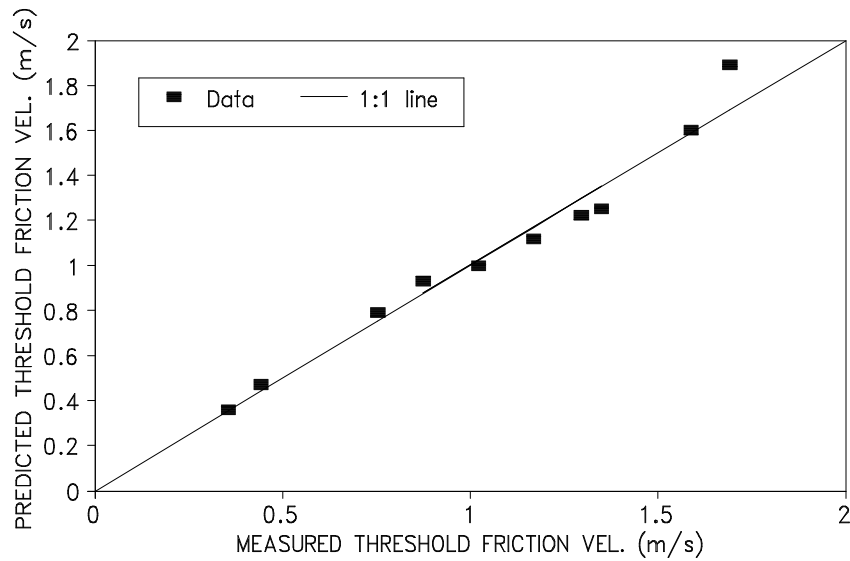


Figure E-11. Predicted threshold friction velocities as a function of measured threshold friction velocities on random rough and ridged surfaces (Hagen, 1991b; Hagen and Armbrust, 1992).

The increase in static threshold friction velocity caused by flat biomass cover is (Fig. E-12) (Hagen, 1995):

$$WUC_{*ts} = 0.02 + SFC_{cv}; \quad SF_{cv} > 0.0 \quad (17)$$

where

WUC_{*ts} = change in static threshold friction velocity caused by flat biomass cover (m/s).

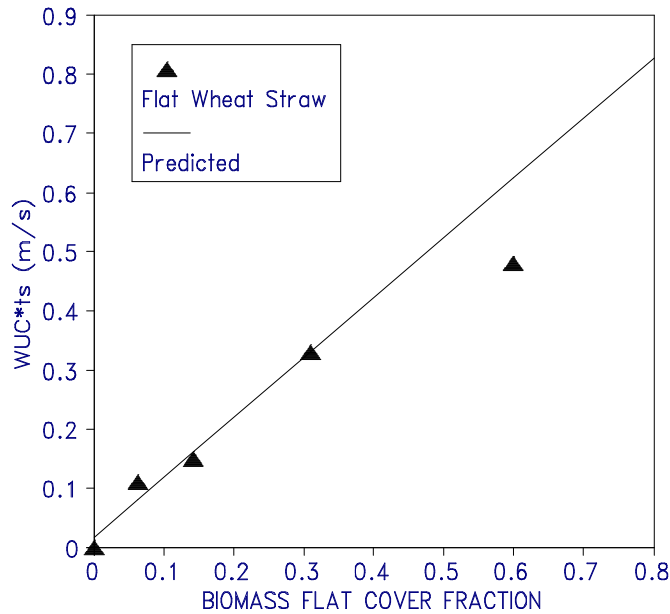


Figure E-12. Increase in static threshold friction velocity of erodible sand; predicted is equation E-17 (0.29-0.42 mm diameter) caused by flat biomass cover (Hagen, 1995).

If the surface is wet, threshold velocity increases as the slope of Fig. E-13 (Saleh and Fryrear, 1995).

$$WUCW_{*ts} = 0.48 \frac{HR0_{wc}}{HR15_{wc}}, \quad \frac{HR0_{wc}}{HR15_{wc}} > 0.2 \quad (18)$$

where

- $WUCW_{*ts}$ = increase in static threshold friction velocity from surface wetness (m/s),
- $HR0_{wc}$ = surface soil water content (kg/kg), and
- $HR15_{wc}$ = surface soil water content at 1.5 MPa (kg/kg).

Finally, static threshold velocity with wetness and flat cover is:

$$WU_{*ts} = WUB_{*ts} + WUC_{*ts} + WUCW_{*ts} \quad (19)$$

where

WU_{*ts} = surface static threshold velocity accounting for both flat biomass cover and wetness effects (m/s).

If friction velocity does not exceed threshold in any of the subregions, control is returned to MAIN. If friction velocity exceeds the threshold, further calculations must be done.

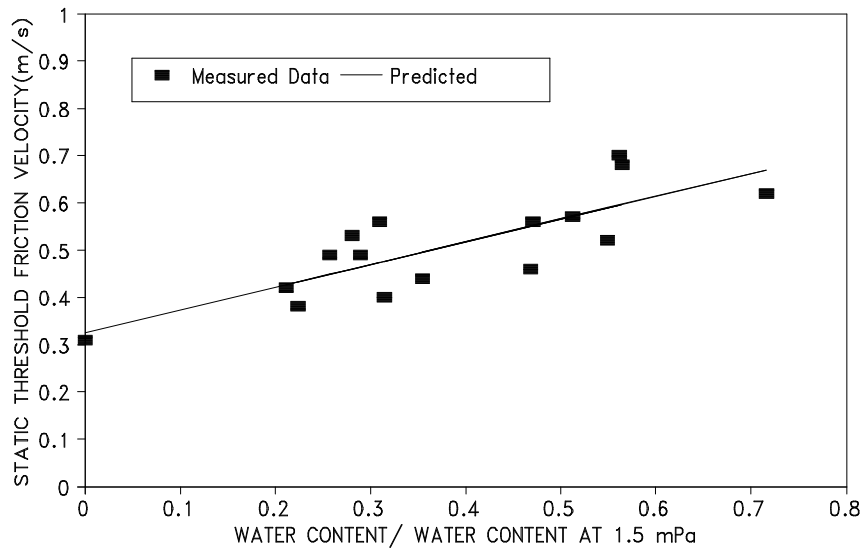


Figure E-13. Static threshold friction velocity change with water content relative to 1.5 MPa water content; predicted slope is equation E-18 (Saleh and Fryrear, 1995).

GENERATION OF THE SIMULATION GRID

Simulation of soil loss/deposition uses finite difference methods to solve partial differential equations that describe the erosion processes. The finite difference procedure requires generation of a grid of computation points on the simulation region. Generation of the grid is started by a flag passed from the supervisory program, MAIN, and is done only once for a simulation run (Fig. E-14). The subroutine "sbgrid" assigns the number and location of the grid points in the simulation region. (Later, inclusion of multigrid techniques or seasonally varying barrier porosity may cause multiple calls to this subroutine.)

INITIALIZATION OF THE SIMULATION GRID

To begin simulation, values of variables must be assigned to each grid point. Thus, at the start of each day with probable erosion, initial values for local and global variables are input at each grid point using the subroutine "sbinit".

HILLS

The subroutine "sbhill" reads an input file that assigns to each grid point a dimensionless wind speed reduction or speed-up factor as influenced by topography. Individual factors are assigned for each of 16 wind directions. Because WEATHER simulates a single wind direction for each day, only one set of factors is used for each day with erosion.

WIND BARRIERS

The subroutine "sbbar" carries out a similar function, but calculates the wind speed reduction factor for each grid point that is influenced by either medium/low or high porosity barriers. Again, a separate reduction factor is assigned for each direction, and only one set of factors is needed each day with erosion. The wind speed reduction factors for high and medium/low porosity barriers are, respectively, (Fig. E-15) (Hagen et al., 1981; van Eimern et al., 1964):

$$\begin{aligned} FUH_{br} = & 1 - \exp[-0.006 xp^2] \\ & + 0.913 \exp[-0.033(xp + 4)^{1.52}] \end{aligned} \quad (20)$$

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Figure E-14. Partial flow chart of subroutine "Sberos" illustrating calls to create simulation region grid and initialize it for each day.

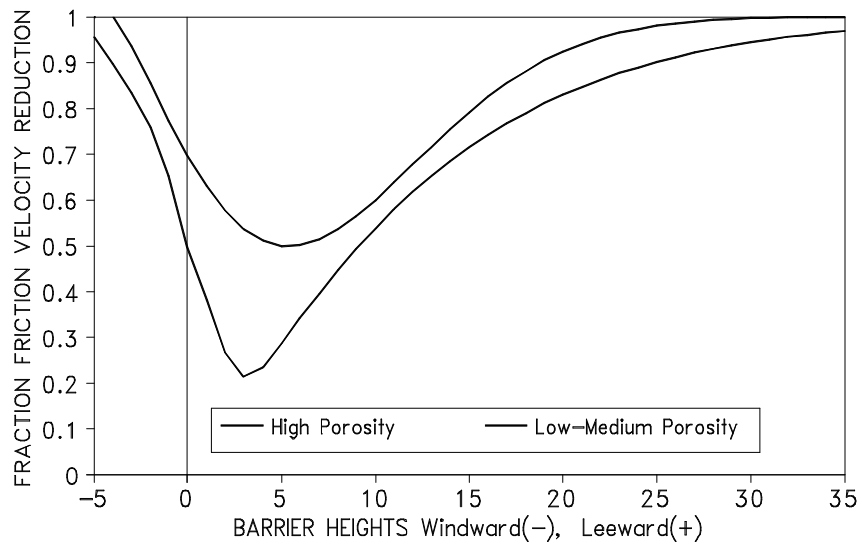


Figure E-15. Barrier function velocity reduction patterns along the wind direction used to modify friction velocity near barriers; predictions are equations E-20 and E-21.

$$\begin{aligned} \text{FUM}_{\text{br}} = & 1 - \exp[-0.0486|\text{xp}|^{1.2}] \\ & + 0.671 \exp[-0.000165(\text{xp} + 5)^{4.66}] \end{aligned} \quad (21)$$

where

- XP = distance from barrier parallel to the wind direction in barrier heights,
 FUH_{br} = fraction friction velocity reduction by high porosity barrier, and
 FUM_{br} = fraction friction velocity reduction by low or medium porosity barriers.

COMPUTATION OF SOIL LOSS/DEPOSITION

This section of the control subroutine, "sberos", steps through the subhourly wind speed values provided by WEATHER and tests whether the friction velocity exceeds the erosion threshold at any point on the simulation grid (Fig. E-16). If the subroutines "sbhill" and "sbbar" are used, this test will account for the effects of both topography and barriers on the friction velocity.

When friction velocity exceeds the erosion threshold, soil loss/deposition is calculated within the subroutine "sberod".

The erosion process is modeled as the time-dependent conservation of mass using linked partial differential equations for three size classes of eroding soil. These are saltation and creep size (0.1 to 2.0 mm), suspension size (<0.1 mm), and PM-10 size (<0.01 mm).

CONSERVATION OF MASS FOR SALTATION AND CREEP

Conservation of saltation and creep size aggregates is simulated with two sources of erodible material (emission and abrasion) and two sinks (surface trapping and suspension). A computational control volume using this scheme for saltation and creep on a bare soil is illustrated in Fig. E-17. The equations for mass conservation of saltation and creep aggregates on a two-dimensional rectangular simulation region can be written as:

$$\frac{\partial(\overline{\text{CH}})}{\partial t} = - \frac{\partial q_x}{\partial x} - \frac{\partial q_y}{\partial y} + G_{\text{en}} + G_{\text{an}} - G_{\text{tp}} - G_{\text{ss}} \quad (22)$$

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Figure E-16. Partial flow chart of subroutine "Sberos" illustrating testing for subhourly friction velocities above the threshold and then computing soil loss/deposition in subroutine "Sberod."

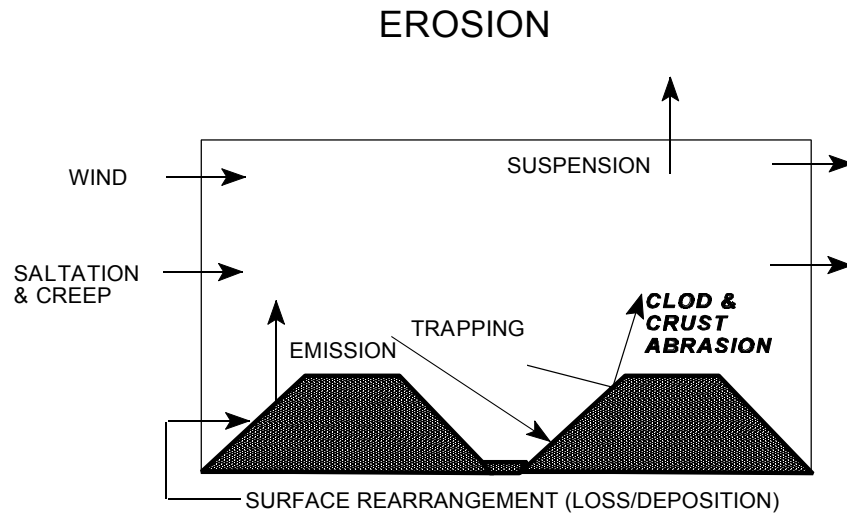


Figure E-17. Diagram of control volume with a ridged bare soil illustrating the sources and sinks used in the EROSION submodel.

$$q = (\bar{C}H) \bar{V}_p \quad (23)$$

$$\bar{V}_p = K_p WU_* \quad (24)$$

$$q_x = (EU_*/WU_*)q \quad (25)$$

$$q_y = (EV_*/WU_*)q \quad (26)$$

where

- x, y = horizontal distances in perpendicular directions parallel to the simulation region boundaries (m),
- t = time (s),
- C = average concentration of saltating particles in the control volume of height H (kg/m^3),
- q_x, q_y = components of the saltation discharge, q , in the x and y directions, respectively (kg/ms),
- V_p = average horizontal saltation particle velocity (m/s),
- K_p = proportionality coefficient,
- WU_* = surface friction velocity (m/s),
- EU_*, EV_* = components of the horizontal friction velocity, WU_* , in the x and y directions, respectively, (m/s),
- $G_{en}, G_{an}, G_{tp}, G_{ss}$ = Net vertical soil fluxes from emission of loose soil, surface abrasion of aggregates/crusts, trapping of saltation, and suspension of fine particles from breakdown of saltation/creep, respectively ($\text{kg}/\text{m}^2\text{s}$).

SOURCE/SINK EQUATIONS FOR SALTATION AND CREEP

Emission Flux

For the loose, erodible portion of the soil, the emission flux can be simulated as

$$G_{en} = C_{en}(1 - SF_{ss_{en}})(q_{en} - q) \quad (27)$$

where

C_{en} = coefficient of emission (1/m),
 $SF_{ss_{en}}$ = soil fraction of suspension size in loose soil emitted, and
 q_{en} = transport capacity for emission calculated using
dynamic threshold friction velocity (kg/ms).

A simplified form of the emission flux equation was tested on a highly erodible, sandy field and provided a good fit to the measured data (Stout, 1990).

For the complex surfaces simulated in EROSION, auxiliary equations were developed to estimate the variables in the emission flux equation. The emission coefficient is calculated as a function of surface complexity as

$$C_{en} = C_{eno} R_{enb} R_{env} \quad (28)$$

where

C_{eno} = coefficient of emission for a bare, smooth, loose, erodible soil.
Typical value is about 0.06 (1/m).

The fractional reduction in emission coefficient to account for flat biomass cover is (Hagen, 1995) (Fig. E-18),

$$R_{env} = 0.075 + 0.934 \exp\left(-\frac{BFF_{cv}}{0.149}\right) \quad (29)$$

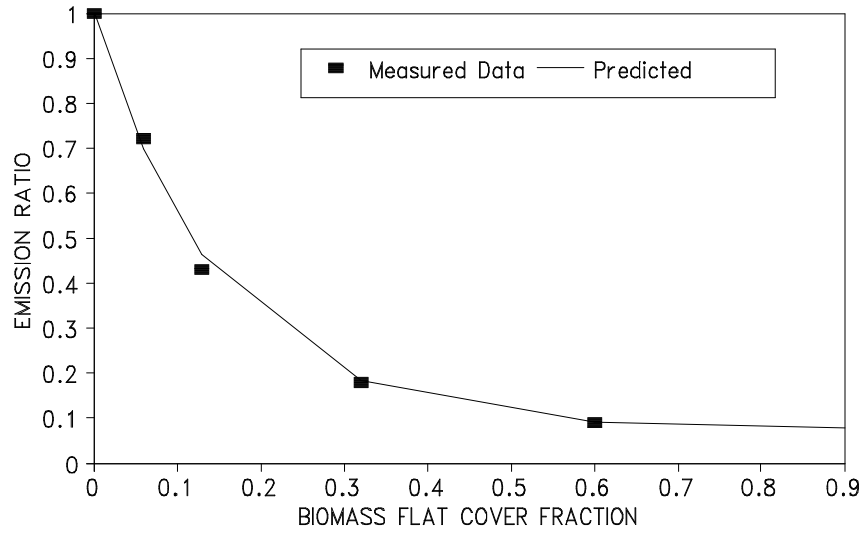


Figure E-18. Reduction in emission of loose soil as a function of increasing biomass flat cover; predicted is equation E-29 (Hagen, 1995).

The fractional reduction in emission coefficient to account for roughness and fraction not emitting of a bare soil is (Fig. E-19, and E-20),

$$R_{\text{enb}} = (1 - SF_{\text{cv}}) \exp(-2.5 SFA_{12}) \quad (30)$$

where

SFA_{12} = soil surface fraction with shelter angles greater than 12 degrees.

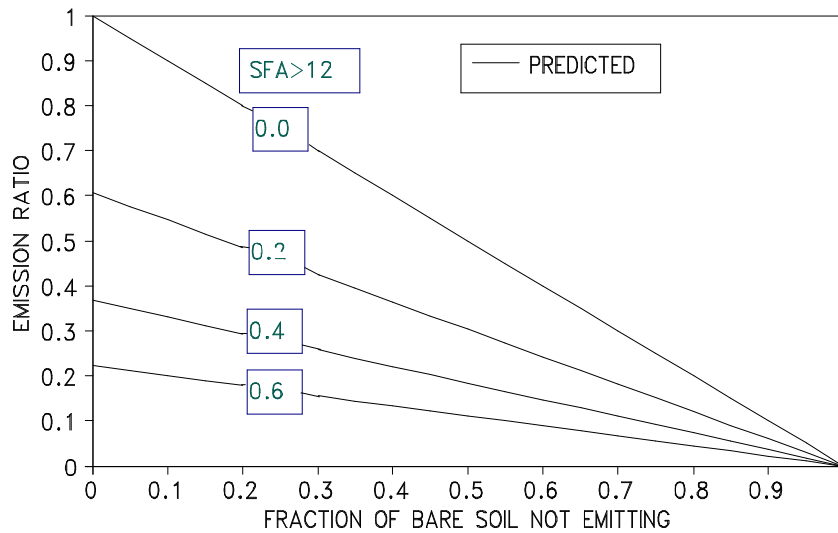


Figure E-19. Predicted reduction in emission of loose soil as a fraction of both soil fraction with shelter angle greater than 12 degrees and fraction of soil not emitting; predicted is equation E-30.

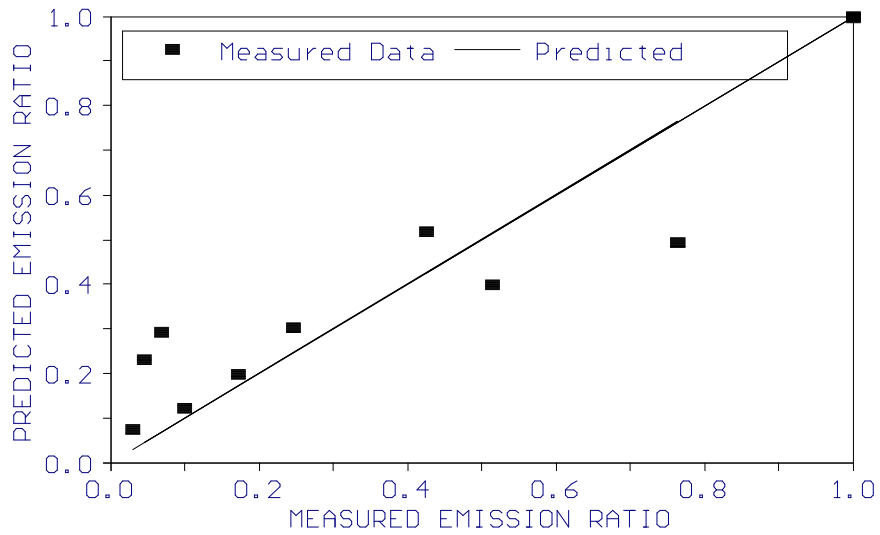


Fig. E-20. Predicted reduction is emission of loose soil compared to values measured in the wind tunnel; predicted is equation E-30 (Hagen, 1991b).

The value of SFA_{12} can be calculated as follows:

$$SAC_{rg} = 65.4 \left(\frac{SZ_{rg}}{SXP_{rg}} \right)^{0.65} \quad (31)$$

$$SFA_{12} = \left[1 - \exp\left(-\frac{12}{SAC_{rg}}\right)^{0.77} \right] \left[\exp\left(-\frac{12}{sac}\right)^{0.77} \right] \quad (32)$$

The soil fraction of suspensions size in the emitted soil is estimated from the aggregate size distribution

$$SFSS_{en} = \frac{SF_{10}}{SF_{84}} \quad (33)$$

where

SF_{10} = soil fraction less than 0.10 mm diameter, and
 SF_{84} = soil fraction less than 0.84 mm diameter.

Finally, the emission transport capacity is calculated with a widely used transport equation (Greeley and Iverson, 1985)

$$q_{en} = C_s WU_*^2 (WU_* - WU_{*t}) \quad (34)$$

where

C_s = saltation transport parameter, value about 0.4 ($\text{kg s}^2/\text{m}^4$).

$$WU_{*t} = 0.8 WU_{*ts} \quad (35)$$

The dynamic threshold friction velocity is calculated as

Trapping Flux

The saltation and creep are decreased whenever the discharge exceeds the transport capacity of the wind for a given surface condition. In addition, standing biomass intercepts saltation and creep. The trapping flux is calculated as (Hagen and Armbrust, 1992; Hagen, 1995)

$$G_{tp} = C_{tp}(q - q_{cp})q + C_i q \quad (36)$$

where

- C_i = coefficient of interception of standing biomass (1/m),
 C_{tp} = coefficient of trapping (kg s/m³), and
 q_{cp} = transport capacity for saltation and creep (kg/ms).

Again, auxiliary equations were developed to calculate the variables in the trapping flux equation. For coefficient of interception,

$$C_i = \frac{BR_{sai}}{BZ} \quad (37)$$

For coefficient of trapping of ridged surface,

$$C_{tprg} = 0.75 \frac{SZ_{rg}}{SXP_{rg}} \quad (38)$$

For coefficient of trapping of random rough surface,

$$C_{tprrr} = 0.0144 \text{ SAC}, \quad (39)$$

Finally, choosing the maximum gives

$$C_{tp} = \max(C_{tprg}, C_{tprrr}) \quad (40)$$

The transport capacity is calculated as

$$q_{cp} = C_s WU_*^2 (WU_* - WU_{*p}) \quad (41)$$

The threshold velocity for transport capacity depends mainly on the surface roughness and is calculated for a surface with 0.4 fraction of armor as

$$WU_{*p} = 0.8[1.7 - 1.35 \exp(-0.4 b_2)] \quad (42)$$

Abrasion Flux

The abrasion of soil clods and crust by saltation creates additional erodible aggregates. The abrasion flux from the soil surface area being abraded ($SA < 12$ degrees) can be computed for the surface portion that is not covered with residue, rocks, or aggregates less than creep size (Hagen, 1991c).

$$G_{an} = (1 - SF_{ss_{an}}) \left(\sum_{i=1}^m F_{ani} C_{ani} \right) q \quad (43)$$

where

- G_{an} = abrasion flux (kg/m^2s),
- $SF_{ss_{an}}$ = soil fraction of suspension size particles from abrasion
- F_{ani} = fraction of saltation abrading surface with i th abrasion coefficient,
- C_{ani} = abrasion coefficient of i th surface ($1/m$), and
- q = saltation and creep discharge entering control volume (kg/ms).

Auxiliary equations were developed to calculate the variables in the abrasion flux equation.

$$a_2 = \frac{SF_{84} - SF_{10}}{SF_{200} - SF_{10}} \quad (44)$$

$$SF_{sn} = 1 - (1 - a_2) \exp\left(-\frac{SFA_{12}}{20}\right) \quad (45)$$

where

- SF_{sn} = fraction of the saltation and creep that is saltation as a function of surface roughness and aggregate size distribution.

The fraction of moving soil abrading clods and crust, F_{an} , is

$$F_{an} = [1 - 4 BFF_{cv} - 2 SV_{roc}(1 - BFF_{cv})] SF_{sn}, \quad F_{an} > 0.0 \quad (46)$$

where

- BFF_{cv} = biomass fraction of flat cover, and
- SV_{roc} = soil volume with rock (m^3/m^3).

The preceding calculation assumes that residue and rocks are generally somewhat above the surrounding surface, and thus, intercept more saltation than indicated by their level of cover.

$$F_{\text{anag}} = (1 - SF_{84})(1 - SF_{\text{cr}}) F_{\text{an}} \quad (47)$$

$$F_{\text{ancr}} = (SF_{\text{cr}} - SF_{\text{los}}) F_{\text{an}} \quad (48)$$

The abrasion coefficient is a function of aggregate dry stability and was determined experimentally as (Fig. E-21) (Hagen, Skidmore, and Saleh, 1992)

$$C_{\text{anag}} = \exp[-2.07 - 0.077 SE_{\text{ags}}^{2.5} - 0.119 \ln(SE_{\text{ags}})] \quad (49)$$

and an estimate for crust abrasion coefficient is (Zobeck, 1991)

$$C_{\text{ancr}} = 1.0 C_{\text{anag}} \quad (50)$$

The soil fraction abraded from clod and crust that is of suspension size was determined experimentally as (Mirzamostafa and Hagen, 1995)

$$0.92SF_{\text{ss}_{\text{an}}} = 0.92 SF_{\text{cla}}, \quad SF_{\text{ss}_{\text{an}}} < 0.4 \quad (51)$$

where

SF_{cla} = soil fraction clay in surface layer.

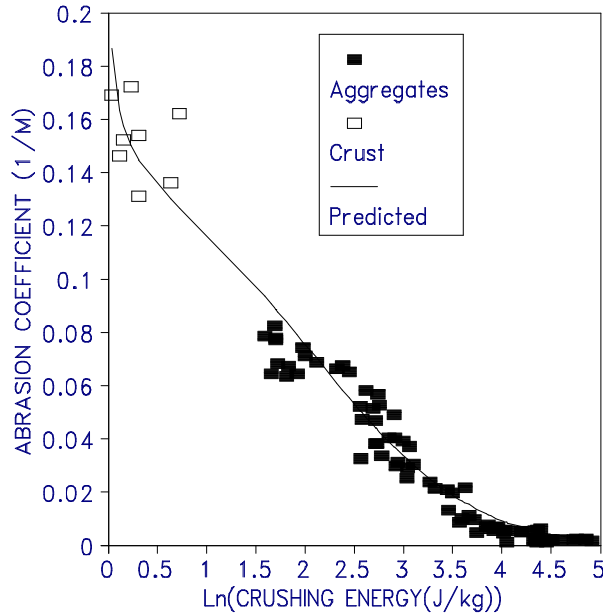


Figure E-21. Abrasion coefficients as a function of crushing energy for soil aggregates and crusts; predicted is equation E-49 (Hagen, Skidmore, and Saleh, 1992).

Suspension Flux:

The suspension component from breakdown of saltation and creep is simulated as

$$G_{ss} = C_{bk} q \quad (52)$$

where

G_{ss} = suspension flux from breakdown of saltation and creep ($\text{kg}/\text{m}^2\text{s}$), and
 C_{bk} = coefficient of breakage (1/m).

The coefficient of breakage is estimated as

$$C_{bk} = 0.08 C_{canag} \quad (53)$$

CONSERVATION OF MASS FOR SUSPENSION

Similar to saltation and creep, a set of equations can be written for mass conservation of the suspension component.

$$\frac{\partial(\overline{C_{ss}H_{ss}})}{\partial t} = -\frac{\partial(q_{ss})_x}{\partial x} - \frac{\partial(q_{ss})_y}{\partial y} + G_{ss_{en}} + G_{ss_{an}} + G_{ss} - G_{tp} \quad (54)$$

where

- t = time (s),
- C_{ss} = mean concentration of suspension particles (Mg/m^3),
- q_{ss} = suspension discharge (kg/ms),
- H_{ss} = height of suspension region over simulation region field (m),
- x,y = horizontal distances in perpendicular directions that are parallel to the simulation boundaries,
- $G_{ss_{en}}$ = net vertical flux of suspension from emission of loose soil (kg/m^2s),
- $G_{ss_{an}}$ = net vertical flux of suspension from abrasion of clods and crust (kg/m^2s),
- G_{ss} = net vertical flux to suspension from breakdown of saltation and creep (kg/m^2s), and
- $G_{ss_{tp}}$ = net vertical flux of suspension from trapping of suspension (kg/m^2s).

SOURCE/SINK EQUATIONS FOR SUSPENSION

The emission flux is calculated as:

$$G_{ss_{en}} = SF_{ss_{en}} C_{en} (q_{en} - q) \quad (55)$$

where all the terms have all been defined previously.

The abrasion flux is calculated as

$$G_{ss_{an}} = SF_{ss_{an}} \sum_{i=1}^m (F_{ani} C_{ani}) q \quad (56)$$

The suspension flux from breakdown of saltation and creep, G_{ss} , was defined previously.

Suspension flux by trapping is simulated only when the suspension discharge passes over a subregion without active saltation to maintain the suspension flux near the surface. The largest particles, 0.05 to 0.1 mm diameter, are roughly half the mass of the suspension

discharge (Chepil and Woodruff, 1958; Zobeck and Fryrear, 1986) and tend to move toward the surface. The process is simulated as

$$G_{ss_{tp}} = C_{dp}(q_{ss} - 0.5 q_{ss_o}), \quad G_{ss_{tp}} > 0.0 \quad (57)$$

where

- q_{ss_o} = maximum q_{ss} calculated (kg/ms), and
 C_{dp} = coefficient of deposition, value about 0.02 (1/m).

CONSERVATION OF MASS FOR PM-10

Conservation of mass for the PM-10 is simulated as a partitioning of the suspension components without any trapping.

$$\frac{\partial(\overline{C10H10})}{\partial t} = -\frac{\partial(q10)_x}{\partial x} - \frac{\partial(q10)_y}{\partial y} + G10_{en} + G10_{an} + G10_{ss} \quad (58)$$

where

- $\overline{q10}$ = PM-10 discharge (kg/ms),
 $\overline{C10}$ = mean concentration of PM-10 particles (Mg/m^3),
 $H10$ = height of PM-10 region over simulation region (m),
 $G10_{en}$ = net vertical flux of PM-10 from emission of loose soil (kg/m^2s),
 $G10_{an}$ = net vertical flux of PM-10 from abrasion of clods and crust (kg/m^2s), and
 $G10_{ss}$ = net vertical flux of PM-10 from breakdown of saltation and creep (kg/m^2s).

SOURCE/SINK EQUATIONS FOR PM-10

The flux from emission is

$$G10_{en} = SF10_{en} SF_{ss_{en}} C_{en} (q_{en} - q) \quad (59)$$

where

- $SF10_{en}$ = soil fraction of PM-10 in the suspended soil that was emitted from the surface.

$$SF10_{en} = \frac{SF_1}{SF_{10}} \quad (60)$$

where

SF_1 = soil surface fraction less than 0.01 mm diameter, and
 SF_{10} = soil surface fraction less than 0.10 mm diameter.

The flux from abrasion is

$$G10_{an} = SF10_{an} SF_{ss_{an}} \sum_{i=1}^m (F_{ani} C_{ani}) q \quad (61)$$

where

$SF10_{an}$ = soil fraction of PM-10 in suspended soil that was abraded from the surface (Hagen, Mirzamostafa, and Hawkins, 1995).

$$SF10_{an} = 0.67 SF_{cla}, \quad SF10_{an} < 0.35 \quad (62)$$

The flux from breakdown of saltation and creep is

$$G10_{ss} = SF10_{bk} C_{bk} q \quad (63)$$

where

$SF10_{bk}$ = soil fraction of PM-10 in suspended soil that was created from breakdown of saltation and creep (Hagen, Mirzamostafa, and Hawkins, 1995).

$$SF10_{bk} = 0.0015 + 0.023 SF_{si}^2 \quad (64)$$

where

SF_{si} = soil fraction silt in surface layer.

SURFACE REARRANGEMENT

Finally, auxiliary equations to describe the changes in the soil surface in response to loss or deposition are needed to complete the system of equations. In general, few field

measurements are available to validate the simulated response of field surfaces to erosion. To simulate the surface rearrangement, simple equations based on mass balance of the surface layer were developed for the area represented by each grid point.

EROSION EFFECT ON LOOSE SOIL ON CRUST

The net vertical deposition is

$$SG = G_{tp} - G_{en} - GSS_{en} \quad (65)$$

where

SG = net vertical deposition of loose soil ($\text{kg}/\text{m}^2\text{s}$).

The net vertical deposition then is portioned between the emitting area on the crust and the total emitting area as

$$\frac{d(SM_{los})}{dt} = SG \left[\frac{SF_{los}}{1 - SF_{cv}} \right] \quad (66)$$

where

SM_{los} = soil mass that is loose and erodible on the crust (kg/m^2),
 SF_{los} = soil fraction cover of loose aggregates on crust,
 SF_{cv} = soil fraction covered and not emitting, and
 t = time (s).

The fraction of crusted area covered by loose material is updated as

$$e \frac{d(SF_{los})}{d(SM_{los})} = \frac{SF_{los}}{SM_{los}} \quad (67)$$

EROSION EFFECT ON CRUST THICKNESS AND COVER

Abrasion from the crust is

$$\frac{d(SZ_{cr})}{dt} = - \frac{F_{ancr} C_{ancr} (G_{an} + GSS_{an})}{SD_{blk}} \quad (68)$$

where

SZ_{cr} = crust thickness (mm).

Next, crust cover is reduced in linear proportion to crust thickness and aggregate cover is increased

$$\frac{d(SF_{cr})}{d(SZ_{cr})} = \frac{SF_{cr}}{SZ_{cr}} \quad (69)$$

$$\frac{d(SF_{ag})}{dt} = - \frac{d(SF_{cr})}{dt} \quad (70)$$

where

SF_{cr} = fraction crust cover, and

SF_{ag} = fraction aggregate cover.

EROSION EFFECT ON SURFACE ROUGHNESS

Typical field surfaces have a clod or crust armor at the highest elevations. During erosion, these elevated points have abrasion losses from the top and trapping or emission in the low areas. The net rate of change in height caused by these processes is approximated as

$$SZ_1 = \frac{2(G_{an} + GSS_{an} - G_{en} - GSS_{en} + G_{tp})}{SD_{blk}}, \quad SF_{cv} > 0.1 \quad (71)$$

where

SZ_1 = change in height per unit time (mm/s).

The factor two is used because it is assumed that the different process act on only about half the area.

In the case of highly erodible surfaces, there is both emission and abrasion from the top and trapping in the low areas. The net rate of change in height is approximated as

$$SZ_2 = \frac{2(G_{en} + GSS_{en} + G_{an} + GSS_{an} + G_{tp})}{SD_{blk}}, SF_{cv} < 0.1 \quad (72)$$

where

SZ_2 = change in height per unit time (mm/s).

The rate of change in ridge height is then

$$\frac{d(SZ_{rg})}{dt} = -SZ_{1,2} \quad (73)$$

Similarly, the effect of erosion on random roughness is approximated as

$$\frac{d(SZ_{sd})}{dt} = -SZ_{1,2} \quad (74)$$

where

SZ_{sd} = soil storage depth in the random roughness (mm).

Analysis of a number of pin meter measurements on random rough surfaces showed the soil storage depth for shelter angles greater than 3 degrees is related to the Weibull scale factor as (Wagner and Hagen, 1992)

$$SAC = 1.563 + 4.534\sqrt{SZ_{sz}} \quad (75)$$

Manipulating the two preceding equations gives

$$\frac{d(SAC)}{dt} = -\frac{10.28 SZ_{1,2}}{(SAC - 1.563)}, \quad SAC > 2.0 \quad (76)$$

where

SAC = the Weibull scale factor of shelter angle distribution (degrees).

EROSION EFFECT ON AGGREGATE-SIZE DISTRIBUTION

The aggregate-size distribution is modeled as an abnormal, log-normal distribution with 4 parameters (Wagner and Ding, 1994). However, the EROSION submodel uses a series of

specific size ranges in the calculation procedures. Hence, during days when EROSION is simulated, the size ranges will be updated periodically during the day in the active surface layer (zero layer) at each grid area. At the end of each day, new aggregate size distribution parameters are calculated for the first (10 mm) layer of each subregion by averaging the changes over the grid points in the subregion.

To update the grid areas, an active layer mass (zero layer) is defined, similar to the procedure of Borah and Bardoloi (1989) as

$$SM_0 = \frac{0.84}{1 - F84} SD_{ag}, \quad \frac{SM_0}{SD_{blk}} < 10 \text{ mm} \quad (77)$$

where

- SM_0 = soil mass that must be removed by emission in order to armor the surface (kg/m^2),
- SD_{ag} = soil aggregate density (Mg/m^3),
- SD_{blk} = soil bulk density (Mg/m^3), and
- $SF84$ = soil mass fraction less than 0.84 mm diameter.

In the case of a low number of clods, the active layer is restricted to 10 mm depth.

The abrasion and trapping processes increase the fraction less than 0.84 mm, whereas emission decreases it. Thus,

$$\frac{d(F84)}{dt} = \frac{(F_{anag} C_{anag})(G_{an} + GSS_{an}) + SF_{ag} G_{tp}}{SM_0} - \frac{(1 - SF_{cv} - SF_{los})(G_{en} + GSS_{en})}{SM_0} \quad (78)$$

The maximum and minimum size aggregates in the distribution are assumed to remain constant. Hence, size fractions finer than 0.84 mm are modified proportionally as

$$\frac{d(SF10)}{dt} = \frac{SF10}{SF84} \frac{d(SF84)}{dt} \quad (79)$$

where

- $SF10$ = soil fraction less than 0.1 mm diameter.

Similarly, for fractions larger than 0.84 mm, say 2.0 mm,

$$\frac{d(\text{SF}200)}{dt} = \frac{(1 - \text{SF}200)}{(1 - \text{SF}84)} \frac{d(\text{SF}84)}{dt} \quad (80)$$

UPDATE OF GLOBAL SUBREGION VARIABLES

During an erosion event, the global subregion variables are updated periodically by subroutine "sbupdt" (Fig. E-22). The reason for this update within an erosion day is to allow changes in the soil surface to impact the calculation of the surface friction velocity and other erosion parameters.

File Contains Data for PostScript Printers Only

Figure E-22. Partial flowchart of subroutine "Sberos" illustrating updating of global subregion variables and output to files from the EROSION submodel. Viewing the results and printing output are controlled by the MAIN control subroutines of WEPS.

Of course, after the last erosion period of the day, the updated variables are passed to other submodels. For global soil layer variables, only the first layer is updated.

One other problem may occur, if a daily erosion event causes large gradients of global variables to develop across a single subregion. This gradient may affect the erosion on subsequent days, but this is not reflected by using average inputs for each subregion to begin the daily erosion simulation. To reduce this problem, the daily gradients will be retained by the EROSION submodel until the surface is significantly changed by other submodels.

OUTPUT FROM EROSION TO FILES

Two subroutines output files of information from the EROSION submodel (Fig. E-22). The first subroutine, "sbout", is a specialized subroutine that is located within the daily erosion cycle. It is to be modified by those developing, verifying, and validating the EROSION submodel.

The second subroutine, "sbrpt", has several outputs:

1. The Julian day,
2. the total soil loss/deposition at each grid point since last output,
3. the total suspension at each grid point since last output, and
4. the total PM-10 production at each grid point since last output.

The outputs to a file from calls to subroutine "sbrpt" are controlled by a flag from the MAIN subroutine.

The grid points that may be included in each user-selected accounting region must form a rectangle, but there are no other restrictions. However, all the information for standard reports for all potential accounting regions is located in the report file generated by subroutine "sbrpt". When MAIN calls the subroutine "sbrpt" for a printed report, the data in the report file are analyzed for each of the specified accounting regions and printed.

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HYDROLOGY SUBMODEL



HYDROLOGY SUBMODEL

A. A. Durar and E. L. Skidmore

INTRODUCTION

The HYDROLOGY submodel of the Wind Erosion Prediction System (WEPS) uses inputs generated by other WEPS submodels such as WEATHER, CROP, SOIL, MANAGEMENT, and DECOMPOSITION to predict the water content in the various layers of the soil profile and at the soil-atmosphere interface throughout the simulation period. Accurate simulation by the other WEPS submodels requires prediction of the daily changes in soil water profiles. However, estimating soil wetness at the soil-atmosphere interface is emphasized, because it significantly influences the susceptibility of the soil to wind erosion.

The HYDROLOGY submodel of WEPS maintains a continuous, daily, soil water balance using the equation:

$$SWC = SWCI + (PRCP + DIRG) + SNOW - RUNOFF - ETA - DPRC \quad (1)$$

where SWC is the amount of water on the soil profile in any given day (mm), SWCI is the initial amount of water in the soil profile (mm), PRCP is the amount of daily precipitation (mm), DIRG is the amount of daily irrigation (mm), SNOW is the daily snow melt minus daily snow accumulation (mm), RUNOFF is the amount of daily surface runoff (mm), ETA is the amount of daily actual evapotranspiration (mm), and DPRC is the amount of daily deep percolation (mm).

The amount of daily precipitation (PRCP) is partitioned between rainfall and snowfall on the basis of the average daily air temperature. If the average daily temperature is 0°C or below, the precipitation takes the form of snowfall; otherwise, it takes the form of rainfall.

The snow term (SNOW) can be either positive, equaling the daily snow melt, or negative, equaling the daily snow accumulation. The melted snow is treated as rainfall and added to the precipitation term in Eq. H1 when accounting for daily runoff and infiltration. On the other hand, the accumulated snow is subtracted from the daily precipitation during the estimation of the daily soil water balance with Eq. H-1.

Simulation of soil-water dynamics on a daily basis by the HYDROLOGY submodel involves three major sequences. First, the submodel partitions the total amount of water available from precipitation, irrigation, and/or snow melt into surface runoff and infiltration. The submodel stores the daily amount of water available for infiltration into the soil profile. Second, the submodel determines the influence of ambient climatic conditions by calculating the potential evapotranspiration. Third, the submodel redistributes soil water in the soil profile on an hourly basis, which provides hourly estimations of water content in the soil profile. The submodel estimates the actual rate of evapotranspiration by adjusting the potential rate on the basis of soil water availability. Deep percolation from the soil profile is estimated to be equal to the conductivity of the lowermost simulation layer, assuming a unit hydraulic gradient.

The HYDROLOGY submodel estimates surface runoff and infiltration for each simulation day that has precipitation and/or irrigation. If measured daily runoff associated with the precipitation and/or irrigation event is available, it is entered as an input to the computer simulation of soil-water dynamics, and daily infiltration is computed simply as precipitation and/or irrigation minus runoff. However, if measured runoff data are not readily available, as is often the case, then a daily estimate of runoff is made using a modified version of the Soil Conservation Service (SCS) soil-cover complex method, which usually is referred to as the curve number (SCS-CN) method. The SCS-CN technique relates runoff to soil properties, antecedent soil moisture conditions, hydrologic conditions of the ground cover, and land use and management practices (Soil Conservation Service, 1972). However, the runoff component of the HYDROLOGY submodel contains four major modifications to the standard SCS-CN method. First, the submodel adjusts the tabulated curve numbers to account for the effects of slope on runoff. Second, the HYDROLOGY submodel uses the daily estimates of crop canopy from the CROP submodel to evaluate the daily conditions of the ground cover. Third, the submodel uses the status of soil wetness in the uppermost simulation layer to directly evaluate the antecedent soil moisture conditions instead of using the antecedent rainfall index. Fourth, the submodel includes a provision for estimating the increase in runoff under frozen soil conditions.

The submodel estimates the daily amount of water available for infiltration into the soil by subtracting the amount of daily surface runoff from the amount of daily precipitation, snow melt, and/or irrigation. The infiltration water is stored in the uppermost simulation layer, until its water content reaches field capacity. Any excess water then is added to the succeeding lower layer, where it is stored with the same maximum storage restriction. This is repeated until complete water storage is obtained. Any excess water that flows out from the lowermost simulation layer becomes a part of a deep percolation.

Potential evapotranspiration is calculated using a revised version of Penman's combination method (Van Bavel, 1966). The total daily rate of potential evapotranspiration then is partitioned on the basis of the plant leaf area index into potential soil evaporation and potential plant transpiration. The potential rate of soil evaporation is adjusted to account for

the effect of plant residues in the simulation region. Furthermore, the daily potential rates of soil evaporation and plant transpiration are adjusted to actual rates on the basis of water availability in the soil profile.

The HYDROLOGY submodel uses a simplified forward finite-difference technique to redistribute soil water with the one-dimensional Darcy equation for water flow. The time step of the soil water redistribution section is 1 hour, which allows for an hourly estimation of soil wetness as needed for WEPS. Knowledge of the relationship between unsaturated hydraulic conductivity and soil water content is required for solving the governing transport equations of water movement through the soil. The submodel uses Campbell's (1974) method to calculate the unsaturated hydraulic conductivity of the soil from the more readily available soil water characteristic curve and saturated hydraulic conductivity data. Because water release curve data of the soil are not always available, the submodel provides alternative options to estimate the hydraulic parameters of the water release curve that are needed as inputs to run the soil water redistribution segment of the submodel.

The HYDROLOGY submodel predicts on an hourly basis soil wetness at the soil-atmosphere interface by using a combination of two techniques. The submodel extrapolates water content to the soil surface from the three uppermost simulation layers. A numerical solution known as Cramer's rule (Miller, 1982) is used to obtain an estimate of the extrapolated water content at the soil surface by solving the three simultaneous equations that describe the relationship between water content and soil depth for the three uppermost simulation layers. The submodel also interpolates the functional relationship between surface-soil wetness and the hourly evaporation ratio.

SUBMODEL DEVELOPMENT AND DESCRIPTION

Some of the algorithms used in the HYDROLOGY submodel are similar to those used in well-established models such as SPAW (Saxton and Bluhm, 1982; Saxton et al., 1974; 1984; Sudar et al., 1981), CREAMS (Smith and Williams, 1980), and EPIC (Williams et al., 1984; 1990). Significant modifications were made, however, and new algorithms were added to meet the unique requirements of WEPS for fast simulation of the diurnal changes in soil water content, particularly at the soil-atmosphere interface.

Snow Melt

The snow melt component of the HYDROLOGY submodel of WEPS is similar to that of the CREAMS model (Smith and Williams, 1980) and the EPIC model (Williams, 1989; Williams et al., 1984; 1990). If snow is present at any simulation day, it is melted when the maximum daily air temperature exceeds 0°C using the equation:

$$\begin{aligned} \text{SNMLT} &= 4.57 \text{ TMAX} & \text{SNMLT} < \text{SNWC} \\ \text{SNMLT} &= \text{SNWC} & \text{SNMLT} \geq \text{SNWC} \end{aligned} \quad (2)$$

where SNMLT is the rate of snow melt (mm/day), SNWC is the water content of snow before melt occurs (mm), and TMAX is the maximum daily air temperature (°C).

Surface Runoff

The HYDROLOGY submodel estimates daily infiltration for each simulation day that has precipitation and/or irrigation. If measured daily runoff associated with the precipitation and/or irrigation event is available, it is entered as an input to the computer simulation of soil-water dynamics, and daily infiltration is computed simply as precipitation and/or irrigation minus runoff. However, if measured runoff data are not readily available, as is often the case, then a daily estimate of runoff is made by a modified version of the Soil Conservation Service (SCS) soil-cover complex method, which usually is referred to as the curve number (SCS-CN) method. The SCS-CN technique was selected because (1) it is a reliable procedure that has been used for many years by such credible simulation models as SPAW (Saxton and Bluhm, 1982; Saxton et al., 1974; 1984; Sudar et al., 1981), CREAMS (Smith and Williams, 1980), and EPIC (Williams, 1989; Williams et al., 1984; 1990); (2) it is computationally efficient; (3) it uses readily available data such as daily rainfall as an input; and (4) it relates runoff to soil properties, antecedent soil moisture conditions, hydrologic conditions of the ground cover, and land use and management practices.

The combination of a hydrologic soil group (soil) and a land use and treatment class (cover) is referred to by the SCS as a hydrologic soil-cover complex. The standard SCS-CN procedure (Soil Conservation Service, 1972) uses a series of tables and graphs to assign runoff curve numbers (CN) for hydrologic soil-cover complexes. The CN of a soil-cover complex indicates the runoff potential of the complex when the soil is not frozen. The higher the CN, the higher is the runoff potential of the soil-cover complex. The procedure uses an antecedent rainfall index to estimate antecedent soil moisture as one of three types, I, II, and III for dry, normal, and wet conditions, respectively. The relationship between rainfall and runoff for these three conditions is expressed as a curve number (CN).

The SCS curve number equation is:

$$\begin{aligned} \text{RUNOFF} &= (\text{DH20} - 0.2\text{S})^2 / (\text{DH20} + 0.8\text{S}) && \text{DH20} > 0.2\text{S} \\ \text{RUNOFF} &= 0.0 && \text{DH20} \leq 0.2\text{S} \end{aligned} \quad (3)$$

where RUNOFF is the daily runoff (mm); DH20 is the total daily amount of water from precipitation, snow melt, and/or irrigation (mm); and S is the retention parameter (mm).

The retention parameter (S) varies according to the hydrologic properties of the soil-cover complex in the simulation region. It is estimated on the basis of a curve number, which reflects the effects of soil properties, antecedent soil moisture conditions, land use, and soil cover hydrologic conditions. The curve number (CN) is related to the retention parameter using the equation:

$$S = 254(100/\text{CN} - 1) \quad (4)$$

where CN is the calculated curve number.

A modification to the standard SCS-CN method similar to the one adopted by the SPAW model (Saxton and Bluhm, 1982; Saxton et al., 1974; 1984; Sudar et al., 1981) is used in the HYDROLOGY submodel to incorporate the predicted daily estimates of crop canopy by the CROP submodel of WEPS and improve the accuracy of runoff simulation. To adjust the curve number, the tabulated CN values (Table H1) under poor and good crop conditions are prorated according to the daily estimated value of crop canopy. The selection of the correct hydrologic soil group is based on the criteria listed in Table H-2.

Table H-1. Runoff curve numbers for hydrologic soil-cover complexes (Class II antecedent moisture conditions).

Land use	Cover		Hydrologic soil group			
	Treatment or practice	Hydrologic condition	A	B	C	D
Fallow	straight row	---	77	86	91	94
Row crops	straight row	poor	72	81	88	91
	straight row	good	67	78	85	89
	contoured	poor	70	79	84	88
	contoured	good	65	75	82	86
	contoured and terraced	poor	66	74	80	82
	contoured and terraced	good	62	71	78	81
Small grain	straight row	poor	65	76	84	88
	straight row	good	63	75	83	87
	contoured	poor	63	74	82	85
	contoured	good	61	73	81	84
	contoured and terraced	poor	61	72	79	82
	contoured and terraced	good	59	70	78	81
Close-seeded legumes* or rotation meadow	straight row	poor	66	77	85	89
	straight row	good	58	72	81	85
	contoured	poor	64	75	83	85
	contoured	good	55	69	78	83
	contoured and terraced	poor	63	73	80	83
	contoured and terraced	good	51	67	76	80
pasture or range		poor	68	79	86	89
		fair	49	69	79	84
		good	39	61	74	80
	contoured	poor	47	67	81	88
	contoured	fair	25	59	75	83
	contoured	good	6	35	70	79
Meadow		good	30	58	71	78
Woods		poor	45	66	77	83
		fair	36	60	73	79
		good	25	55	70	77
Farmsteads		---	59	74	82	86
Roads						
dirt**		---	72	82	87	89
hard surface**		---	74	84	90	92

Source: Soil Conservation Service (1972)

* Close-drilled or broadcast-seeded

** Including right-of-way

Table H-2. Criteria for selecting the correct hydrologic soil group.

Hydrologic soil group	Final infiltration rate (m/s)	Soil characteristics
A	2.117E-06 - 3.175E-06	Deep sand, deep loess, aggregated silts
B	1.058E-06 - 2.117E-06	Shallow loess, sandy loam
C	3.528E-07 - 1.058E-06	Clay loams, shallow sandy loam, soils low in organic content, and soils usually high in clay
D	0 - 3.528E-07	Soils that swell significantly when wet, heavy plastic clays, certain saline soils, soils with permanent high water table, and shallow soils over nearly impervious material

Source: Hjelmfelt, Jr. and Cassidy (1975) and Soil Conservation Service (1972).

The difference (CNDIF) between the SCS curve numbers for poor (CNIIP) and good (CNIIG) soil-cover hydrologic conditions for the average antecedent soil moisture conditions (class II) is calculated

$$\text{CNDIF} = \text{CNIIP} - \text{CNIIG} \quad (5)$$

The calculated runoff curve number for class II antecedent soil moisture conditions is then adjusted according to the daily estimate of crop canopy using the equation

$$\text{CNII} = \text{CNIIP} - (\text{CNDIF} * \text{CANP}) \quad (6)$$

where CANP is the daily estimate of crop canopy (ratio of ground cover), and CNII is the curve number for class II antecedent soil moisture conditions.

Furthermore, an adjustment similar to the one proposed by the EPIC model (Williams, 1989; Williams et al., 1984; 1990) is used to express the effects of slope on runoff. This adjustment is based on the assumption that the tabulated curve number values in the handbook (Soil Conservation Service, 1972) are appropriate only for a 5% slope. The equation for adjusting the handbook curve number values is

$$\text{CNIIS} = 1/3 (\text{CNIII} - \text{CNII})(1 - 2 \exp(-13.86\text{SLP})) + \text{CNII} \quad (7)$$

where CNIIS is the curve number for class II antecedent soil moisture conditions adjusted for slope, SLP is the average slope of the simulation region (m/m), and CNIII is the curve number for class III antecedent soil moisture conditions.

The class III antecedent soil moisture conditions (CNIII) is related to class II with the equation

$$\text{CNIII} = 6.9368 + 1.6425 \text{ CNII} - 0.0071 \text{ CNII}^2 \quad (8)$$

With the standard curve number method (Soil Conservation Service, 1972), the antecedent rainfall index is used to evaluate antecedent soil moisture conditions. However, this is no longer necessary, because direct evaluation of antecedent soil moisture conditions can be obtained from the simulation of soil water dynamics by the HYDROLOGY submodel. The surface runoff component of the submodel uses a procedure similar to the one used in the SPAW model (Saxton and Bluhm, 1982; Saxton et al., 1974; 1984; Sudar et al., 1981) to adjust the calculated curve number from Eq. H7 for the type II antecedent soil moisture condition according to the current status of surface soil moisture. If the soil water content of the uppermost simulation layer is less than 60% of the field capacity, the curve number is adjusted to the type I condition. On the other hand, if the soil water content of the top simulation layer is greater than field capacity, the curve number is adjusted to the type III condition. The slope-adjusted curve number values for antecedent soil moisture condition types I and III are related to type II with the following equations:

$$\text{CNIS} = 0.4678 (1.0113)^{\text{CNIIS}} (\text{CNIIS})^{0.9191} \quad (9)$$

$$\text{CNIIS} = 6.9368 + 1.6425 \text{ CNIIS} - 0.0071 \text{ CNIIS}^2 \quad (10)$$

where CNIS is the slope-adjusted curve number for class I antecedent soil moisture conditions, CNIIS is the slope-adjusted curve number for class II antecedent soil moisture conditions, and CNIIS is the slope-adjusted curve number for class III antecedent soil moisture conditions. Therefore, the calculated curve number used in Eq. H4 to determine the retention parameter will be equal to one of the three curve numbers (CNIS, CNIIS, or CNIIS) according to the current status of surface soil moisture. Equations H9 and H10 were obtained by regression analysis of the tabulated data (Hjelmfelt, Jr. and Cassidy, 1975; Soil Conservation Service, 1972). The coefficients of determination (r^2 values) for Eq. H9 and Eq. H10 are 1.00 and 0.99, respectively.

Finally, a refinement of the retention parameter (S) will be added to account for the increase in runoff under frozen soil conditions. An equation similar to the one used in the EPIC model (Williams, 1989; Williams et al., 1984; 1990) is used to determine the frozen ground retention parameter when the temperature of the surface soil is less than 0°C.

$$\text{SF} = \text{S} [1 - \exp(-0.00292 \text{ S})] \quad (11)$$

where SF is the frozen ground retention parameter (mm).

Hence, the surface runoff component is linked with the rest of the HYDROLOGY submodel as well as other WEPS submodels, such as CROP, to maintain a continuous daily soil-water balance.

Soil Water Storage

The soil-water storage segment of the HYDROLOGY submodel of WEPS is similar to that of the SPAW model (Saxton and Bluhm, 1982; Saxton et al., 1974; 1984; Sudar et al., 1981). The submodel estimates the daily amount of water available for infiltration into the soil by subtracting the amount of daily surface runoff from the amount of daily precipitation, snow melt, and/or irrigation. However, the submodel does not give time distribution to the predicted daily infiltration.

The water is added to the uppermost simulation layer, until its water content reaches field capacity; then any excess water is cascaded downward to succeeding layers and stored without exceeding field capacity, until adequate storage is achieved. Any excess water that infiltrates below the lower boundary layer becomes a part of deep percolation. The soil-water redistribution segment of the submodel carries out all further water redistribution in the simulation.

Potential Evapotranspiration

Potential evapotranspiration is calculated using the revised combination method of Van Bavel (1966), which combines a surface energy balance equation and an approximate expression of water vapor and sensible heat transfer as influenced by surface roughness and ambient air properties. Van Bavel considered his method an improvement over the original version of the combination equation (Penman, 1948), because it contains no empirical constants or functions.

Van Bavel (1966) conducted an extensive validation of his method at Phoenix, Arizona, concluding that the method provides an excellent estimation of potential evapotranspiration on an hourly and daily basis under a wide variety of test conditions. Further evaluation of the combination method of Van Bavel in Kansas (Skidmore et al., 1969) and Texas (Wendt, 1970) showed that it can provide reasonably good estimates of potential evapotranspiration, particularly in areas with large amounts of advection. Furthermore, Jensen (1974) evaluated 16 different methods to estimate potential evapotranspiration at 10 different locations throughout the world. The elevations of these sites ranged from 30 m below sea level to 2774 m above sea level, and the latitudes ranged from 38°S at Victoria, Australia to 56°N at Copenhagen, Denmark. He then ranked Van Bavel's method as one of the best methods to estimate potential evapotranspiration especially in the inland semi-arid to arid regions.

For use on a daily basis, the Van Bavel equation is expressed as:

$$ETP = \frac{(SVPG (H/VLH)) + ((TTC) (VPD))}{(SVPG + 1)} \quad (12)$$

where ETP is the potential evapotranspiration (mm/day), H is the sum of surface energy inputs (MJ/m²/day), and SVPG is the adjusted ratio of the slope of the saturation vapor pressure curve taken at mean air temperature to the psychrometric constant. The ratio is adjusted according to the ambient barometric pressure, TTC is the turbulent transfer coefficient for water vapor (kg/m²/kPa/day), and VPD is the saturation vapor pressure deficit of air (kPa).

Because the psychrometric constant is proportional to the ambient pressure, the adjusted ratio of the slope of the saturation vapor pressure curve to the psychrometric constant (SVPG) is estimated with the equation:

$$SVPG = SVPG0 (101.325/ BP) \quad (13)$$

where SVPG0 is the unadjusted ratio of the slope of the saturation vapor pressure curve taken at mean air temperature to the psychrometric constant, and BP is the ambient barometric pressure (kPa).

The (SVPG0) term in Eq. H13 is a dimensionless number dependent on air temperature. The tabulated values of the term are listed versus air temperature in Table 5 of Van Bavel's (1966) article. However, to simplify the computation of the term in our computer coding, the data of the table were regressed, and the following expression of (SVPG0) as a function of temperature was obtained:

$$SVPG0 = 67.5242 \exp\left(\frac{(TAIR - 149.531)^2}{-4859.0665}\right) \quad (14)$$

where TAIR is the mean daily air temperature (°C). The coefficient of determination (r²) for Eq. H14 is 1.00.

The U.S. Standard Atmosphere, 1976 (NOAA, NASA, and USAF, 1976), which is an idealized, steady-state representation of the earth's atmosphere, provides an approximation of atmospheric pressure that is sufficiently accurate for estimating potential evapotranspiration. The tabulated data of that report were regressed, and the following expression of atmospheric pressure as a function of elevation was obtained:

$$BP = 824.4996 \exp\left(\frac{(ELEV + 35702.8022)^2}{-607940000}\right) \quad (15)$$

where BP is the barometric pressure (kPa), and ELEV is the elevation of the site (m). The coefficient of determination (r^2) for Eq. H15 is 1.00. The range of elevations used in the regression analysis was between -500 m and 30,000 m.

The daily sum of surface energy inputs (H) can be computed using the equation

$$H = RN + G \quad (16)$$

where RN is the net radiation (MJ/m²/day), and G is the soil heat flux (MJ/m²/day).

However, soil heat flux data, are not always readily available, and the soil heat flux is often negligible on a daily basis. Therefore, the soil heat flux component of the daily surface energy balance is ignored, and the daily sum of surface energy inputs is assumed to equal the daily net radiation.

Whenever net radiation data are not available, the HYDROLOGY submodel of WEPS estimates daily net radiation from solar radiation, air temperature, and vapor pressure using Wright's modified version of Penman's general relationship outlined by Allen et al. (1989) as:

$$RN = [(1 - ALBEDO)RS - BC \frac{(T_{\max}^4 + T_{\min}^4)}{2}] \quad (17)$$

$$[A1 - 0.139\sqrt{E}](A \frac{RS}{RSO} + B)$$

where ALBEDO is the albedo (reflectance) of the surface; RS is the measured solar radiation (MJ/m²/day); BC is the Stephan-Boltzman constant (4.903×10^{-9} MJ/m²/day/K⁴); T_{\max} is the maximum daily air temperature (K); T_{\min} is the minimum daily air temperature (K); E is the saturation vapor pressure at the dew-point temperature (kPa); RSO is the clear sky short wave radiation (MJ/m²/day); and A1, A, B are empirical coefficients.

The empirical coefficients in Eq. H17 were estimated by Wright (1982) as:

$$A1 = 0.26 + 0.1 \exp[-0.0154(\text{IDOY} - 180)]^2 \quad (18)$$

where IDOY is the day of year (1 to 366). A and B are affected by the ratio RS/RSO, which indicates cloudiness. For RS/RSO > 0.7, which indicates few clouds, A = 1.126 and B = -0.07. For RS/RSO < 0.7, which indicates prevalent clouds, A = 1.017 and B = -0.06.

RSO, which is the clear sky radiation, was estimated as:

$$RSO = 0.75 RA \quad (19)$$

where RA is extraterrestrial radiation (MJ/m²/day). RA was estimated using the following equation by Duffie and Beckman (1980):

$$RA = (24(60)/\Pi)(GSC)(DR)[(WS)\text{SIN}(\text{RLAT})\text{SIN}(\text{SIGMA}) + \text{COS}(\text{RLAT})\text{COS}(\text{SIGMA})\text{SIN}(WS)] \quad (20)$$

where GSC is the solar constant (MJ/m²/min), DR is the relative distance of the earth from the sun, RLAT is the latitude of the station in radians, WS is the sunset hour angle (radians), and SIGMA is the declination of the sun. GSC was determined to be 0.08202 MJ/m²/min (London and Frohlich, 1982). DR, WS, and SIGMA in Eq. H20 were determined from the following equations:

$$DR = 1 + 0.033 \text{ COS}(2\Pi \text{ IDOY}/365) \quad (21)$$

$$WS = \text{ARCCOS}(-\text{TAN}(\text{RLAT})\text{TAN}(\text{SIGMA})) \quad (22)$$

$$\text{SIGMA} = 0.4093 \text{ SIN}(2\Pi(284 + \text{IDOY})/365) \quad (23)$$

The latent heat of vaporization (VLH) varies with temperature. A regression analysis was performed on the tabulated temperature-latent heat data in Table 2.1 of Hillel (1971), and the following expression of latent heat as a function of temperature was derived:

$$\text{VLH} = 2.500277 - 0.002364 \text{ TAIR} \quad (24)$$

where VLH is the latent heat of vaporization (MJ/kg), and TAIR is the mean daily air temperature (°C). The coefficient of determination (r²) for Eq. H24 is 1.00. The range of temperatures used in the regression analysis was between -10 °C and 50 °C.

The saturation vapor pressure deficit of air is estimated using the equation

$$\text{VPD} = \text{VPS} - \text{VPA} \quad (25)$$

where VPD is the saturation vapor pressure deficit (kPa), VPS is the saturation vapor pressure (kPa), and VPA is the actual vapor pressure (kPa).

The daily saturation vapor pressure is calculated as the average of the saturation vapor pressure at minimum and maximum daily air temperatures.

$$\text{VPS} = (\text{VPSMN} + \text{VPSMX}) / 2 \quad (26)$$

where VPSMN is the saturation vapor pressure at minimum air temperature (kPa), and VPSMX is the saturation vapor pressure at maximum air temperature (kPa).

The saturation vapor pressure at minimum and maximum air temperatures can be estimated using the equations

$$VPSMN = 129.07487 \exp\left(\frac{(TMIN - 149.195)^2}{-4160.7968}\right) \quad (27)$$

$$VPSMX = 129.07487 \exp\left(\frac{(TMAX - 149.195)^2}{-4160.7968}\right) \quad (28)$$

where TMIN is the daily minimum air temperature (°C), and TMAX is the daily maximum air temperature (°C).

The actual vapor pressure can be estimated as a function of dew-point temperature using the equation

$$VPA = 129.07487 \exp\left(\frac{(TDP - 149.195)^2}{-4160.7968}\right) \quad (29)$$

where TDP is the mean daily dew-point temperature (°C). Equations H27, H28, and H29 were obtained by regression analysis of the tabulated vapor pressure versus temperature data as listed in the Smithsonian meteorological tables (List, 1971). The coefficient of determination (r^2) for the equations is 1.00. The range of temperatures used in the regression analysis was between 0 °C and 40 °C.

The turbulent transfer coefficient for water vapor is estimated with the equation

$$TTC = \{(ARHO)(E)(VK)^2(U*86400)\} / \{(BP)[\text{LOG}(ZA/ZO)]^2\} \quad (30)$$

where TTC is the turbulent transfer coefficient (kg/m²/kPa/day), ARHO is the density of air (kg/m³), E is the water-air molecular weight ratio, VK is the Von Karman's constant, BP is the barometric pressure (kPa), U is the mean daily wind speed (m/s), ZA is the height of measurement of meteorological sensors (m), and ZO is the roughness parameter (m).

The Von Karman's constant (VK) is usually used as a universal, dimensionless constant in turbulent flow. Its value has been determined to be near 0.4, with a range of 0.36 to 0.43. However, for Eq. H30 calculations, the (VK) value is assumed to be equal to 0.41.

The (E) term in Eq. H30 is a dimensionless constant equal to 0.622, which represents the ratio of water-vapor/air molecular weights. The term (ZA) represents the height of temperature, humidity, radiation, and wind speed measurements.

The roughness parameter (Z_0), which is sometimes referred to as the roughness thickness or length, is defined as the actual height above the bare soil surface at which the wind velocity extrapolates to zero. It is related directly to the maximum height of surface protuberances. When the wind blows across a bare soil surface, it is usually slowed down by any surface protuberance (i.e., surface ripples, clods, or individual soil grains) that cause its velocity to decrease to zero. The zero plane elevation is slightly above the average height of the bare soil surface but below the top of soil surface irregularities. Jensen (1974) evaluated 16 different methods to calculate potential evapotranspiration, including the Van Bavel's combination method with various values for (Z_0) and found that the Van Bavel method with $Z_0 = 0.0025$ m gave the best estimates of potential evapotranspiration, particularly in the inland-semiarid to arid regions. Therefore, the (Z_0) term in Eq. H30 was assumed as a constant equal to 0.0025 m. In the future validation of the submodel, we will evaluate changing the roughness parameter of vegetated surfaces using the equation proposed by Jacobs and Von Boxel (1988).

$$Z_0 = 0.063 \text{ CH} \quad (31)$$

where CH is the crop height (m).

The air density (ARHO) is directly proportional to ambient pressure and inversely proportional to temperature. It is estimated by the equation:

$$\text{ARHO} = 1000 \{ [\text{BP}/101.325][0.001293/(1+0.00367(\text{TAIR}))] \} \quad (32)$$

where ARHO is the density of air (kg/m^3), BP is the ambient pressure (kPa), and TAIR is the mean daily air temperature ($^{\circ}\text{C}$). Eq. H32 is a revised version of the density of dry air equation listed in the CRC Handbook of Chemistry and Physics (Weast et al., 1983).

Furthermore, Skidmore et al. (1969) proposed that Van Bavel's (1966) combination equation can be separated into two terms to get estimates of the potential evapotranspiration by radiation and wind. Accordingly, Eq. H12 can be rewritten as follows:

$$\text{ETPR} = \frac{(\text{SVPG} (\text{H/VLH}))}{(\text{SVPG} + 1)} \quad (33)$$

$$\text{ETPW} = \frac{((\text{TTC}) (\text{VPD}))}{(\text{SVPG} + 1)} \quad (34)$$

where ETPR is the potential evapotranspiration by radiation (mm/day), and ETPW is the potential evapotranspiration by wind (mm/day).

Potential Soil Evaporation and Plant Transpiration

The total daily potential evapotranspiration (ETP) as computed with Eq. H12 is then partitioned on the basis of the plant leaf area index into potential soil evaporation (EP) and potential plant transpiration (TP). The plant leaf area index, which is defined as the area of plant leaves relative to the land area, is estimated on a daily basis by the CROP submodel of WEPS.

Firstly, the daily potential soil evaporation is estimated with an equation that was proposed originally by Richardson and Ritchie (1973).

$$EP = ETP \exp(-0.398 \text{ PLAI}) \quad (35)$$

where ETP is the potential evapotranspiration (mm/day), EP is the potential soil evaporation (mm/day), and PLAI is the plant leaf area index.

Secondly, the potential plant transpiration then is estimated by subtraction

$$TP = ETP - EP \quad (36)$$

where TP is the potential plant transpiration (mm/day).

As described earlier in the snow melt section, snow is melted during days when the maximum daily air temperature exceeds 0°C. However, if there is any remaining snow cover, soil evaporation is considered to come first from the snow and then from the soil. Furthermore, the potential soil evaporation is reduced with increased plant residues using an equation similar to that of the WEPP model (Savabi et al., 1989), which is based on the research conducted by Steiner (1989)

$$EP = EP \exp(-0.000064 \text{ PRES}) \quad (37)$$

where PRES is the amount of plant residues on the soil surface (kg/hectare). It is estimated on a daily basis by the DECOMPOSITION submodel of WEPS.

Furthermore, the daily potential rates of soil evaporation and plant transpiration are adjusted to actual rates on the basis of soil water availability.

Actual Plant Water Uptake and Water Stress Factor

The HYDROLOGY submodel estimates actual plant water uptake and plant growth water stress factor using an approach similar to that of the EPIC (Williams, 1989; Williams et al.,

1984; 1990) and WEPP (Savabi et al., 1989) models. Firstly, the potential plant transpiration is distributed in the root zone with the equation

$$WUP(i) = \frac{TP}{(1 - \exp(-WUD))} * (1 - \exp(-WUD * (\frac{DLAYR(i)}{PRTD}))) - TWU \quad (38)$$

where WUP(I) is the potential plant water-uptake from soil layer I (mm/day), TP is the potential plant transpiration (mm/day), WUD is the water use distribution parameter, DLAYR(I) is the depth to the bottom of soil layer I, from the soil surface (m), PRTD is the plant root zone depth (m), and TWU is the accumulated actual water use from the soil layers above layer I (mm).

The HYDROLOGY submodel of WEPS uses a depth parameter (WUD) of 3.065 based on the assumption that about 30% of the total water use comes from the top 10% of the soil root zone. Williams and Hann (1978) described in more detail how to evaluate the water use distribution parameter.

The potential water use in each soil layer is modified on the basis of soil water availability to obtain the actual water use.

$$\begin{aligned} WUA(i) &= WUP(i) & AWCR(i) &\geq 0.70 \\ WUA(i) &= WUP(i) * AWCR(i) & AWCR(i) &< 0.70 \end{aligned} \quad (39)$$

where WUA(I) is the actual plant water-uptake from soil layer I (mm/day), and AWCR(I) is the relative amount of available water content from soil layer I.

The relative amount of available water content (AWCR) for each simulation layer is a fraction (0-1.0), which can be computed using the equation

$$AWCR(i) = \frac{(THETA(i) - THETAW(i))}{AWCT(i)} \quad (40)$$

where AWCT(I) is the total amount of available water content (m^3/m^3), THETA(I) is the volumetric water content (m^3/m^3), and THETAW(I) is the soil water content at wilting point (m^3/m^3).

The total amount of available water content for each simulation layer is estimated using the equation

$$AWCT(i) = THETA F(i) - THETA W(i) \quad (41)$$

where THETA F(I) is the soil water content at field capacity (m^3/m^3).

The actual water use equation (Eq. H39) stipulates that the rate of water uptake by plants from a given soil layer will proceed at the potential rate as long as 30% or less of the total available water from that soil layer is depleted. However, a linear decline will occur in the actual transpiration relative to the potential transpiration with increasing depletion of available soil water beyond the initial 30%. This approach represents a compromise among the various models that have been proposed in the literature to describe the relationship between actual and potential transpiration as influenced by soil water availability (Denmead and Shaw, 1962; Holmes and Robertson, 1963).

Finally, the water stress factor is computed by considering the demand and supply of soil water in the root zone

$$\text{WSF} = \text{TA}/\text{TP} \quad (42)$$

where WSF is the water stress factor, TP is the potential plant transpiration (mm/day), and TA is the actual plant transpiration (mm/day).

The water stress factor (WSF) is a fraction (0-1) that is used by the CROP submodel to adjust daily plant growth by accounting for water stress if it exists. The actual plant transpiration is the sum of actual water use from all of the soil layers.

$$\text{TA} = \sum_{i=1}^{\text{LAYRSN}} \text{WUA}(i) \quad (43)$$

where LAYRSN is the number of soil layers used in the simulation.

Soil Water Redistribution

Soil water is continually moving, mainly in response to gradients of soil water potential. Soil conductive properties also control soil water flow between the different layers of the soil profile.

Redistribution of soil water plays a significant role in the various components of the soil water balance, particularly soil evaporation, deep percolation, and water uptake by plants. Therefore, an accurate evaluation of soil water redistribution is an essential prerequisite for any realistic simulation of soil-water dynamics.

The governing principles that describe water flow in soils are Darcy's law and the equation of continuity. Darcy's law states that the flow of water is proportional to the driving force of the soil hydraulic gradient. The continuity equation states that the time rate of change in water content is proportional to the divergence of water flux. Richards (1931) derived a

water flow equation by combining Darcy's law with the continuity equation. A water flow equation based on Darcy's law similar to the one used by Hillel (1977) and the SPAW model (Saxton et al., 1984) is used by the HYDROLOGY submodel of WEPS to estimate redistribution of soil water. The WEPS water flow equation in finite-difference form is

$$WFLUX(i) = (SWH(i-1) - SWH(i)) * CONDA(i) * DTIME / DIST(i) \quad (44)$$

where WFLUX is the amount of soil water flow (m), SWH is the soil water hydraulic head (m), CONDA is the average hydraulic conductivity for flow between adjoining soil layers (I) and (I-1) (m/s), DTIME is the time step (s), and DIST is the distance of flow between adjacent soil layers (I) and (I-1) (m).

The flow distance (DIST) can be calculated using the equation

$$DIST(i) = 0.5 * (TLAYR(i-1) - TLAYR(i)) \quad (45)$$

where TLAYR(I) is the thickness of soil layer I (m).

The soil water hydraulic head (SWH) is obtained by summing the soil water matric head and the gravitational head (- DMLAYR(I))

$$SWH(i) = SWM(i) - DMLAYR(i) \quad (46)$$

where SWM is the soil water matric head (m), and DMLAYR(I) is the depth to the midpoint of soil layer I from the soil's surface (m).

The soil water matric head (SWM) can be computed by converting the soil water matric potential with the equation

$$SWM(i) = POTM(i) / 10 \quad (47)$$

where POTM is the soil water matric potential (Joules/kg).

The average hydraulic conductivity for flow between adjoining soil layers (I) and (I-1) is weighted according to the thicknesses of the two layers

$$CONDA(i) = (COND(i-1) * TLAYR(i-1) + COND(i) * TLAYR(i)) / (2 * DIST(i)) \quad (48)$$

where COND(I) is the unsaturated soil hydraulic conductivity (m/s).

The daily potential soil evaporation computed with Eq. H35 is partitioned to obtain hourly estimates of potential soil evaporation using a sine function of daytime

$$EPH = \text{AMAX1}(0, \text{AMEP} * \text{SIN}(2 * \pi * \text{TIME}/24)) \quad (49)$$

where EPH is the hourly potential soil evaporation (mm/hr), AMEP is the amplitude of the daily wave of potential soil evaporation (mm/hr), and TIME is the time from sunrise. The use of the specification (AMAX1) in Eq. H49 prevents the simulated hourly potential evaporation from becoming negative. Accordingly, the simulated hourly potential evaporation during nighttime is set at zero.

The (AMEP) term is computed using the equation

$$\text{AMEP} = \pi * \text{AVEP} \quad (50)$$

where AVEP is the time-average value of the daily potential soil evaporation (mm/hr).

The term (AVEP) is derived from the daily potential soil evaporation (EP)

$$\text{AVEP} = \text{EP}/24 \quad (51)$$

where EP is the daily potential bare soil evaporation (mm/day).

The time term (TIME) is computed by subtracting (IRISE + 1) from the hour of the day, where (IRISE) represents the hour of sunrise as an integer.

The time of sunrise for any simulation site is calculated based on the global position of the site and the day of the year as follows:

$$\text{RISE} = \text{HANGL}/15 + \text{SN} \quad (52)$$

where RISE is the time of sunrise, HANGL is the hour angle, and SN is the solar noon.

SN is determined by the following equation:

$$\text{SN} = 12 - \text{E}/60 - 4 * (\text{DMER} - \text{DLONG})/60 \quad (53)$$

where E is the equation of time, DMER is the standard meridian of the site (degrees) and DLONG is the longitude of the site (degrees). The standard meridian for the site is calculated based on the fact that the earth rotates 15° per hour; therefore, the earth is divided into time zones that occupy 15° of longitude. Each time zone has a standard meridian which, is its eastern boundary. For the central zone, the standard meridian is 90°. The central time zone extends from 90° to 105° west longitude. The prime meridian (0°) is at Greenwich, England.

E is defined by the following equation:

$$E = 9.87 * \sin(2 * \pi / 180) - 7.53 * \cos(B * \pi / 180) - 1.5 * \sin(B * \pi / 180) \quad (54)$$

where B is defined as:

$$B = (360/365) * (\text{IDOY} - 81.25) \quad (55)$$

and IDOY is the day of the year.

HANGL is defined by the following equation:

$$\text{HANGL} = - \frac{[\pi/2 - \text{ATAN}(\text{COSHR} / \sqrt{1 - \text{COSHR}^2})] * 180}{\pi} \quad (56)$$

where COSHR is the cosine of the hour angle at sunrise and is defined as:

$$\text{COSHR} = -\frac{\sin(\text{DLAT} * \pi / 180)}{\cos(\text{DLAT} * \pi / 180)} * \frac{\sin(\text{DEC} * \pi / 180)}{\cos(\text{DEC} * \pi / 180)} \quad (57)$$

where DLAT is the latitude of the site and DEC is the angle of declination (RAD).

The angle of declination (DEC) is calculated as follows:

$$\text{DEC} = 23.5 * \sin(B * \pi / 180) \quad (58)$$

Soil water evaporation from the soil surface usually proceeds at a potential rate as long as there is an adequate supply of water from the interior of the soil profile. Accordingly, the water redistribution section of the HYDROLOGY submodel of WEPS assumes that the actual rate of soil evaporation is equal to the potential rate, if the water flux from the underlying layer exceeds the potential evaporation flux. However, if the incoming water flux to the uppermost soil layer is less than the potential evaporation, the actual evaporation rate is obtained by adjusting the potential rate of soil evaporation in accordance with soil water availability in the uppermost simulation layer. The approach is similar to the one used in the plant water-uptake segment of the submodel

$$\begin{aligned} \text{EAH} &= \text{EPH} & \text{ASWCR} &\geq 0.70 \\ \text{EAH} &= \text{EPH} * (\text{ASWCR}/0.7) & \text{ASWCR} &< 0.70 \end{aligned} \quad (59)$$

where EAH is the hourly rate of actual soil evaporation (mm/hr), and ASWCR is the relative amount of available water content in the surface layer.

The relative amount of available water in the surface layer (ASWCR) is a fraction (0-1.0), which is computed using the equation

$$ASWCR = \frac{(THETEV - THETA(1))}{AWCT(1)} \quad (60)$$

where AWCT(1) is the total amount of available water in the uppermost simulation layer (m^3/m^3), THETEV is soil wetness of the evaporation zone of the surface layer (m^3/m^3), and THETA(1) is soil water content at wilting point for the uppermost simulation layer (m^3/m^3).

The total amount of available water in the uppermost simulation layer is estimated using the equation

$$AWCT(1) = THETA(1) - THETA(1) \quad (61)$$

where THETA(1) is soil water content at field capacity for the uppermost simulation layer (m^3/m^3).

The soil water content of the evaporation zone (THETEV) is dependent on the thickness of the first simulation layer. If the thickness of the first simulation layer is less than or equal to 10 mm, then THETEV is calculated as follows:

$$THETEV = (THETA(1) + THETA(1))/2 \quad (62)$$

where THETA(1) is the volumetric water content of the first simulation layer (m^3/m^3) and THETA(1) is the extrapolated water content at the soil surface (m^3/m^3). On the other hand, if the thickness of the first simulation layer is greater than 10 mm, then the soil water content of the evaporation zone (THETEV) is calculated as the weighted average water content based on the water contents of the first simulation layer and the extrapolated surface water content. This assumes that the extrapolated water content represents only the uppermost 5 mm of the soil. Accordingly, THETEV is calculated as follows:

$$THETEV = \frac{THETA(1) + 0.005 + [THETA(1)*(TLAYR(1)-0.005]}{TLAYR(1)} \quad (63)$$

where TLAYR(1) is the thickness of the first layer (mm). The extrapolated water content at the soil surface (THETA(1)) is obtained by extrapolating water content to the soil surface from the three uppermost simulation layers. A numerical solution known as Cramer's rule (Miller, 1982) is used to obtain an estimate of the extrapolated water content at the soil surface (THETA(1)) by solving the three simultaneous equations:

$$THETA(1) = THETA(1) + b * DLAYR(1) + c * (DLAYR(1))^2 \quad (64)$$

$$THETA(2) = THETA(1) + b * DLAYR(2) + c * (DLAYR(2))^2 \quad (65)$$

$$\text{THETA}(3) = \text{THETA}X + b * \text{DLAYR}(3) + c * (\text{DLAYR}(3))^2 \quad (66)$$

where THETA(1), THETA(2), and THETA(3) are the volumetric soil water contents for simulation layers 1, 2, and 3, respectively (m^3/m^3), and DLAYR(1), DLAYR(2), and DLAYR(3) are the depths to the bottom of simulation layers 1, 2, and 3, respectively (m).

The equation that calculates soil evaporation (Eq. H59) stipulates that the actual rate of evaporations from a given soil will proceed at the potential rate as long as 30% or less of the total amount of available water content in the surface layer is depleted. However, the soil evaporation rate will decline linearly relative to the potential rate with increasing depletion of available soil water beyond the initial 30%.

The water flux from the uppermost simulation layer is computed by converting the actual evaporation rate with the equation

$$\text{WFLUX}(1) = - \text{EAH}/\text{CMTOMM} \quad (67)$$

where WFLUX(1) is the flux of water through the soil surface (m), and CMTOMM is a conversion factor from meters to millimeters ($\text{CMTOMM} = 1000.0$). The minus sign in Eq. H67 is used to indicate that latent heat flux in the upward direction from the soil surface represents an energy loss in accordance with the principles of the energy balance equation.

A unit hydraulic gradient approach is applied to the lower boundary condition for the one-dimensional water flow in the soil profile. The flux from the lowermost soil layer is set to equal the hydraulic conductivity

$$\text{WFLUX}(\text{LAYRSN}+1) = \text{COND}(\text{LAYRSN}) * \text{DTIME} \quad (68)$$

where LAYRSN is the number of soil layers used in the simulation, and WFLUX(LAYRSN+1) is the amount of soil water flow from the lowermost simulation layer (m).

Hourly estimates of deep percolation are obtained by converting the flux from the lowermost simulation layer

$$\text{DPH} = \text{WFLUX}(\text{LAYRSN}+1) * \text{CMTOMM} \quad (69)$$

where DPH is the hourly deep percolation (mm).

According to the continuity equation, the change in water content of each simulation layer is related to the net flux of water into the layer. The net water flux for each layer is computed using the equation

$$\text{WFLUXN}(i) = \text{WFLUX}(i) - \text{WFLUX}(i-1) \quad (70)$$

where $\text{WFLUXN}(I)$ is the net amount of soil water flow into layer I (m).

The net amount of water flux (WFLUXN) enters into the determination soil wetness using the equations

$$\text{WC}(i) = \text{WCI}(i) + (\text{WFLUXN}(i) * \text{CMTOMM}) \quad (71)$$

$$\text{THETA}(i) = \text{WC}(i) / (\text{TLAYR}(i) * \text{CMTOMM}) \quad (72)$$

where WC is the amount of soil layer wetness (mm), WCI is the initial amount of soil layer wetness (mm), and THETA is the volumetric soil water content (m^3/m^3).

The HYDROLOGY submodel of WEPS, thus, uses a simplified forward finite-difference technique to redistribute soil water with the one-dimensional Darcy equation for unsaturated water flow. Accordingly, the wetness of a soil layer at a future time increment is expressed in terms of the water contents of the same layer and the adjacent layers at the beginning of the time increment. The technique allows for an explicit expression of soil wetness in terms of the water contents at the previous time step. The main advantage of the explicit forward finite-difference procedure is the direct calculation of future soil water contents of the simulation layers.

The default time step (DTIME) of the soil water redistribution section is 1 hour, which allows for an hourly estimation of soil wetness as needed by the Wind Erosion Research Model. However, under certain situations, such as strong hydraulic gradients and/or high soil hydraulic conductivity, the default time step can result in significant changes in the simulated soil wetness, adversely affecting the stability and, consequently, the quality of the computation. To overcome this problem, a tolerance level is established as the maximum allowable change in soil water matric potential in each time step. The tolerance level is -20 Joules/kg soil matric potential (200 mb soil water tension). If the tolerance level is exceeded, the initial time step is halved, and all calculations are repeated until the tolerance level is not exceeded in that time step.

Estimating Soil Hydraulic Properties

Knowledge of the relationship between unsaturated hydraulic conductivity and soil water content is required for solving the governing transport equations of water movement through the soil. However, reliable estimates of unsaturated hydraulic conductivity (COND) as a function of soil water content are extremely difficult to obtain not only because of the extensive spatial variability of the parameter in the field but also because its determination in

the field and/or laboratory is very difficult, laborious, and expensive. To overcome this problem, many methods have been proposed to predict the unsaturated hydraulic conductivity from more easily determined soil parameters. Most of these methods calculate the unsaturated hydraulic conductivity of the soil from the relatively more easily and routinely obtainable soil water characteristic curve and saturated hydraulic conductivity (Millington and Quirk, 1959; Brooks and Corey, 1964; 1966; Campbell, 1974; Mualem, 1976; and Van Genuchten, 1978; 1980).

The HYDROLOGY submodel of WEPS uses Campbell's (1974) relatively simple method to calculate the unsaturated hydraulic conductivity as a function of soil water content. This method assumes that the soil water characteristic curve can be represented by the equation

$$\text{POTM} = \text{POTE} * \text{ESAT}^{-\text{CB}} \quad (73)$$

where CB is the power of Campbell's model of the soil water characteristic curve, POTE is the air-entry potential of soil water (Joules/kg), POTM is the matric potential of soil water (Joules/kg), and ESAT is the effective saturation.

The effective saturation (ESAT) in Eq. H73 is a dimensionless term, which is referred to sometimes as the reduced water content. It is calculated using the equation:

$$\text{ESAT} = \text{THETA} / \text{THETAS} \quad (74)$$

where THETA is the volumetric soil water content (m^3/m^3), and THETAS is the soil water content at saturation (m^3/m^3).

Campbell's function of the soil unsaturated hydraulic conductivity is represented by the equation:

$$\text{COND} = \text{SATK} * \text{ESAT}^{\text{CM}} \quad (75)$$

where SATK is the saturated soil hydraulic conductivity (m/s), and CM is the exponent of Campbell's function of unsaturated hydraulic conductivity.

The exponent parameter (CM) in Eq. H75 is calculated using the equation:

$$\text{CM} = (2 * \text{CB}) + 3. \quad (76)$$

Both (POTE) and (CB) are considered as characteristic hydraulic parameters of the soil. The air-entry potential, which usually is referred to as the bubbling pressure, is related to the maximum pore size forming a continuous network of flow channels within the soil. The air entry potential is defined as the minimum capillary pressure on the drainage cycle at which a

continuous nonwetting condition exists in the soil, i.e., the potential at which the largest water-filled pores start to drain and, hence, gas flow can be observed. The (CB) parameter is a function not only of the size of soil pores but also of the interfacial forces, contact angles, shape of soil pores, etc.

The (CB) parameter is the inverse of the pore size distribution (λ) term of the model developed by Brooks and Corey (1964) for the soil water characteristic curve. The parameter evaluates the distribution of sizes of the flow channels within the soil medium, which is a function of the microscopic geometry of the soil. Theoretically, the (CB) parameter can have any positive value greater than zero. However, the parameter is usually larger for soils with a wide range of pore sizes than for soils with a relatively uniform distribution of pore sizes.

Brooks and Corey (1964) proposed a graphical procedure for determining the air-entry potential and the pore size distribution index of the soil by plotting the water release data on a log-log graph paper and fitting a straight line to the data. The negative slope of the best-fit line is designated as the pore size distribution index of the soil and, hence, its inverse is the (CB) parameter of the soil. Furthermore, the extrapolation of the best-fit line to the ordinate representing the effective saturation value of 1.0 gives the air-entry potential of the soil.

Soil hydraulic parameters, including the air-entry potential (POTE) and the power of Campbell's model of the soil water characteristic curve (CB), are required as inputs to run the HYDROLOGY submodel of WEPS. However, these parameters are not always readily available. To circumvent the problem, the HYDROLOGY submodel provides an approximation of these properties from easily and routinely obtainable soil texture and bulk density data based on a set of equations proposed by Campbell (1985).

The air-entry potential at a standard bulk density of 1.3 Mg/m³ is calculated using the equation

$$\text{POTES} = -0.2 * \text{GMD}^{-0.5} \quad (77)$$

where POTES is the air-entry potential at a standard bulk density of 1.3 Mg/m³ (Joules/kg), and GMD is the geometric mean particle diameter (mm).

Originally, Campbell (1985) proposed a coefficient of -0.5 for use in Eq. H77, but more recently, Flerchinger (1987) reported that a better fit between predicted and measured soil hydraulic parameters can be obtained by using a coefficient of -0.2.

The (CB) term is calculated with the equation

$$\text{CB} = -2 * \text{POTES} + 0.2 * \text{GSD} \quad (78)$$

where GSD is the geometric standard deviation (mm).

The air-entry potential (POTE) adjusted to the soil bulk density can be computed using the equation

$$\text{POTE} = \text{POTES} * (\text{BD}/1.3)^{(0.67 * \text{CB})} \quad (79)$$

where BD is the soil bulk density (Mg/m^3).

The saturated hydraulic conductivity (SATK) is established by the following equation

$$\text{SATK} = 3.9167\text{E}-05 \left(\frac{\text{BD}}{1.3} \right)^{1.3b} \exp(-9.6\text{CLAYM} - 3.7\text{SILTM}) \quad (80)$$

The geometric mean particle diameter (GMD) and geometric standard deviation (GSD) are calculated from the particle size distribution using the following equations

$$\text{GMD} = \exp X \quad (81)$$

$$\text{GSD} = \exp((Y - X^2)^{0.5}) \quad (82)$$

where

$$X = \text{SANDM} * \text{LOG}(0.316) + \text{SILTM} * \text{LOG}(0.01) + \text{CLAYM} * \text{LOG}(0.0002) \quad (83)$$

$$Y = \text{SANDM} * (\text{LOG}(0.316))^2 + \text{SILTM} * (\text{LOG}(0.01))^2 + \text{CLAYM} * (\text{LOG}(0.0002))^2 \quad (84)$$

where SANDM is the mass fraction of sand, SILTM is the mass fraction of silt, and CLAYM is the mass fraction of clay.

The coefficients 0.316, 0.01, and 0.0002 listed in Eqs. H83 and H84 represent the geometric mean diameters of the sand, silt, and clay soil particle-size fractions, respectively.

The expected range for the geometric mean particle diameter (GMD) is 0.003 to 0.7 mm, whereas the expected range for the geometric standard deviation (GSD) is 1 to 30 (Campbell, 1985).

The detailed soil texture and bulk density data that are required to estimate soil hydraulic parameters are not always available. Therefore, the HYDROLOGY submodel of WEPS provides an additional approximation of the hydraulic parameters based exclusively on the

textural class of the soil. McCuen et al. (1981) determined that soil hydraulic parameters, such as the pore size distribution index and the air entry potential, are unique for each soil texture class, i.e., these parameters differ collectively and not singularly across soil texture classes. Furthermore, Rawls et al. (1982) collected soil hydraulic properties from 1,323 soils with about 5,320 horizons from 32 states in an extensive search of literature and data sources. Table H3 is a revised summary of the means of soil hydraulic parameters for the 11 USDA soil texture classes as reported by Rawls et al. (1982). The silt textural class is missing; however, it is rare to find a soil sample having that textural class.

In summary, soil hydraulic parameters that are required to run the HYDROLOGY submodel of WEPS are relatively simple. The first and most desired option is to use measured values. However, the HYDROLOGY submodel provides other options to estimate soil hydraulic parameters in order to accommodate the varying degrees of data availability.

Table H-3. Soil hydraulic parameters classified by soil textural class (water contents on volumetric basis).

	(POTE)	(CB)	(THETAS)	(THETAF)	(THETAW)	(SATK)
USDA Textural Class	Air-entry potential (Joules/kg)	Campbell's b parameter	Saturation (m ³ /m ³)	Field capacity (m ³ /m ³)	Wilting point (m ³ /m ³)	Saturated K (m/s)
Sand	-1.598	1.441	0.437	0.091	0.033	5.833E-05
Loamy sand	-2.058	1.808	0.437	0.125	0.055	1.697E-05
Sandy loam	-3.020	2.646	0.453	0.207	0.095	7.194E-06
Loam	-4.012	3.968	0.463	0.270	0.117	3.667E-06
Silt loam	-5.087	4.274	0.501	0.330	0.133	1.889E-06
Sandy clay loam	-5.941	3.135	0.398	0.255	0.148	1.194E-06
Clay loam	-5.643	4.132	0.464	0.318	0.197	6.389E-07
Silty clay loam	-7.033	5.650	0.471	0.366	0.208	4.167E-07
Sandy clay	-7.948	4.484	0.430	0.339	0.239	3.333E-07
Silty clay	-7.654	6.667	0.479	0.387	0.250	2.500E-07
Clay	-8.560	6.061	0.475	0.396	0.272	1.667E-07

Source: Rawls, et al. (1982).

Table H-4. Soil hydraulic parameters classified by soil textural class (water contents on gravimetric basis).

	(aheaep)	(ah0cb)	(ahrwcs)	(ahrwcf)	(ahrwcw)	(ahrsk)
USDA Textural Class	Air-entry potential (Joules/kg)	Campbell's b Parameter	Saturation (kg/kg)	Field capacity (kg/kg)	Wilting point (kg/kg)	Saturated K (m/s)
Sand	-1.598	1.441	0.293	0.061	0.022	5.833E-05
Loamy sand	-2.058	1.808	0.293	0.084	0.037	1.697E-05
Sandy loam	-3.020	2.646	0.312	0.143	0.066	7.194E-06
Loam	-4.012	3.968	0.325	0.190	0.082	3.667E-06
Silt loam	-5.087	4.274	0.379	0.250	0.101	1.889E-06
Sandy clay loam	-5.941	3.135	0.250	0.160	0.093	1.194E-06
Clay loam	-5.643	4.132	0.327	0.224	0.139	6.389E-07
Silty clay loam	-7.033	5.650	0.336	0.261	0.148	4.167E-07
Sandy clay	-7.948	4.484	0.285	0.224	0.158	3.333E-07
Silty clay	-7.654	6.667	0.347	0.280	0.181	2.500E-07
Clay	-8.560	6.061	0.341	0.285	0.196	1.667E-07

Source: Rawls et al., (1982).

Soil Wetness at the Soil-Atmosphere Interface

The water redistribution section of the HYDROLOGY submodel of WEPS accounts for water flux only in the liquid phase. However, when the soil is relatively dry, significant water flux can occur in the vapor phase. Campbell (1985) compared simulated water content profiles with and without vapor flux. He showed that the profile with the vapor flux was significantly drier particularly at the surface and, therefore, resulted in a better fit with the observed water content profile of the drying soil. Therefore, it is essential to account somehow for vapor flux in any attempt to correctly predict surface-soil wetness, particularly at or below the critical level of threshold of erodibility. This is not a simple task, because many factors have to be considered. For example, heat flux, because thermally induced vapor flow can be an important factor in soil drying. However, a complete simulation that accounts for linked fluxes of liquid, vapor, and heat is probably too complex, long, and slow to meet the unique requirements of WEPS for fast simulation of the diurnal changes in soil water content, particularly at the soil-atmosphere interface. Therefore, the HYDROLOGY submodel of WEPS neglects vapor flux except at the soil surface, where the relationship

between actual and potential evaporation is used as an estimator of surface soil wetness. Water usually evaporates from the soil surface at the potential rate only when the soil is adequately wet. However, when the soil begins to dry and water is not conducted to the soil-atmosphere interface fast enough to meet the atmospheric evaporation demand, actual evaporation falls behind the potential rate. Holmes and Robertson (1963) verified the unique relationship between soil wetness and the ratio of actual to potential evaporation in a growth chamber experiment conducted with samples from three soil materials (North Gower clay, Matilda silt loam, and 26-mesh quartz sand). In order to make the relationship between evaporation ratio and soil wetness useful in predicting surface soil wetness as needed by WEPS, the functional relationship between equivalent water content and the ratio of actual to potential evaporation has to be determined first. We used Jackson's (1973) original soil water and meteorological data from a 1971 bare soil evaporation experiment conducted on an Avondale loam (fine-loamy, mixed (calcareous), hyperthermic Typic Torrifuvent) at the U.S. Water Conservation Laboratory, Phoenix, Arizona to derive the relationship between equivalent water content and the evaporation ratio. On the afternoon of March 2, 1971, the bare field was irrigated thoroughly with about 10 cm of water. After irrigation, actual soil evaporation was monitored at 0.5-hour intervals by measuring weight loss from two lysimeters located within the experimental field. Intensive soil sampling at 0.5-hour intervals was carried out from 2300 on March 4, 1971 to 0130 on March 19, 1971. Six sites were sampled each time and composited for the surface soil layer of 0-5 mm. Soil water content was measured gravimetrically. Water contents were converted to the volumetric basis by multiplying the gravimetric data by the soil bulk density. Net radiation, wind speed, vapor pressure, and air temperature were recorded at 0.5-hour intervals by a data acquisition system. We converted the raw data from Jackson's experiment to obtain hourly estimates of lysimeter evaporation and meteorological variables from 0000 on March 5 to 2400 on March 18. Furthermore, we smoothed the raw hourly water-content data for the surface soil using a 1-2-3-2-1 weighted running average procedure similar to the one described by Jackson et al. (1973). We also used the hourly meteorological data to calculate the hourly potential evaporation using Van Bavel's (1966) combination equation.

Figure H-1 depicts the relationship between the hourly evaporation ratios of actual lysimeter evaporation to potential evaporation and surface soil wetness expressed as equivalent water content. The hourly values of equivalent water content were obtained by dividing the smoothed water content data by $0.146 \text{ m}^3/\text{m}^3$, which represents the amount of water retained by the Avondale loam at -1500 J/kg soil water potential. Figure H-1 shows two clusters of data points on the graph; the first at an evaporation ratio of 0.2, and the second at an evaporation ratio of 0.7. The relationship between measured hourly soil water contents at the soil-atmosphere interface and measured evaporation ratios can be well-represented with a sigmoid function. We would have preferred more data points to confirm the sigmoidal functional relationship; however, because of equipment malfunctions, no hourly lysimeter data were available during March 6 and 7, 1971. However, for the available data, agreement was good between hourly measured lysimeter evaporation rates and the simulated hourly

evaporation rates by the HYDROLOGY submodel of WEPS (Figure H-2). Therefore, to overcome the problem of the missing data, simulated evaporation data for the 2 days were substituted. Figure H3 depicts the functional relationship between the hourly measured surface soil-water contents at the soil-atmosphere interface and the simulated evaporation ratios for March 6 and 7 and the measured evaporation ratios for the remainder of the experiment.

The functional relationship between equivalent water content of the soil surface and hourly evaporation ratios is described with the equation.

$$\text{THETA E} = 0.24308 + \frac{1.37918}{1 + \exp\left[-\left(\frac{\text{ERATIO} - 0.44882}{0.08100}\right)\right]} \quad (85)$$

where THETA E is the equivalent water content defined as the ratio of volumetric soil-water content (m^3/m^3) to volumetric soil-water content for the same soil at -1.5 kJ/kg soil matric potential, and ERATIO is the ratio of hourly actual evaporation (E_{ah}) to hourly potential evaporation (E_{ph}).

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Figure H-1. Measured hourly soil water contents at the soil-atmosphere interface versus measured evaporation ratios from the 1971 Arizona experiment (data for March 6 & 7 were missing).

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Figure H-2. Regression analysis between measured and simulated hourly evaporation ratios from the 1971 Arizona experiment excluding March 6 & 7.

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Figure H-3. Measured hourly soil water contents at the soil-atmosphere interface versus measured and simulated evaporation ratios from the 1971 Arizona experiment (March 6 & 7 evaporation ratios were simulated).

The surface soil water content (THETER) as interpolated from the relationship between evaporation ratio and equivalent surface soil water content is calculated with the equation

$$\text{THETER} = \text{THETA E} * \text{THETA W}(1) \quad (86)$$

where THETER is the surface soil water content based on the relationship between evaporation ratio and equivalent surface water content (m^3/m^3).

At the start of simulation, the initial soil wetness at the soil-atmosphere interface (THETOI) is estimated using the equations

$$\text{THETOI} = \text{AMAX1}(\text{THETA X}, \text{THETI3}) \quad \text{THETI3} \geq \text{THETF3} \quad (87)$$

$$\text{THETOI} = \text{THETA X} \quad \text{THETI3} < \text{THETF3} \quad (88)$$

where THETI3 is the weighted average of the initial soil water contents from the three uppermost simulation layers (m^3/m^3), and THETF3 is the weighted average of soil water contents at field capacity of the three uppermost simulation layers (m^3/m^3).

Furthermore, soil wetness at the soil-atmosphere interface (THETA0) is estimated throughout the rest of the simulation period by using the equations

$$\text{THETA0} = \text{AMIN1}(\text{THETER}, \text{THETA X}, \text{THETOI}) \quad \text{EPH} > 0.0 \quad (89)$$

$$\text{THETA0} = \text{AMAX1}(\text{THETA X}/2, \text{THETOI}) \quad \text{EPH} = 0.0 \quad (90)$$

where THETA0 is the soil water content at the soil-atmosphere interface (m^3/m^3), THETOI is the soil water content at the soil-atmosphere interface from the previous time increment (m^3/m^3), THETA X is the extrapolated water content at the soil surface (m^3/m^3), and EPH is the hourly potential of soil evaporation (mm/hr).

If an irrigation, precipitation, and/or snow melt event occurs on a given simulation day, the amount of water available for infiltration is distributed in the soil profile as described in the soil water storage section of the submodel. Furthermore, the extrapolated soil wetness (THETA X) is used exclusively to represent soil wetness at the soil-atmosphere interface at the first hour of the day.

The extrapolated soil wetness (THETA X) also is used as the sole indicator of soil wetness at the soil-atmosphere interface, when an abundance of water is present in the surface soil, i.e., only 30% or less of the surface available water is depleted.

Simulation of Soil Temperature

Subroutine HEAT simulates soil temperature based on the algorithm described by Campbell (1985). The subroutine estimates daily minimum, maximum, and average soil temperatures at the center of each simulation layer. The inputs needed to run the program are maximum and minimum daily air temperatures. In addition, soil bulk density, volumetric water content, and clay fraction are used to calculate soil thermal properties.

The basic assumption is that the hourly soil temperature is estimated about an average soil temperature distributed over a sine function. The following equation gives the estimated hourly soil temperature:

$$\begin{aligned} \text{TSOIL}(K,J) = & \text{TSAVG}(K) + \text{TAMP} * \text{EXP}(-\text{DMLAYR}(K)/\text{ZDAMP}) \\ & * \text{SIN}((\text{FREQ} + \text{TIME}(J)) - (\text{DMLAYR}(K)/\text{ZDAMP}) + \text{PHI}) \end{aligned} \quad (91)$$

where TSOIL is the hourly soil temperature ($^{\circ}\text{C}$), TSAVG is the average soil temperature ($^{\circ}\text{C}$), TAMP is amplitude of the temperature wave at the soil surface ($^{\circ}\text{C}$), DMLAYR is the depth from the soil surface to the center of the simulation layer (m), ZDAMP is the diurnal damping depth, FREQ is the angular frequency of the temperature oscillation, TIME is the time of simulation (s), PHI is the phase constant, J is the simulation hour (h), and K is the simulation layer.

TAMP and PHI are determined by the following as:

$$\text{TAMP} = \text{TMAX} - \text{TAIR} \quad (92)$$

$$\text{PHI} = -(7.0 * \pi) / 12 \quad (93)$$

where TMAX is the daily maximum air temperature ($^{\circ}\text{C}$), and TAIR is the mean air temperature ($^{\circ}\text{C}$).

The basic assumption in simulating soil temperature is that the temperature at the upper boundary condition, i.e., the soil-atmosphere interface over a 24-hour period is equal to the average air temperature for the same period. Furthermore, the temperature at the lower boundary condition is equal to the average annual air temperature at the site. The average soil temperature for each simulation layer is interpolated between the temperatures at the upper and lower boundary conditions and is given as:

$$\text{TSAVG}(K) = \text{TUBC} + (\text{TDIF} * (\text{DMLAYR}(K)/\text{DLBC})) \quad (94)$$

where TUBC is the temperature at the upper boundary condition ($^{\circ}\text{C}$), TDIF is the temperature difference between the upper and lower boundary conditions ($^{\circ}\text{C}$), and DLBC is the depth of the lower boundary condition (m).

The depth of the lower boundary condition (DBLC) is determined by taking the larger of either the annual damping depth or the depth of the lowermost simulation layer. The annual damping depth is defined as:

$$\text{ZDAMPY} = \text{ZDAMP} * \sqrt{365} \quad (95)$$

where ZDAMPY is the annual damping depth (m).

The diurnal damping depth, ZDAMP, is calculated using the following equation:

$$\text{ZDAMP} = \sqrt{(2 * (\text{THERMK} / \text{VSHEAT})) / \text{FREQ}} \quad (96)$$

where THERMK is the soil thermal conductivity ($\text{W}/\text{m}\cdot\text{C}$), and VSHEAT is the volumetric specific heat ($\text{J}/\text{m}^3\cdot^{\circ}\text{C}$).

The angular frequency of the temperature oscillation, FREQ, is calculated as:

$$\text{FREQ} = (2 * \pi) / (86400 * \text{PERIOD}) \quad (97)$$

where PERIOD is the length of the simulation in days.

The volumetric specific heat is determined by the following equation:

$$\text{VSHEAT} = \text{CMJTOJ} * (((\text{CM} * \text{PBD}) / 2.65) + (\text{CW} * \text{PTHETA})) \quad (98)$$

where CMJTOJ is the conversion factor to convert from MJ to J (1×10^6), CM is the volumetric specific heat for the soil mineral fraction ($\text{MJ}/\text{m}^3\cdot\text{C}$, $\text{CM} = 2.26$), CW is the volumetric specific heat for the soil water fraction ($\text{MJ}/\text{m}^3\cdot\text{C}$, $\text{CW} = 4.18$), PBD is the weighted average bulk density of the soil profile (Mg/m^3), and PTHETA is the weighted average water content of the soil profile (m^3/m^3).

The soil thermal conductivity, THERMK, is defined as:

$$\text{THERMK} = \text{A} + (\text{B} * \text{PTHETA}) - (\text{A} - \text{D}) * \text{EXP}(-(\text{C} * \text{PTHETA})^4) \quad (99)$$

where,

$$A = 0.65 - 0.78 * PBD + 0.6 * PBD^2 \quad (100)$$

$$B = 1.06 * PBD \quad (101)$$

$$C = 1.0 + (2.6 / \sqrt{PCLAYM}) \quad (102)$$

$$D = 0.03 + (0.1 * PBD^2) \quad (103)$$

Subroutine STAT is called to calculate the maximum and minimum temperatures at the center of each simulation layer.

The Structure and Procedures of the HYDROLOGY Submodel

The processes that were described in the previous sections of this chapter play a significant role in the water balance of the soil. The physical basis of these processes were defined, and a set of algorithms were developed to complete the simulation of each process. These algorithms were coded using FORTRAN 77 programming language and then arranged in an orderly computational sequence to form the HYDROLOGY submodel of WEPS.

The structure of the submodel is modular; therefore, the submodel can be updated easily by substituting alternative algorithms for specific processes when needed. The HYDROLOGY submodel of WEPS contains 10 subroutines and 3 function calls.

Subroutine HYDRO is the main (supervisory) program for the HYDROLOGY submodel. The subroutine controls the calling of the major subprograms of the HYDROLOGY submodel and also initializes the depth variables of the simulation layers and converts the water content variables from mass basis to volume basis.

Subroutine HINIT controls the initialization of the HYDROLOGY submodel of WEPS.

Subroutine EXTRA extrapolates soil water content to the surface from the three upper simulation layers. A numerical solution known as Cramer's rule is used to obtain an estimate of the extrapolated water content at the soil surface by solving the three simultaneous equations that describe the relationship between soil water content and soil depth for the three uppermost simulation layers.

Subroutine SNOMLT predicts daily snow melt when the maximum daily air temperature exceeds 0°C. The melted snow is added to the daily precipitation.

Function SCSQ estimates daily surface runoff using a modification of the Soil Conservation Service soil-cover complex method, which is known commonly as the curve number method (Soil Conservation Service, 1972).

Subroutine STORE stores the daily amount of water available for infiltration into the soil profile. First, water is stored in the uppermost simulation layer, until its water content reaches field capacity. The excess water is then added to the succeeding lower soil layer, where it is stored with the same maximum storage restriction. This is repeated, until complete water storage is obtained. Any excess water that flows out from the lowermost simulation layer becomes a part of deep percolation.

Subroutine ET calculates daily potential evapotranspiration using Van Bavel's (1966) revised combination method.

Subroutine DARCY uses a simplified forward finite-difference technique to redistribute soil water in the soil profile using Richards (1931) water flow equation. This subroutine predicts on an hourly basis soil water profile, soil water content at the soil-atmosphere interface, potential and actual soil evaporations, and deep percolation.

Subroutine TRANSP predicts the daily actual plant transpiration rate by distributing the potential amount of plant transpiration throughout the root zone and then adjusting the potential rate on the basis of soil water availability.

Subroutine PSD calculates the geometric mean diameter and geometric standard deviation of primary soil particles on the basis of particle size distribution (percent sand, silt, and clay) of the soil. The geometric mean diameter and geometric standard deviation are used to estimate soil hydraulic parameters that are needed as inputs to the submodel when they are not readily available.

Subroutine HEAT simulates soil temperature based on the algorithm described by Campbell (1985). The subroutine estimates daily minimum, maximum, and average soil temperatures at the center of each simulation layer. The inputs needed to run the program are maximum daily air temperature and minimum daily air temperature. The basic assumption is that the temperature at the upper boundary condition, i.e., the soil-atmosphere interface, over a 24-hour period is equal to the average air temperature for the same period. Furthermore, the temperature at the lower boundary condition, i.e., the center of the lowermost simulation layer, is equal to the average annual air temperature at the site. Furthermore, soil bulk density, volumetric water content, and clay fraction are used to calculate soil thermal properties.

Function RADNET converts the radiation data from global radiation (ly/day) as read from the climate generator (CLIGEN) files into net radiation (MJ/m²/day) as needed by

subroutine ET of the HYDROLOGY submodel of WEPS. Using Wright's modified version of Penman's general relationship outlined by Allen et al. (1989), the subroutine initially estimates the surface albedo by considering the soil, crop, and snow cover. If a snow cover exists with 5 mm or greater water content, the value of albedo is set to 0.6. If the snow cover is less than 5 mm and no crop is growing, the soil albedo is the appropriate value. When crops are growing, albedo is estimated on the basis of soil albedo, crop albedo, and soil cover index.

Function DAWN calculates the time of sunrise for any simulation day based on the position of the simulation site and day of the year. Time of sunrise is used by subroutine DARCY of the HYDROLOGY submodel of WEPS to partition the daily soil evaporation and obtain hourly estimates of potential soil evaporation.

Function WATERK estimates the soil saturated hydraulic conductivity, if it is not readily available as a function of percent silt, percent clay, and soil bulk density.

Figures H4-H8 show the computational sequence of the major subroutines of the HYDROLOGY submodel of WEPS in a flowchart form.

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Figure H-4. Simplified flowchart of the HYDROLOGY submodel of WEPS.

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Figure H-5. Simplified flowchart of the HYDROLOGY submodel of WEPS
(continued).

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Figure H-6. Simplified flowchart of the HYDROLOGY submodel of WEPS
(continued).

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Figure H-7. Simplified flowchart of the HYDROLOGY submodel of WEPS
(continued).

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Figure H-8. Simplified flowchart of the HYDROLOGY submodel of WEPS
(continued).

Winter Routines

The winter routines from the most-recent version of the SPAW model (Saxton, 1995; K.E. Saxton, 1995, personal communication) are in the process of being adapted with some modifications to the HYDROLOGY submodel of WEPS. The routines consist of three interactive components which deal with snow melt, soil frost formation, and snow drifting. The interactions of the three components allow for simulating the extent and timing of snow cover, the number of freeze-thaw cycles, and the changes in soil moisture during winter. These parameters significantly influence the soil susceptibility to wind erosion, particularly in the spring.

The snow melt component of the winter routines is based on Eq. H-2. If snow is present on any given day, it begins to melt when the maximum daily air temperature exceeds 0°C. The daily amount of snow melt depends on the maximum air temperature of that day and the initial water content of the snow. As described by Male and Gray (1981) the temperature index methods for predicting snow melt often give melt estimates that are comparable to those determined from more complex methods that take into account other factors such as radiation, wind velocity, atmospheric humidity, and albedo of the snow.

The soil freeze-thaw component of the winter routines is based on the method outlined by Jumikis (1966) with some minor modifications. The approach is to estimate the cumulative freezing degree-days required from the surface downward through a multilayered soil system. Each additional layer has a freezing requirement and the thermal resistance of the overlying soil layers and snow. The soil freezing depth is estimated by comparing the soil freezing index with the cumulative degree day climatic freezing index. Soil freezing sets the soil freezing coefficient of each soil layer. The freezing coefficients reduce the soil hydraulic conductivity of frozen soil layers by 90%.

The snow drift component of the winter routines assumes that snow depth accumulate until surface storage capacity is filled. The surface storage capacity for snow is influenced by soil random roughness, ridges, and vegetative cover. When the surface storage capacity is filled, a fraction of the new snow is assumed to drift, if it falls during low temperatures and high wind speeds.

SUBMODEL TESTING AND EVALUATION

The HYDROLOGY submodel of WEPS uses tested technology from well-established watershed models such as SPAW (Saxton and Bluhm, 1982; Saxton et al., 1974; Sudar et al., 1981), CREAMS (Smith and Williams, 1980), and EPIC (Williams et al., 1984, 1990) to simulate the different components of the soil water balance such as snow melt, runoff, infiltration, deep percolation, soil evaporation, and plant transpiration. The unique ability of the submodel to predict soil wetness at the soil-atmosphere interface has been tested using data set from two soils.

As a first step in the validation of the submodel, its performance was evaluated by comparing its predictions with the measured soil water content and evaporation data from a 14-d field experiment conducted during March 1971 (Jackson, 1973; Jackson et al., 1973) on an Avondale loam (fine-loamy, mixed (calcareous), hyperthermic Typic Torrifuvent). In general, the submodel predictions compared favorably to actual measurements of daily evaporation ($r^2 = 0.99$) and soil water content measurements ($r^2 = 0.91$) throughout the experiment. Furthermore, the submodel provided good hourly estimates of soil wetness at the soil-atmosphere interface as compared with the measured water contents from the uppermost 5 mm of soil (Durrar, 1991). However, the data from Jackson (1973) were used to develop a key algorithm in the submodel that defines the functional relationship between surface soil wetness and the ratio of actual to potential evaporation.

Another study was conducted to independently evaluate the performance of a stand-alone version of the HYDROLOGY submodel of WEPS in predicting surface soil drying with different soil and climatic conditions (Durrar, 1995). The field experiment was conducted during July-August 1991 on a Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll). The experimental site was a 210- by 250-m field situated at the USDA-ARS Conservation and Production Research Laboratory at Bushland, TX (35° 11' N, 102° 6' W, and 1169 m above MSL). A lysimeter was located at the center of the 5-ha rectangular field. The lysimeter (NE) was one of four weighing lysimeters located at the research center. Water content was measured gravimetrically in a bare 5 x 30-m plot for 14 d after irrigation. The plot was located 5 m directly north of the bare NE lysimeter. Hourly samples were taken from 0 to 2, 2 to 6, 6 to 10, 10 to 30, and 30 to 50-mm depth increments. Furthermore, soil cores were taken to 900 mm at 6-h intervals. Water content also was measured daily at the lysimeter and between the lysimeter and gravimetric sampling plot using a neutron probe to 2.1 m. Simulation with the HYDROLOGY submodel of WEPS started on 1 Aug. 1991 (DOY 213) and continued for 14 d. Daily weather variables, soil hydrological and physical properties, and the initial water content profile were required as inputs in the simulation. The soil profile was divided into eight simulation layers: 0 to 0.05, 0.05 to 0.15, 0.15 to 0.3, 0.3 to 0.5, 0.5 to 0.9, 0.9 to 1.3, 1.3 to 1.7, and 1.7 to 2.1 m.

The submodel accurately predicted that no deep percolation occurred throughout the simulation period. Figure H-9 shows that simulation results agreed well with the measured daily evaporation rates from the lysimeter ($r^2= 0.96$). The fit between simulated and measured hourly soil water content was good for the eight simulation layers throughout the experiment (Fig. H-10). The mean absolute error, which describes the average absolute deviation between measured and simulated soil water contents, was $0.015 \text{ m}^3/\text{m}^3$. Figure H-11 shows that the hourly simulated soil water content at the soil-atmosphere interface exhibited the same diurnal pattern of soil drying during daytime and partial rewetting during nighttime as was observed in the 0- to 2-mm sampling layer throughout the experiment. Hence, the submodel reasonably estimated the soil water content profiles, particularly the status of soil water at the soil-atmosphere interface. The submodel successfully predicts the changes in water content at the soil surface, which relate to the susceptibility of the soil to wind erosion. The stand-alone version of the of the submodel used in the Bushland, TX, validation experiment has one additional climatic input parameter i.e., hour of precipitation during days on which precipitation occurs. The HYDROLOGY submodel of WEPS does not require hour of precipitation as an input parameter because the climate component (CLIGEN) of the WEATHER submodel of WEPS does not generate values for the parameter.

Based on our limited testing, the HYDROLOGY submodel of WEPS shows a potential to accurately simulate soil water dynamics, as needed for wind erosion modeling. The development of the HYDROLOGY submodel of WEPS has highlighted the need for further research. Areas for future research include:

1. Broaden the validation efforts to include a wider range of soils, hydrologic, surface and cover conditions;
2. Combine the HYDROLOGY submodel with the WEATHER, SOIL, and perhaps other WEPS submodels to simulate the impact of soil wetness on the threshold wind velocity over time;
3. Analyze the sensitivity of the submodel by evaluating the changes in the prediction of soil wetness by the submodel as influenced by the changes in the values of the input variables that are needed to run the submodel.

File Contains Data for PostScript Printers Only

Figure H-9. Regression analysis between measured and simulated daily evaporation rates from Bushland, TX, 1991 validation experiment.

File Contains Data for PostScript Printers Only

Figure H-10. Measured vs. simulated hourly soil water contents from the eight simulation layers, Bushland, TX 1991, validation experiment.

File Contains Data for PostScript Printers Only

Figure H-11. Measured soil water contents in the uppermost 2 mm versus simulated hourly soil water contents at the soil-atmosphere interface, Bushland, TX, validation experiment.

LIST OF SYMBOLS

This list contains symbols that are used in the source code and the technical description document of the HYDROLOGY submodel of WEPS. Where two symbols are given, they both may be used in the source code, changing from one to another when passed as arguments between the HYDROLOGY submodel and the MAIN supervisory program of WEPS.

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
am0hfl	Switch for production of hydrology outputs	--
am0ifl	Initialization flag for printing output headers	--
AMEP	Amplitude of the daily wave of potential soil evaporation	mm/hr
ARHO	Air density	kg/m ³
ASWC	Actual amount of available water in the surface layer	m ³ /m ³
ASWCR	Ratio of actual to total amounts of available water in the surface layer	--
AVEP	Time-average value of the daily potential soil evaporation	mm/hr
AWCR	Ratio of actual to total amounts of available water in the soil	--
AWCT	Total amount of available soil water content	m ³ /m ³
BD (asdbl)	Soil bulk density	Mg/m ³
bhrwc0	Hourly surface soil water content on a mass basis	kg/kg
BP	Barometric pressure	kPa
CANP	Daily crop canopy (ratio of ground cover)	--
CB	Power of Campbell's model of the soil water characteristic curve	--

H-52	HYDROLOGY SUBMODEL	WEPS
(ah0cb)		
CLAY	Percent clay	%
CLAYG	Geometric mean diameter of the clay-size fraction (CLAYG = 0.0002)	mm
CLAYM (asfcla)	Clay mass fraction	--
CM	Exponent of Campbell's model of the soil unsaturated hydraulic conductivity	--
CMTOMM (mTOMm)	Conversion factor from meters to millimeters (CMTOMM = 1000)	--
CN	Curve number	--
CNDIF	Difference between condition II SCS curve numbers for poor and good hydrologic conditions	--
CNI	SCS curve number for class I antecedent soil moisture conditions (dry soil moisture conditions)	--
CNII	SCS curve number for class II antecedent soil moisture conditions (average soil moisture conditions)	--
CNIIG (ah0cng)	SCS curve number for class II antecedent soil moisture conditions, under good cover conditions	--
CNIII	SCS curve number for class III antecedent soil moisture conditions (wet soil moisture conditions)	--
CNIIS	Slope-adjusted SCS curve number for class III antecedent soil moisture conditions	--
CNIIP (ah0cnp)	SCS curve number for class II antecedent soil moisture conditons, under poor cover conditions	--
CNIIS	Slope-adjusted SCS curve number for class II antecedent soil moisture conditions	--

WEPS	HYDROLOGY SUBMODEL	H-53
CNIS	Slope-adjusted SCS curve number for class I antecedent soil moisture conditions	--
COND	Unsaturated soil hydraulic conductivity	m/s
CONDA	Average hydraulic conductivity for flow between adjoining soil layers	m/s
DFLOUT	Daily amount of infiltration water that flows out from the bottom of the lowermost layer and treated as deep percolation during soil water storage	mm/day
DH2O	Daily amount of water available from precipitation, snow melt, and/or irrigation	mm
DINF	Daily amount of water infiltration into the soil profile	mm/day
DIRG	Daily amount of irrigation water	mm
DIST	Distance of flow between adjacent soil layers	m
DLAYR (aszlyd)	Depth to the bottom of soil layer from the soil surface	m
DMLAYR (aszlym)	Depth to the midpoint of soil layer from the soil surface	m
DPH	Hourly amount of deep percolation	mm
DPRC	Daily amount of deep percolation	mm/day
DTIME	Time step in subroutine DARCY	s
E	Ratio of the molecular weights of water to air (E = 0.622)	--
EA (ahzea)	Daily rate of actual soil evaporation	mm/day
EAH	Hourly rate of actual soil evaporation	mm/hr
ELEV	Elevation of the simulation region above sea level	m

H-54	HYDROLOGY SUBMODEL	WEPS
(amzele)		
EP (ahzep)	Daily rate of potential soil evaporation	mm/day
EPH	Hourly rate of potential soil evaporation	mm/hr
ERATIO	Ratio of actual to potential soil evaporation	--
ESAT	Effective saturation	Dec. %
ETA (ahzeta)	Daily amount of actual evapotranspiration	mm/day
ETP (ahzeta)	Daily amount of potential evapotranspiration	mm/day
ETPR	Potential evapotranspiration by radiation	mm/day
ETPW	Potential evapotranspiration by wind	mm/day
G	Soil heat flux	MJ/m ²
GMD	Geometric mean diameter of primary soil particles	mm
GSD	Geometric standard deviation of primary soil particles	mm
H	Sum of energy inputs at the soil surface	MJ/m ²
IRISE	Time of sunrise	--
LAYRSN (nslay)	Number of soil layers used in the simulation	--
mc	Soil water content on a mass basis	kg/kg
mcfs	Soil water content at field capacity mass basis	kg/kg
mcs	Soil water content at saturation on a mass basis	kg/kg
mcw	Soil water content at wilting point on a mass basis	kg/kg

HYDROLOGY SUBMODEL		H-55
WEPS		
PLAI (acrlai)	Plant leaf area index	--
POTE (aheaep)	Air entry potential of soil water	J/kg
POTES	Air entry potential at a standard bulk density of 1.3 Mg/m ³	J/kg
POTM	Matric potential of soil water	J/kg
POTMI	Initial matric potential of soil water	J/kg
PRCP (awzdpt)	Daily amount of precipitation	mm
PRES	Amount of plant residues on the soil surface	kg/ha
PRTD (aczrtd)	Depth of the root zone of the plant	m
RN	Net radiation	MJ/m ²
RNOFFM	Daily amount of measured surface runoff	mm
RUNOFF	Daily amount of estimated surface runoff	mm
S	Retention parameter	mm
SAND	Percent sand	%
SANDG	Geometric mean diameter of the sand-size fraction (SANDG = 0.316)	mm
SANDM (asfsan)	Sand mass fraction	--
SATK (ahrsk)	Saturated hydraulic conductivity of the soil	m/s
SILT	Percent silt	%
SILTG	Geometric mean diameter of the silt-size fraction	mm

H-56	HYDROLOGY SUBMODEL	WEPS
	(SILTG = 0.01)	
SILTM (asfsil)	Silt mass fraction	--
SLP (amrslp)	Average slope of the simulation region	m/m
SNMLT (ahzsmt)	Rate of snow melt	mm/day
SNOW	Daily snow melt minus daily snow accumulation	mm
SNWC (ahzsno)	Water content of snow	mm
SNWCI	Initial water content of snow	mm
SVPG	Ratio of the slope of the saturation vapor pressure curve to the psychrometric constant, adjusted to ambient barometric pressure	--
SVPG0	Unadjusted ratio of the slope of the saturation vapor pressure curve to the psychrometric constant	--
SWC	Amount of water in the soil profile in any given day	mm
SWCI	Initial amount of water in the soil profile	mm
SWH	Hydraulic head of soil water	m
SWM	Matric head of soil water	m
SWMI	Initial matric head of soil water	m
TA (ahzpta)	Actual plant transpiration	mm/day
TAIR (awtdav)	Daily mean air temperature	°C
TDP (awtdpt)	Daily mean dew-point temperature	°C

WEPS	HYDROLOGY SUBMODEL	H-57
THET0I	Initial soil water content at the soil-atmosphere interface	m ³ /m ³
THETA	Volumetric water content of the soil	m ³ /m ³
THETA0	Soil water content soil at the soil-atmosphere interface	m ³ /m ³
THETAE	Equivalent water content of the surface layer	m ³ /m ³
THETAf	Soil water content at field capacity	m ³ /m ³
THETAi	Initial soil water content	m ³ /m ³
THETAS	Soil water content at saturation	m ³ /m ³
THETAw	Soil water content at wilting point	m ³ /m ³
THETAx	Extrapolated water content at the soil surface	m ³ /m ³
THETER	Soil water content of the surface layer based on the relationship between evaporation ratio and equivalent water content	m ³ /m ³
THETE _v	Soil water content of the evaporation zone of the surface layer	m ³ /m ³
THET _{f3}	Weighted average field capacity of the three uppermost simulation layers	m ³ /m ³
THET _{i3}	Weighted average initial water content of the three uppermost simulation layers	m ³ /m ³
THET0I	Initial soil water content at the soil-atmosphere interface	m ³ /m ³
TLAYR (aszlyt)	Thickness of soil layer	m
TOL	Tolerance value in subroutine DARCY. Maximum change in soil matric potential values between iterations in any soil layer (TOL = 2 m = 20 J/kg = 200 mb)	m
TMAX (awtdmx)	Daily maximum air temperature	°C
TMIN	Daily minimum air temperature	°C

H-58	HYDROLOGY SUBMODEL	WEPS
(awtdmx)		
TP (ahzptp)	Potential plant transpiration	mm/day
TTC	Turbulent transfer coefficient of water vapor	kg/m ² /kPa
TWU	Accumulated actual water use from the overlying soil layers	mm
U (awudav)	Mean daily wind speed	m/s
VK	Von Karman's constant (VK = 0.41)	--
VLH	Latent heat of vaporization	MJ/kg
VPA	Actual vapor pressure	kPa
VPD	Saturation vapor pressure deficit	kPa
VPS	Saturation vapor pressure	kPa
VPSMN	Saturation vapor pressure at minimum air temperature	kPa
VPSMX	Saturation vapor pressure at maximum air temperature	kPa
WC	Amount of water in the soil layer	mm
WCI	Initial amount of water in the soil layer	mm
WCS	Amount of water in the soil layer at saturation	mm
WFLUX	Amount of soil water flow in subroutine DARCY	m
WFLUXN	Net amount of soil water flow into a given soil layer	m
WSF	Water stress factor of plant growth	--
WUA	Actual rate of water use from a given layer	mm/day
WUD	Water use distribution parameter	--

WEPS	HYDROLOGY SUBMODEL	H-59
	(WUD = 3.065)	
WUP	Potential rate of water use from a given layer	mm/day
Z0	Roughness thickness	m
ZA	Height of measurements of meteorological sensors	m

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MANAGEMENT SUBMODEL



MANAGEMENT SUBMODEL

L. E. Wagner and D. Ding

INTRODUCTION

WEPS is expected to reflect effects of various management practices upon wind erosion. The diversity of current practices applied to cropland by land managers makes this a daunting task. However, WEPS must adequately simulate typical cultural practices to accurately assess their effects upon wind erosion control. The MANAGEMENT submodel is assigned the task of handling the cultural practices applied by land managers which affect the soil/surface "state" within WEPS.

Purpose

All cultural practices applied by land managers are by definition "human initiated". These human-controlled processes affecting the soil and field surface "state" are initiated by typical management practices such as tillage operations, planting, harvesting, irrigation, etc. Therefore, the purpose of the MANAGEMENT submodel is to model what are considered the major human-controllable actions that can affect the "system state" within WEPS, in particular the system state variables defining the temporal soil and surface conditions.

Objectives

The MANAGEMENT submodel objectives are:

To model the primary human-initiated processes that can affect a site's susceptibility to wind erosion.

To provide the framework necessary to process a list of specified human-initiated actions, i.e., the cultural practices applied to a field such as a tillage/crop rotation sequence.

Keeping with the WEPS philosophy, The MANAGEMENT submodel simulates processes via a physical basis if possible, incorporates the conservation of mass and energy concepts, and uses a minimum number of parameters with readily available and/or attainable values.

Assumptions and Limitations

Several assumptions and limitations have been imposed on the MANAGEMENT submodel. The reasons vary from simply limiting the scope of the submodel, to inadequate knowledge of specific processes that may have a significant impact on the soil and/or surface. Here is the list of current assumptions and limitations, provided in no particular order, that impact the MANAGEMENT submodel.

1. Total soil water content within the current tillage zone is assumed to be unaffected by a tillage operation. The HYDROLOGY submodel is expected to handle changes in surface water content and therefore appropriately represent the usual rapid drying of the surface layer following tillage.
2. Tillage speed is not included as an independent variable affecting how a tillage operation modifies the soil and surface. A "typical" tillage speed is assumed for each tillage operation upon which the effects upon the soil and surface are based. Future versions of the MANAGEMENT submodel may incorporate tillage speed if sufficient data becomes available to model its effects upon the soil and surface.
3. Tillage depth is assumed to not influence how a tillage operation affects the soil and surface except for determining which soil layers are directly affected by a tillage operation. Again, the MANAGEMENT submodel may be extended to incorporate tillage depth effects if sufficient data becomes available in the future.
4. Effects of tillage operations on soil layers below the tillage depth are not considered, i.e., subsoil compaction below the tillage zone due to tillage. This will be addressed in a future release of the MANAGEMENT submodel.
5. The effects of a management operation are assumed to be homogeneous within a subregion. Effects due to tractor tires will not be considered. Certain zone-related tillage operations, such as row cultivator, will be treated in a manner such that the result will be "averaged" or "equivalent" values which represent the homogeneous region.
6. Emergency tillage, for wind erosion prevention or control, and strip cropping practices is considered in WEPS by specifying multiple separate, non-contiguous homogeneous subregions.
7. Ridge and dike geometric specifications (oriented roughness) will be provided by the user. If the tillage depth specified is not sufficient to create or destroy them (for a particular tillage operation that does so), the MANAGEMENT submodel will modify

the tillage depth accordingly to obtain the desired ridge and/or dike specifications. Tillage operations that do not modify the current ridge and/or dike specifications will not do so (i.e., ridge tillage equipment).

8. Soil tillage depths will be adjusted to the nearest soil layer boundary. This will ensure that the most recent tillage operation modifications on the soil "state" are adequately represented. In the future, soil layer boundaries may be adjusted appropriately to accommodate tillage depths that would split a soil layer, i.e., a new layer boundary would be created at the prescribed tillage depth.
9. Aggregate stability and aggregate density are assumed to be unaffected by tillage operations. This decision is based on limited field data analysis. Future research may provide statistically significant affects that could then be modeled. These properties may still change among soil layers within the tillage zone due to aggregate mixing among layers caused by tillage operations.

SUBMODEL DESCRIPTION

The approach taken within the MANAGEMENT submodel to deal with the variety of land management actions was to:

Identify the primary physical processes involved.

Represent individual management operations as a sequence of those primary physical processes.

Develop a MANAGEMENT file format allowing the input of user-specified sequences of management operations, i.e., a management practices/crop rotation file.

All operations modeled within the MANAGEMENT submodel fall within the following defined management categories as listed in Table T-1.

Table T-1. Management operation classes.

Operation Class	Description
Primary tillage	Tillage performed to primarily reduce surface residue, increase short-term infiltration rates, loosen subsoil hardpans, and control weed growth. Usually after-harvest tillage operations fall in this category.
Secondary tillage	Tillage typically performed in preparation for seeding or planting operations. Usually these operations are intended to smooth the soil surface, reduce the average aggregate size, and control weed growth if present.
Cultivation	Tillage specifically designed to eliminate weed growth after crop germination.
Planting/Seeding	Operations required to plant or seed a crop into a field.
Harvesting	Operation to remove biomass from a field. Biomass removed may be grain, root material, or the entire above ground biomass.
Irrigation	The artificial application or addition of water to the soil.
Fertilization	The application or addition of specific nutrients to a soil.
Burning	The removal of surface biomass with fire.
Grazing	The removal of surface biomass via livestock.

When a management or tillage operation is performed, it is simulated through a group of individual physical processes that represent the total effects of that operation. The basic individual physical processes to be modeled within the MANAGEMENT submodel of WEPS have been grouped according to the target of their actions and outlined in Table T-2.

Table T-2. MANAGEMENT submodel processes.

Action	Process	Description
Soil Mass Manipulation	Crush	The application of forces to the soil to modify the soil aggregate structure by breaking down soil aggregates.
	Loosen/ Compact	The process of decreasing soil bulk density and increasing porosity (incorporation of air) or the inverse process of increasing soil bulk density by removing air from the soil.
	Mix	The process of uniting or blending of soil layer properties, including biomass.
	Invert	The reversing of the vertical order of occurrence of soil layers within the current specified tillage zone.
Surface Manipulation	Ridge/Dike	The process of creating or destroying ridges and/or dikes (oriented surface roughness).
	Roughen	The process of modifying the random surface roughness.
	Crust	The process of modifying the soil surface crust characteristics.
Biomass Manipulation	Bury/Lift	The process of moving above ground biomass into the soil or the inverse process of bringing buried biomass to the surface.
	Cut	The process of cutting standing biomass to a prescribed height.
	Drop	The process of moving a portion of the standing biomass to the soil surface.
	Kill	The death of live biomass.
	Remove	The removal of biomass from the system (harvest, grazing, and burning).
Soil Amendments	Fertilize	Addition of nutrients to the soil.
	Plant	Addition of seeds/plants to the soil.
	Irrigate	Addition of water to the soil.

The underlying philosophy behind the MANAGEMENT submodel was to attempt to develop physical law based representations, if possible, for each of the chosen physical processes. These processes are assumed to be independent with respect to each other and are to be simulated sequentially, even though many of them occur simultaneously in the real world. The order they are initiated in the submodel is dependent upon the specific operation.

The list of management operations performed for a given management plan (crop rotation or cyclical management practices) on a homogeneous region (subregion) is specified in a MANAGEMENT input file. The MANAGEMENT submodel checks on a daily basis for any operations to be performed on that day. If operations are needed, the MANAGEMENT submodel will execute the specified routines required to simulate the effects of those operations as instructed in the MANAGEMENT input file. When the last operation is

performed for that particular crop rotation cycle, the same sequence will be repeated for the next year(s) of simulation.

A single MANAGEMENT input file may include multiple management operation lists, one for each subregion being simulated.

PHYSICAL PROCESSES MODELED

The physical processes simulated within the MANAGEMENT submodel of WEPS are listed in Table T-2. A description of each process follows along with how it is implemented within the MANAGEMENT submodel. The processes are grouped and discussed according to their primary target of action.

Spatially, the submodel considers the soil mass, surface, and biomass properties to be homogeneous in a horizontal plane (subregion), but variable in the vertical direction (horizontal spatial variability is dealt with by WEPS through the use of multiple subregions). The soil surface is considered to be flat, ridged, or ridged and diked. Live (crop) and dead (crop residue) biomass may exist in the soil or on the surface in standing and/or flat orientations.

A concept utilized throughout equation development has been that of a first-order rate process. Since we are concerned with determining the change of soil and biomass properties with time, i.e., during a tillage event, we have assumed that we can describe the time rate of change of each variable affected². This incremental change has the general form:

$$\Delta X = a(X - X_{lim})$$

where:

$a = a_t \Delta t$, Proportional coefficient

a_t = Time coefficient

Δt = Time increment of change

ΔX = Change in X during operation

X = Initial value

X_{lim} = Limiting value of X

(1)

Thus, the change in X during a tillage event is directly proportional to its value at the beginning of the event and perhaps limited by a specified value (i.e., X_{lim}) other than zero. For example, if X were to represent the soil bulk density, then X_{lim} would represent the lower limit for the bulk density.

² Or more correctly, the time increment of change since we must use a finite difference representation in the submodel.

Since the speed of individual operations are assumed to be approximately the same, Δt is a constant and hence we can work with the dimensionless proportional coefficient a rather than the true time coefficient a_t . Therefore, it is expected that a will be a function of parameters that may cause ΔX to change, i.e.,

$$a = f(\text{Tillage Implement, Soil Texture, Soil Moisture, ...})$$

The development of this functional relationship(s), or constants, are determined for many of the surface manipulation, soil mass, and biomass manipulation actions.

Soil Surface Manipulation

The soil surface is considered to be flat, ridged, or ridged and diked. Any of these surface configurations may also be crusted to some degree. The flat configuration assumes that there is no oriented roughness (OR) but random roughness (RR) exists. The ridged configuration implies that oriented roughness exists and is defined by the ridge direction, height and spacing. Ridged and diked surfaces imply that another distinct oriented roughness exists, due to dikes, which is perpendicular to the oriented roughness represented by the primary ridges. Ridge and dike slopes are assumed to be constant regardless of height and spacing.

The soil surface is described within WEPS by random and oriented roughness values, fraction of surface that is crusted, and the amount of loose, erodible material on a fully crusted surface. The post-operation surface state is determined based upon parameters affecting the following properties:

1. Percent of surface area modified (tilled).

The fraction of surface tilled by a management operation is assigned to each management operation. Primary and secondary tillage operations typically till the entire surface while row cultivation operations may till only the area between crop rows.

2. Fraction of crust destroyed.

Management operations that modify the soil surface such as tillage can destroy crust if present prior to the operation. The amount of the surface crust destroyed by a management operation is specified by the de-crusting parameter as defined in Eq. [T-2]. Most management operations that affect the surface configuration will destroy all of the crust area, however, some operations do not modify (till) the entire surface area. Thus, the de-crusting factor is applied only to the fraction of surface being tilled.

$$Cr_f = (1-\kappa) \zeta Cr_o$$

where:

$$\begin{aligned} Cr_f &= \text{Fraction of surface crusted after operation} \\ Cr_o &= \text{Fraction of surface crusted before operation} \\ \kappa &= \text{Fraction of crust removed } (0 \leq \kappa \leq 1) \\ \zeta &= \text{Fraction of surface tilled } (0 \leq \zeta \leq 1) \end{aligned} \quad (2)$$

3. Random roughness.

The random roughness of the surface within the MANAGEMENT submodel is represented in terms of Allmaras' random roughness index (Allmaras, et al, 1966). The nominal random roughness value, RR_o , expected from a tillage operation is usually what is obtained under typical field conditions. However, some tillage tools cannot reduce the surface roughness to the value usually associated with the operation in some conditions. Therefore, a tillage intensity factor, λ , is also assigned to each tillage operation as in WEPS (Lane and Nearing, 1989). If the pre-tillage random roughness is greater than the nominal random roughness associated with the implement, then the post-tillage random roughness value is computed using the tillage intensity factor as shown in Eq. [T-3]. If the tillage operation does not modify the entire surface, the post-tillage random roughness is weighted accordingly.

$$RR_f = \begin{cases} \zeta RR_{impl} + (1-\zeta) RR_o & RR_{impl} \geq RR_o \\ \zeta [\lambda RR_{impl} + (1-\lambda) RR_o] + (1-\zeta) RR_o & RR_{impl} < RR_o \end{cases}$$

where:

$$\begin{aligned} RR_f &= \text{Final tilled surface random roughness (mm)} \\ RR_o &= \text{Pre-tillage surface random roughness (mm)} \\ RR_{impl} &= \text{Assigned nominal RR value for tillage operation (mm)} \\ \lambda &= \text{Tillage intensity factor } (0 \leq \lambda \leq 1) \\ \zeta &= \text{Fraction of surface tilled } (0 \leq \zeta \leq 1) \end{aligned} \quad (3)$$

4. Oriented roughness.

Oriented roughness is defined within the MANAGEMENT submodel of WEPS as uniform rows of ridges and furrows running in parallel lines. Thus, oriented roughness can be specified via the ridge height, ridge spacing, and row direction (currently ridge slopes are assumed a constant 4:1 ratio and ridge top and furrow channel widths are assumed equal). If there are dikes in the furrows, they are assumed to be equally spaced with the same slope as the ridges. Therefore, only dike height and spacing are required to define them within the model. Default values for ridge and dike parameters are provided for each tillage operation, but the values are modifiable by the user.

A "ridge modification" flag will be assigned to each management operation. If the flag value is set to "destroy ridges", it is assumed that the tillage operation being specified can change the current surface configuration into the desired configuration with respect to oriented roughness. If the flag value is "modify ridges", the operation will modify the current oriented roughness and may completely eliminate the original ridges, depending on tillage depth specified. If the flag value is "no effect", then the operation will leave the current oriented roughness alone.

Soil Mass Manipulation

Soil mass manipulation is represented by a group of variables related to a series of stacked parallel homogeneous layers with a specified thickness. A fundamental principle used in developing the submodel processes affecting the soil layer properties is that of conservation of mass.

Crush The crush process produces a status change in aggregate size distribution (ASD) within a soil layer. This change occurs due to the application of forces to the soil (for example a tillage operation), usually resulting in a breakdown of soil aggregates in the tillage zone.

The soil surface aggregate size distribution is important in wind erosion because it provides the necessary information to determine the quantity of erodible-size aggregates available for direct emission and saltation as well as the degree of shelter provided to erodible-size aggregates by larger aggregates. Aggregate size distribution below the surface is also of interest because emergency tillage operations used to control wind erosion fail if insufficient non-erodible aggregates exist to bring to the surface.

Aggregate size distributions are represented within WEPS as a 4-parameter modified lognormal distribution (Wagner and Ding, 1994). The 4-parameter modified lognormal probability function is:

$$p(x') = \frac{1}{x' \sqrt{2\pi} \ln(\sigma'_g)} \exp \left[-\frac{1}{2} \left(\frac{\ln(x'/x'_g)}{\ln(\sigma'_g)} \right)^2 \right]$$

where:

$$x' = \frac{(x-x_0)(x_\infty-x_0)}{(x_\infty-x)}, \quad 0 < x' < \infty$$

x' = transformation variable (mm) (4)

x = aggregate size (mm)

x_0 = minimum aggregate size (mm)

x_∞ = maximum aggregate size (mm)

x'_g = geometric mean dia. of transformed distribution (mm)

σ'_g = geometric std dev of transformed distribution

and the cumulative distribution function, in terms of percent, is:

$$P(\% \leq x) = 50 \left\{ 1 + \operatorname{erf} \left[\frac{\ln \left(\frac{(x-x_0)(x_\infty-x_0)}{(x_\infty-x)x'_g} \right)}{\sqrt{2} \ln(\sigma'_g)} \right] \right\} \quad (5)$$

where:

erf = error function

$$0 \leq x_0 < x_\infty < +\infty$$

Tillage-induced aggregate breakage is simulated within the MANAGEMENT submodel of WEPS with a Markov³ chain-based, two-parameter stochastic model⁴ (Wagner and Ding, 1993) which can be stated as follows in the context of the soil aggregate crushing process:

A soil aggregate is assumed to consist of many particles, with each having an infinitesimal volume and a unit mass. The soil particles can travel only downward from a larger aggregate size class to smaller aggregate size classes after each tillage pass (crushing of an aggregate). If a size class i is called a "state", then the transition of soil particles from one state to another can be treated as a completely random event. A probability matrix, $P[i,j]$, can be constructed for all possible transitions occurring in the soil when its aggregate size distribution (mass fractions across different size classes) shifts or transfers from $w[i]$ to $\hat{W}[k]_{(0 \text{ to } i-1)}$ size, after one crushing stage (tillage pass). $P[i,j]$, often

³ A Markov process is one in which the next "state" is dependent only on the present "state" and is independent of any previous "state".

⁴ A stochastic model is one having at least one component that will be treated as exhibiting random behavior.

called a transition matrix, maintains the properties of a Markov chain and does not change with the number of tillage passes performed but depends on the type of tillage and the specific soil conditions.

Mathematically, the Markov chain-based crushing model is of the form:

$$\hat{w}[i]_{(1 \times n)} = w[i]_{(1 \times n)} P[i,j]_{(n \times n)}$$

where:

$$\begin{aligned} \hat{w}[i] &= \text{post-tillage array of aggregate size class fractions} \\ w[i] &= \text{pre-tillage array of aggregate size class fractions} \\ P[i,j] &= \text{transition matrix} \\ i,j &= \text{indices for soil aggregate size classes} \\ n &= \text{maximum number of aggregate size classes} \end{aligned} \quad (6)$$

The effectiveness of the model relies on how accurately the transition matrix, $P[i,j]$, can be estimated. According to the model statement, the transition matrix can be generalized as a lower triangular matrix, where the states with smaller index values correspond to the smaller aggregate size classes (size intervals) and vice versa.

$$P[i,j] = \begin{pmatrix} p_{11} & 0 & \dots & 0 \\ p_{21} & p_{22} & 0 & \dots & 0 \\ \vdots & & & & \\ \vdots & & & & \\ p_{i1} & \dots & p_{ij} & \dots & p_{ii} & 0 & \dots & 0 \\ \vdots & & & & & & & \\ p_{n1} & p_{n2} & p_{n3} & \dots & p_{nn-1} & p_{nn} \end{pmatrix}_{n \times n} \quad (7)$$

Because it is almost impossible to estimate each transition probability, p_{ij} , individually, it was assumed that the p_{ij} follows a binomial distribution⁵ as shown in Eq..[T-8]. The binomial distribution is a typical discrete probability distribution function.

$$p_{ij} = \binom{i-1}{j-1} p_i^{j-1} (1-p_i)^{i-j} \quad i = 1, 2, \dots, n, \quad j = 1, 2, \dots, i \quad (8)$$

⁵ This probability distribution of Bernoulli trials, which are repeated independent trials. Each trial has two possible outcomes, and the corresponding probability remains the same for all trials.

In Eq.[T-8], p_i is defined as the probability function of breakage, which has a value within the interval [0,1] and generally can be expressed as an algebraic function of sieve size, x_i , and a number of parameters, a_1, a_2, \dots, a_m .

$$p_i = f(x_i, a_1, a_2, \dots, a_m) \quad (9)$$

The probability function of breakage, p_i , reflects how much breaking is occurring in the aggregate size class i . A large p_i indicates a small percentage of soil aggregates of size class i that will break into smaller size classes. If $p_i = 1$, then no aggregates of size class i are being broken down, and if $p_i = 0$, then all of the aggregates in size class i are being broken down into smaller size classes.

It is presumed that p_i is related to the tillage tool, tillage speed, tillage depth, soil conditions and sieve cut sizes used in measuring $w[i]$ and $\hat{w}[i]$. Therefore, the a_i parameters in Eq.[T-9] are expected to be functions of those conditions. The most suitable two-parameter functional representation for p_i was found to be:

$$p_i = \frac{1.0}{1.0 + \exp\left(-\alpha + \beta \frac{\text{gmd}_i}{\text{gmd}_{\max}}\right)} \quad (10)$$

where⁶:

$i = 1, 2, 3, \dots, n, n+1$ ($n =$ number of sieve cuts)

$\text{gmd}_i =$ geometric mean dia. of aggregates in size class i (x_{i-1} to x_i)

$\text{gmd}_{\max} =$ geometric mean dia. of aggregates in largest size class (x_n to x_{n+1})

Parameter α reflects the breakage of all soil aggregates regardless of size. As α decreases, the percentage of soil aggregates breaking increases. Parameter β reflects the unevenness of breakage among aggregates in different size classes. Large β values indicate that crushing mainly affects the large soil aggregates.

The parameters in the model represented by Eq.[T-6],[T-7], [T-8], and [T-10] were estimated for four tillage tools and listed in Table T-3. Although the parameters in Table T-3 are derived from a limited number of field data sets, they give a good indication of how much crushing occurred with each tillage tool. To judge how much crushing is caused by a tillage

⁶ For a rotary sieve of n sieves, the x_0 and x_{n+1} are arbitrary minimum and maximum aggregate sizes assumed to exist in the data. The values used during model development analysis were 0.01 mm and 152.4 mm, respectively. These values also correspond to the x_0 and x_∞ values from a four-parameter "modified" lognormal function describing an aggregate size distribution.

implement based upon its two parameters, the following rules of thumb in Table T-4 can be applied.

Table T-3. Parameters of crushing model for four types of tillage tools.

Tillage Implement		Silt Loam			Silty Clay Loam		
		α	β	# data sets	α	β	# data sets
Rotary Tiller	Mean	1.40	-1.20	5	1.50	0.56	3
	S.D.	0.60	1.70		0.30	0.55	
Disk Harrow	Mean	2.80	0.75	9	4.30	2.00	8
	S.D.	0.50	0.28		1.60	1.50	
Chisel Plow	Mean	-	-	-	2.40	-2.00	4
	S.D.	-	-		1.20	4.60	
Field Cultivator	Mean	3.00	-0.22	1	3.00	1.80	2
	S.D.	-	-		0.90	0.50	

Table T-4. Rules of thumb for determining degree of crushing from parameters.

Rule 1	If α is small	$\alpha < 2$	Then a high percentage of aggregates from all size classes are being broken down.
Rule 2	If α is not small and β is approximately one-half of α	$\alpha \geq 2$ and $\beta \approx \frac{1}{2}\alpha$	Then a high percentage of large aggregates are being crushed or broken down.
Rule 3	If α is large and β is small	$\alpha \geq 3$ and $\beta \leq 1.5$	Then only a small amount of aggregates are being crushed.

Tillage-induced aggregate breakage and thus the crushing parameters are dependent upon soil type and water content at time of tillage (Wagner, Ambe, and Barnes, 1992; Wagner and Ding, 1993, Wagner, Ambe, and Ding, 1994), but determination of those functional relationships have not yet been pursued.

Mix The mixing process represents the uniting or blending of soil layer properties within soil layers only. The burial of surface constituents such as crop residue, fertilizer, etc. below the surface is not represented by this mixing process but rather the burial process described later.

The mixing process employed in the MANAGEMENT submodel uses a single mixing parameter. The values range from zero for no mixing to one for complete mixing. All layers within the tillage zone are currently weighted equally in the layer mixing process. Eq..[T-11] describes the mixing process which is similar to what the EPIC and WEPP models (Sharpley

and Williams, 1990 and Lane and Nearing 1989) use except this one is mass-based rather than volume-based:

$$\hat{X}_1 = (1 - \mu) X_1 + \mu \left(\frac{\sum_{k=1}^m (\rho_k \Delta Z_k X_k)}{\sum_{k=1}^m (\rho_k \Delta Z_k)} \right)$$

where:

$$\begin{aligned} \hat{X}_1 &= \text{Final mass concentration in layer 1} \\ X_1, X_k &= \text{Initial mass concentrations in layers 1 and k} \\ \mu &= \text{Mass mixing efficiency coefficient} \\ \rho_k \Delta Z_k &= \text{Mass of soil in layer k} \\ l, k &= \text{Soil layer indices} \\ m &= \text{Maximum number of soil layers} \end{aligned} \tag{11}$$

All soil layer variables defined as concentrations of the soil mass in the layer, e.g. intrinsic soil properties such as the fractions of sand, silt, clay, organic matter, cation exchange capacity, nutrient levels, etc. can be mixed directly using Eq. [T-11].

Loosen/compact The loosen/compact process is defined as the addition or removal of air in the soil layer.

This is represented as a change in the soil layer bulk density in the MANAGEMENT submodel by Eq. [T-12] as defined in the EPIC model (Sharpley and Williams, 1990). The "settled" bulk density, ρ_{s1} , is determined using an interpolation of published soil texture triangle values (Rawls, 1983). Applying the conservation of mass principle requires a corresponding change to the soil layer thickness as shown in Eq. [T-13].

$$\hat{\rho}_1 = \rho_1 - \left(\rho_1 - \frac{2}{3} \rho_{s1} \right) \mu$$

where:

$$\begin{aligned} \hat{\rho}_1 &= \text{Post-tillage bulk density for layer 1} \\ \rho_1 &= \text{Pre-tillage bulk density for layer 1} \\ \rho_{s1} &= \text{Settled bulk density for layer 1} \\ \mu &= \text{Mass mixing efficiency coefficient} \end{aligned} \tag{12}$$

$$\Delta\hat{Z}_1 = \Delta Z_1 \frac{\rho_1}{\hat{\rho}_1}$$

where:

$\Delta\hat{Z}_1$ = Post-tillage layer thickness for layer 1 (13)

ΔZ_1 = Pre-tillage layer thickness for layer 1

$\hat{\rho}_1$ = Post-tillage bulk density for layer 1

ρ_1 = Pre-tillage bulk density for layer 1

Invert The inversion process is the reversal of the vertical order of soil layers within the working depth of the tillage tool.

Thus, inversion is simply the re-ordering of the soil layers in the model and layer thicknesses re-assigned based on the layer thickness constraints imposed by WEPS. Since the new layer boundaries are not likely to match the original boundaries, the original layer properties are repartitioned into the new layers.

Biomass Manipulation

The biomass manipulation processes describe the effects that management operations have on the growing crop and the various biomass pools maintained in the WEPS model. The biomass manipulation processes invoked during the management operations are:

Bury/Lift Transferring above ground biomass into the soil or the inverse process of bringing buried biomass to the surface. This process will be invoked by most tillage operations.

Cut Cutting standing biomass to a prescribed height. The biomass above the "cut" height will either be removed or added to the surface biomass pool.

Drop Moving a portion of the standing biomass to the soil surface. The process is usually the result of an operation flattening standing residue (Wagner and Nelson, 1995).

Kill Stopping the growth of biomass. The process may be initiated by tillage operations, the application of herbicides, or burning.

Remove Removing biomass from the site. This process is usually the result of harvest, grazing, or burning operations.

Soil Amendments

The addition of specific materials to the soil and/or surface are also addressed in the MANAGEMENT submodel. Currently, fertilizers (nitrogen and phosphorous), irrigation water, and biomass can be applied to the surface or incorporated into the soil. The quantity of amendments applied are user specified for those operations. The process of applying seeds to the surface and/or soil is also present in the sense that this process triggers the CROP submodel to begin simulating the growth of a new crop.

SUBMODEL IMPLEMENTATION

Submodel Logic

The following description outlines the six basic sections of the MANAGEMENT submodel and the process flow from one section to another.

1. MANAGEMENT initialization subroutine (mfinit).

The MANAGEMENT submodel requires a one-time initialization step for each simulation run. The MANAGEMENT initialization routine is executed from within the MAIN program's initialization section. The routine's primary purpose is to initialize the file pointers⁷ within the MANAGEMENT file marking the start of each subregion's list of management practices (tillage and crop sequences, irrigation schedules, fertilization dates, etc.). A "current management practice" file pointer is also initialized to the first management operation for each subregion. These file pointers are used to keep track of the progression through the management lists for each subregion throughout the simulation run. When the "current management practice" file pointer reaches the end of a management practice list, it is then reset to the start of the list. A representation of a MANAGEMENT file depicting the file pointers is shown in Figure T-1.

⁷Variables containing the pertinent line number within a fixed record length file.

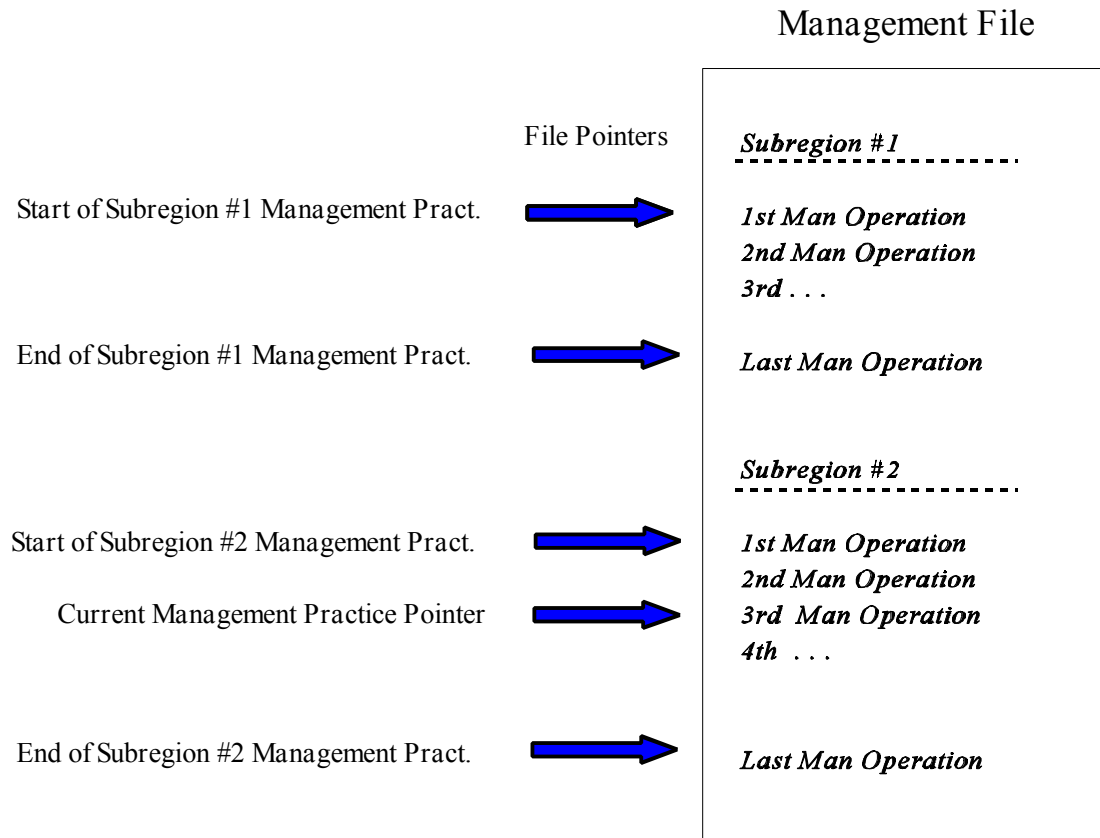


Figure T-1. MANAGEMENT file record/location pointers.

2. Top-level MANAGEMENT subroutine (manage).

The top-level MANAGEMENT subroutine is called daily for each subregion by the MAIN program (Figure T-2). If the current simulation date corresponds to the date specified for the next management operation (date previously obtained from MANAGEMENT file) to be performed for that subregion, then that management operation is performed via the "Do Operation" (dooper) subroutine. If the dates do not match, control is returned to the MAIN program (Figure T-3).

3. Do management operation subroutine (dooper).

This routine determines which management operation was specified for this date. After making this determination it performs the management operation via the individual operation subroutines like till, plant, harv, etc. When the operation is completed, the MANAGEMENT file is consulted to determine the date of the next management operation for this subregion (Figure T-4).

4. Individual operation subroutines (till, plant, harv, etc.).

Each individual operation subroutine performs four basic functions (Figure T-5):

- a. Get operation specific data from MANAGEMENT file and do any initializations required for the processes modeling that operation.
- b. Obtain the information from the MANAGEMENT file pertaining to the first listed process describing this management operation.
- c. Do the first and all subsequent processes that describe the specific management operation via the doproc subroutine. When each process is completed, the MANAGEMENT file is consulted to determine the next process or embedded operation for the current management operation being performed on this subregion.
- d. Do any post-operation processes required for this management operation.

5. Do process subroutine (doproc).

This subroutine determines the next process specified for this operation. After making this determination it performs that process via the individual process subroutines like crush, loosen, mix, drop, etc. (Figure T-6).

6. Individual process subroutines (crush, loosen, mix, drop, etc.).

Each individual process subroutine simulates a physical process that is performed by any given management operation. A management operation may consist of one or more physical processes that are simulated by process subroutines in the MANAGEMENT submodel.

*Contains Data for
Postscript Only.*

Figure T-2. WEPS MAIN routine.

File Contains Data for PostScript Printers Only

Figure T-3. Top-level MANAGEMENT subroutine.

*Contains Data for
Postscript Only.*

Figure T-4. MANAGEMENT select operation routine.

*Contains Data for
Postscript Only.*

Figure T-5. Individual MANAGEMENT operation routine.

*Contains Data for
Postscript Only.*

Figure T-6. MANAGEMENT select process routine.

Management File Format Description

The MANAGEMENT file format was developed to meet the following criteria:

1. Consolidate the list of management operations (tillage sequences, crop rotations, fertilization and irrigation schedules, etc.) performed for each subregion into a single MANAGEMENT file.
2. Devise a format that allows only one subroutine or function call to extract all information from the MANAGEMENT file. This routine should be sufficiently general so that it can read a specified number of variables of an indicated type (integer, real, double precision, character string) in a free-style format from the MANAGEMENT file. This routine should also be able to extract multi-dimensioned array values of an indicated type.
3. The MANAGEMENT file format should be constructed such that any individual management operation may be defined to consist of any number of processes and other management operations. For example, a fertilization operation may consist of both the application of fertilizer (fertilize process) and a tillage operation. The order of the processes and other possible embedded operations for a specific management operation should dictate the order in which those processes and embedded operations are simulated in the MANAGEMENT submodel. Examples of processes and embedded operations associated with individual management operations are presented in Table T-5.

Table T-5. Embedded operations/processes for selected MANAGEMENT tasks.

Operation	Processes/Embedded Operations	Explanation
till_lay	crush _(p) , loosen _(p) , mix _(p) , invert _(p)	Tillage processes affecting soil layers
till_surf	ridge/dike _(p) , roughen _(p) , crust _(p)	Tillage processes affecting soil surface
till_bio	bury/lift _(p) , cut _(p) , drop _(p) , kill _(p) , remove _(p)	Tillage processes affecting biomass
tillage	till_lay _(o) , till_surf _(o) , till_bio _(o)	Typical tillage operation
rotary_hoe	till_lay _(o) , till_surf _(o)	Tillage which does not affect biomass
fertilize	tillage _(o) , fertilize _(p)	Fertilizer applied with a tillage implement
plant1	tillage _(o) , plant _(p)	Planting process applied with implement
plant2	tillage _(o) , plant _(p) , fertilize _(p)	Planting and fertilizing with implement
plant3	tillage _(o) , plant _(p) , fertilize _(o)	Planting and fertilizing with implement(s)

(p) is a process, (o) is an operation.

Each individual process may require some specific parameters for the process to be simulated. Examples of some process parameters are shown in Table T-6.

Table T-6. Operation and process parameters.

Operation or Process	Parameter(s)	Description
tillage _(o)	tillage depth, direction, ...	Tillage operation info
crush _(p)	alpha, beta	Crushing model coefficients
mix _(p)	gamma	Mixing model coefficient
loosen _(p)	sigma	Loosening model coefficient
plant _(p)	seed depth, density, type, ...	Crop model inputs
irrigate _(o)	amount of water applied	Irrigation input
fertilize _(p)	amount/type of nutrients applied	Fertilization inputs

(p) is a process, (o) is an operation.

- The MANAGEMENT file should be designed so that the language the MANAGEMENT submodel is coded in (FORTRAN 77) can perform random, indexed seeks within the file.

Table T-7. Sample MANAGEMENT input file.

```

# This is a sample management input file          70th char--><
#
# It does one tillage operation every three years. <
# That operation crushes aggregates and mixes soil layers. <
#
# Characters that begin a line in this file represent the following <
#
#   '#' <-- comment line <
#   '+' <-- continuation line <
#   '*' <-- control line <
#   'D' <-- date line (date an operation is to be performed on) <
#   'O' <-- operation line <
#   'P' <-- process line <
#
#
#
#           +----- subregion no. <
#           | +----- no. of years in management cycle <
#           | | <
# *START 001 003 <
#
#
#   +- Operation date in 'dd/mm/yyyy' format (yyyy is year of cycle) <
#   | +----- Operation Class code <
#   | +----- Operation Class name <
#   | | <
# D14/02/0001 01 Primary-Tillage <
#
# +-----Operation code <
# | +----- Operation name <
# | | <
# O 01 Tillage <
#
#
# +----- Tillage Speed <
# | +----- Tillage Depth <
# | +----- Tillage Direction <
# | +----- Tillage Implement <
# | | <
# + 6.0 15.2 NE Disk-Offset <
#
#
# +-----Process code <
# | +----- Process name <
# | | <
# P 01 Crushing <
#
# +----- alpha (crushing coefficient) <
# | +----- beta (crushing coefficient) <
# | | <
# + 2.8 .75 <
#
# P 02 Mixing <
#
# +----- gamma (mixing coefficient) <
# | <
# + 0.78 <
#
#
# *END 001 # end of subregion no. 1 management list <
#
# *EOF # end of MANAGEMENT input file <

```

A sample MANAGEMENT input file is shown in Table T-7. The file format is as follows:

1. All lines must be of equal length (ie. same number of characters on each line). This is required for FORTRAN 77 to perform random, indexed seeks within a file. Extra characters to pad a line to the selected line length should be spaces. Our current convention is to use a non-numeric character as the last displayable character on the line. The selected character is the less-than sign, '<'.
2. The maximum line length selected cannot exceed 80 characters. A good choice is 70 printable characters. This will provide an actual line length of 72 for DOS ascii files (a non-printable carriage return and linefeed are appended to the end of each line by DOS). The MANAGEMENT initialization subroutine (mfinit) attempts to determine the actual line length of the MANAGEMENT input file at run time.
3. All lines that begin with the sharp character, '#', are treated as comment lines and are ignored.
4. All lines that begin with the plus character, '+', are treated as continuation lines.
5. All lines that begin with the star character, '*', are treated as control lines. The MANAGEMENT submodel uses these lines to determine the start and end of the management lists for each subregion. The special control keywords are:
 - a. *STARTThe subregion no. and years of rotation should follow this keyword (separated by white space).
 - b. *ENDThe subregion no. should follow this keyword (separated by white space).
 - c. *EOFMarks the end of the MANAGEMENT input file.
6. All lines that begin with a 'D' character are considered to be a date line. Every date line should have the date of an operation listed in dd/mm/yyyy format following the 'D'. The actual operation class code and the operation class name should follow the date. These may be separated by any amount of white space (space characters) or placed on continuation lines.
7. All lines that begin with an 'O' character are considered to be operation lines. Every operation line should have the operation code and operation name following the 'O' character. Any necessary parameters or inputs required for a specific operation will follow the operation name. These may be separated by any amount of white space or placed on continuation lines.
8. All lines that begin with a 'P' character are considered to be process lines. Every process line should have the process code and process name following the 'P' character. Any necessary parameters or inputs required for a specific process will follow the

process name. These may be separated by any amount of white space or placed on continuation lines.

Subroutine Code Descriptions

Each of the individual MANAGEMENT submodel subroutines are described in this section. The purpose of each routine and the arguments required are provided. If any assumptions, limitations, caveats, etc. relate to the routine, they are also presented.

mfinit Mfinit is called only once, preferably from the MAIN routine. It searches the MANAGEMENT input file, determining the actual record (line) length, marking the START sections of each subregion's management cycle, and initializing the file pointers for each subregion's management cycle to the first operation date.

Arguments: number of subregions and MANAGEMENT input file name.

Caveats: Currently, mfinit does not try to validate that a MANAGEMENT file truly consists of fixed record lengths throughout the file, although it will usually abort if it encounters such a file.

manage Manage is top-level MANAGEMENT submodel routine. It checks the current simulation date with the next management operation date for each subregion. When the dates match, the appropriate subroutine (doclas) is called to initiate simulation of that operation. When all operations for the current date is complete (or if the no operation is to be performed for the subregion), control is returned to the MAIN calling routine.

Arguments: number of subregions, current simulation day, month, and year, and the simulation starting year.

Caveats: Code should be using the generic MANAGEMENT file read routine (getr).

doclas Doclas is the routine that determines the operation class. If any operation class information is necessary, it will obtain that info from the MANAGEMENT file also. It currently prints this information and calls the routine (pr find) to find the specific operation to simulate.

Arguments: subregion number.

Caveats: This routine may possibly be eliminated if enough commonality does not surface in the future among the specific operations within any of the operation classes.

prfind Prfind is the routine that is called to find the next operation or process line in the MANAGEMENT file.

Arguments: subregion number.

Caveats: Poorly named.

dooper Dooper is the routine that determines the actual operation that is to be performed. It extracts any necessary parameters from the MANAGEMENT file for the operation if necessary. It uses any arithmetic if statement to emulate a case or switch statement available in other, more sophisticated languages.

Arguments: subregion number.

Caveats: Need to eventually remove the independent operation code into separate subroutines for each unique operation.

doproc Doproc is the routine that determines the actual process that is to be performed. It extracts any necessary parameters from the MANAGEMENT file for the process if necessary. It uses any arithmetic if statement to emulate a case or switch statement available in other, more sophisticated languages.

Arguments: subregion number.

Caveats: Need to eventually remove the independent process code into separate subroutines for each unique process.

getr Getr is a function that is called to extract desired data from the MANAGEMENT input file in a generic form. It is capable of reading integer, real, or character string values as well as arrays of these variable types. It "understands" the MANAGEMENT input file's format and can extract the desired information regardless of the amount of white space separating the variables. It searches across (continuation) lines, and skips comment lines.

Arguments: integer variable, real variable, character* variable, no. of values (array size), and type of variable.

Return: The function returns the character position of the current line being searched after all values have been extracted for the present call.

Caveats: Alas, it would be nice if FORTRAN 77 had a generic pointer type. However, there may be a cleaner way of returning values than using the same name in the first three arguments of the function call.

tillay Tillay is a function that determines the number of soil layers that are to be tilled. It finds soil layer boundary nearest the specified tillage depth.

Arguments: tillage depth, soil layer thicknesses (array), and the number of soil layers.

Return: The function returns the number of soil layers that will be tilled.

Caveats: If soil layers are defined to coarsely, this approach will not be very accurate. It is desirable to eventually have new soil layers appear at the specified tillage depth.

crush Crush is a routine that performs the crushing or breaking down of soil aggregates into smaller sizes based on the initial aggregate size distribution and two crushing coefficients (alpha and beta). The crushing parameters are assumed to be a function of the soil intrinsic properties, soil water content, and tillage implement.

Arguments: crushing coefficients (alpha and beta), number of soil layers, mass fractions of aggregates within the sieve cuts.

Caveats: Should probably make this routine more "self-contained" and make the calls required to convert from and to the modified log-normal aggregate size distribution parameters or make another routine that does the ASD conversions and makes the call to crush.

asdini Asdini initializes the asd/sieve global variables. This includes the number of sieves and their sizes, the geometric mean diameter of each sieve cut, and the type of log-normal case will be used to represent the aggregate size distributions in the model. Crush, asd2m, and m2asd use these global variables. It is currently called from within the mfini routine.

Arguments: none.

Caveats: Another routine, such as MAIN may be more appropriate for calling this initialization routine.

asd2m Asd2m performs the inverse of subroutine m2asd. Asd2m computes the mass fractions for each sieve cut from the log-normal representation (log-normal type specified by the global variable 'logcas') of the soil aggregate size distribution.

Arguments: minimum and maximum size aggregate, geometric mean diameter and standard deviation of aggregate size distribution (or transformed ASD for "modified log-normal cases"), number of soil layers, and the mass fractions of aggregates within the sieve cuts for each soil layer.

Caveats: None known, yet.

m2asd M2asd performs the inverse of subroutine asd2m. M2asd computes the log-normal representation (log-normal type specified by the global variable 'logcas'), geometric mean and standard deviation, of the soil aggregate size distribution from the mass fractions for each sieve cut.

Arguments: number of soil layers, mass fractions of aggregates within the sieve cuts for each soil layer, minimum and maximum size aggregate, and the geometric mean diameter and standard deviation of aggregate size distribution (or transformed ASD for "modified log-normal cases").

Caveats: Speed savings and more modularity are possible with code changes.

LIST OF SYMBOLS

Symbol	Definition	Unit
f	generic function	dimensionless
a	dummy proportional coefficient	dimensionless
a_t	dummy time coefficient	s^{-1}
Δt	time increment of change	s
X	dummy variable	dimensionless
Cr	fraction of surface consisting of crust	$m^2 m^{-2}$
κ	fraction of surface crust destroyed in tilled region	$m^2 m^{-2}$
ζ	fraction of surface area tilled by operation	$m^2 m^{-2}$
RR	random roughness	mm
λ	tillage intensity factor	dimensionless
p	probability function	dimensionless
P	cumulative distribution function	dimensionless
x	aggregate size	mm
x_g	geometric mean diameter of aggregate size distribution	mm
σ_g	geometric std. deviation of aggregate size distribution	dimensionless
x_0	minimum aggregate size in a distribution	mm
x_∞	maximum aggregate size in a distribution	mm
erf	error function	dimensionless
w[i]	array of aggregate size class mass fractions	dimensionless
P[i,j]	probability transition matrix	dimensionless
p_{ij}	transition probability	dimensionless
p_i	probability function of breakage	dimensionless

Symbol	Definition	Unit
gmd_i	geometric mean diameter of aggregate size class	mm
ρ	soil layer bulk density	Mg m ⁻³
ΔZ	soil layer thickness	mm
μ	mixing coefficient	kg kg ⁻¹
ρ_s	settled bulk density	Mg m ⁻³
Subscripts		
f	final value	
i	index for the soil aggregate size classes	
j	index for the soil aggregate size classes	
k	dummy summation index	
l	index for the soil layers	
m	maximum number of soil layers	
n	maximum number of aggregate size classes	
o	initial value	
Superscripts and other symbols		
Δ	change in symbol value	
/	transformed value of the primed symbol	
\wedge	final value of the capped symbol	

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DRAFT

SOIL SUBMODEL



SOIL SUBMODEL

L.J. Hagen, T.M. Zobeck, E.L. Skidmore, and I. Elminyawi

INTRODUCTION

The SOIL submodel is one of seven major submodels included in a Wind Erosion Prediction System (WEPS). The objective of the SOIL submodel is to simulate the soil temporal properties which control wind erodibility of soil on a daily basis in response to various driving processes. On days when wind erosion or management activities occur, the EROSION and MANAGEMENT submodels also may update some of the same soil temporal variables.

The spatial domain affected by the SOIL submodel consists of subregions with boundaries that are specified by the user. Each subregion is assumed to be homogeneous in the horizontal direction. In the vertical direction, two uppermost layers are specified to be always present in the submodel. The first layer is 10 mm thick and the second layer is 40 mm thick. The SOIL submodel updates the relevant temporal variables in a series of selected layers in the tillage zone and simulates effects of both aggregation and deaggregation processes. Soil layers below the tillage zone are believed to change very slowly and, at present, are not updated from their initial conditions as input by the user. During each day, the SOIL submodel updates the temporal soil variables in each portion of the simulation region, dubbed a subregion, except in those subregions specified as sinks, ie., traps.

Symbols, definitions, and units used in this technical description are defined in the text and at the end of the chapter. The development of the SOIL submodel represents a new area in wind erosion research. In general, the variation in the temporal variables which control soil wind erodibility has not been widely investigated, so additional experimental research is ongoing for many of the topics addressed in this technical description. Updates and maintenance to this submodel will be necessary as new and more reliable data become available.

SOIL SUBMODEL COMPUTATION SCHEME

Table S-1 presents a matrix of the temporal soil variables that are updated by SOIL and the driving processes that are currently considered in updating the temporal variables. Note the furrow irrigation and biological "glue" processes are not yet simulated.

In selecting a computation scheme, we consider several characteristics of the problem. First, the temporal variable to be updated is generally a function of more than one driving process as well as intrinsic soil properties. Unfortunately, temporal properties at a point in time are often the result of a combination of prior processes, and thus, difficult to interpret. However, researchers generally try to sort the field data and conduct laboratory experiments, in order to determine the relationship between individual driving processes and a selected temporal soil variable.

A simple, typical case is illustrated in Fig S-1., where the individual effects of cumulative precipitation and wind erosion on ridge height degradation are known. In the field, however, the precipitation and wind erosion driving processes may occur in an almost infinite combination of sequences. An example is illustrated by the arrow sequence of Fig S-1. Thus, the computation scheme must be able to accommodate the relationships which have been developed and combine them in a variety of sequences.

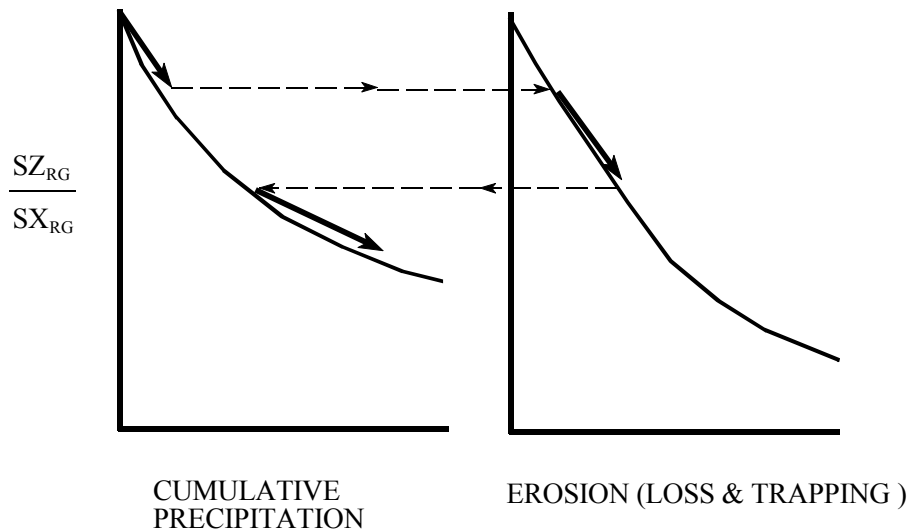


Figure S-1. Typical example of temporal variable, (ie., ratio of ridge height to ridge spacing) affected by two processes.

Because a flexible simulation scheme is needed, the general approach selected for the submodel is illustrated in the following section.

It is assumed that an explicit relationship [S-1] is known from field data or other experiments.

$$Y = f(X_j) \quad (1)$$

where

- Y = a dependent soil temporal variable, and
- X_j = an independent driving processes variable which changes Y.

Now, in principle, one can express X_j in terms of Y, i.e.,

$$X_j = F(Y) \quad (2)$$

Equation [S-2] often can be derived from [S-1] algebraically. However, some solutions may not be analytic, so numerical values for X_j must be obtained using an iteration scheme. Further, note that [S-2] should be single-valued. In the event that a process is not single valued in Y , i.e., causes both aggregation and deaggregation under different conditions, it is useful to separate the effects into separate aggregation and deaggregation equations and calculate the effects successively.

Because the dependent Y variable can be changed by several processes, updating the Y on a daily basis requires two steps. First, an "equivalent" value for the independent variable must be calculated, i.e.,

$$X_{i,j} = F(Y_i) \quad (3)$$

where,

$X_{i,j}$ = the current "equivalent" value which the j th process would have, if it alone had caused the current value of the dependent variable Y_i ; I refers to the day.

The second step is then to update the dependent variable using the equation

$$Y_{i+1} = f(X_{i,j} + \Delta X_j) \quad (4)$$

where,

ΔX_j = the daily increment of the j th driving force.

PROCESS EFFECTS ON SOIL TEMPORAL PROPERTIES

RIDGE AND FURROW DIKE HEIGHT

As a starting point, an empirical equation developed by Lyles and Tatarko (1987) from field measurements was approximated, along with two empirical coefficients, as

$$\frac{SZ_{rg}}{SZ_{rgo}} = 1 - 0.055(CUMP)^{0.5}(CF1_{rg}CF2_{cov}) \quad (5)$$

where

CUMP = cumulative depth of snowmelt, rainfall and sprinkler irrigation water in mm,
 SZ_{rg} = current ridge height (mm),

SZ_{rgo} = initial ridge height after tillage (mm),
 $CF1_{rg}$ = correction factor for ridge scale, and
 $CF2_{cov}$ = correction factor for biomass cover.

Ridges with various height/spacing ratios respond differently to precipitation. The ridges used to derive the response to precipitation in equation [S-5] ranged from 30 to 100 mm in height. Thus, the effect of scale for large ridges, such as lister ridges, was missing. An empirical correction factor for ridge scale was developed. Typical initial ridges (Lyles and Tatarko, 1987) had the relation

$$X_{rg} = 4.17 SZ_{rg} \quad (6)$$

where

X_{rg} = ridge spacing (mm).

From geometric calculations, one can show that volume of soil which must be eroded to reach new height/spacing ratios is directly proportional to ridge height. The correction factor for ridge scale was estimated as

$$CF1_{rg} = \left(\frac{348}{X_{rg}}\right)^{0.3} \quad (7)$$

The correction factor for biomass cover sheltering the soil surface is estimated as

$$CF2 = 1 - 0.4 BF_{cov} \quad (8)$$

where

BF_{cov} = fraction of growing plant and residue biomass cover.

Equation [S-5] can be solved for the independent variable as follows:

$$CUMP = \left[\frac{(1 - SZ_{rg} / SZ_{rgo})}{0.055 CF1_{rg} CF2_{cov}} \right]^2 \quad (9)$$

Eq. [S-5] and [S-9] correspond to equations [S-4] and [S-3], respectively.

RANDOM ROUGHNESS

Reduction in random roughness height is predicted for bare soil (Potter, 1990; Zobeck and Onstad, 1987), but equation [S-10] also includes the empirical cover factor

$$\frac{SZ_{rr}}{SZ_{rro}} = \exp \left[- \left(\frac{CF2_{cov} CUMP}{A_{cr}} \right)^{C_{cr}} \right] \quad (10)$$

where

SZ_{rr}, SZ_{rro} = current and initial (after tillage) random roughness, respectively, using Allmaras' et al. (1966) definition (mm),
 A_{rr}, C_{rr} = regression coefficients.

$$A_{rr} = 91.08 + 765.8 SF_{sil} \quad (11)$$

$$C_{rr} = 0.53 + 4.66 SF_{san} - 3.8 SF_{san}^{1.5} - 1.22 SF_{san}^{0.5} \quad (12)$$

where

SF_{san} = soil fraction sand in first layer (kg/kg), and
 SF_{sil} = soil fraction silt in first layer (kg/kg).

Rearranging the random roughness equation gives:

$$CUMP = - \frac{A}{CF2_{cov}} \left[\ln \left(\frac{SZ_{rr}}{SZ_{rro}} \right) \right]^{\frac{1}{C_{cr}}} \quad (13)$$

CRUST

The term 'crust' in WEPS refers to the near-surface consolidated zone which occurs after the addition of water to the surface or the puddling of surface soil when super-saturated. The equations which govern the changes in crust properties from addition of water will be presented in this section, and equations for the puddling effect will be included later in the layer process section.

CRUST THICKNESS

The basic structure for simulation of crust thickness is based on that reported by Farres (1978) and data of Zobeck (personal communication). The initial surface condition is aggregated, and the crust thickness grows toward limits imposed by intrinsic soil properties. An estimate of the crust thickness by water additions is

$$SZ_{cr} = A_{cr} CUMP + B_{cr} CUMP^{0.5}, \quad CUMP < 200 \text{ mm} \quad (14)$$

where

SZ_{cr} = crust thickness (mm), and
 A_{cr} , B_{cr} = empirical coefficients.

$$A_{cr} = -0.072 + 0.2 SF_{cla} \quad (15)$$

$$B_{cr} = 1.56 - 2.9 SF_{cla} \quad (16)$$

CRUST COVER FRACTION

The surface crust cover fraction after rainfall was developed from a 3-year study at Big Spring, Texas (Zobeck and Popham, 1992).

$$SF_{cr} = 0.36 + 0.0024 CUMP, \quad CUMP > 10 \text{ mm} \quad (17)$$

where

SF_{cr} = soil fraction crust cover,
 $CUMP$ = cumulative snowmelt, sprinkler irrigation, and rainfall (mm).

CRUST STABILITY

Current data on crust stability show it may be less or close to that of the parent surface aggregates. Measured abrasion resistance on simulated crusts (Zobeck, 1991) found abrasion rates similar to that predicted for aggregates. Hence, crust stability will be estimated as

$$SE_{cr} = SE_{ag} \quad (18)$$

where

SE_{ag} = aggregate stability, $\ln(\text{J/kg})$ of crushing energy, and
 SE_{cr} = crust stability, $\ln(\text{J/kg})$ of crushing energy.

LOOSE ERODIBLE MATERIAL ON CRUST

The loose erodible material is defined as the single grains and water stable aggregates which occur on crusted surfaces after rainfall or sprinkler irrigation. Loose material on the crust was sampled using a vacuum system (Zobeck, 1989). Simulated crusts using two rainfall intensities on 13 mineral soils were tested (Zobeck and Popham, 1992). A prediction equation for maximum loose mass is:

$$SMX_{los} = 0.1 \exp[-0.57 + 0.22 \frac{SF_{san}}{SF_{cla}} + 7.0 SF_{cce} - SF_{om}] \quad (19)$$

where

$$\begin{aligned} SF_{cce} &= \text{soil fraction calcium carbonate equivalent (kg/kg),} \\ SF_{om} &= \text{soil fraction organic matter (kg/kg), and} \\ SMX_{los} &= \text{maximum loose erodible material on crust (kg/m}^2\text{).} \end{aligned}$$

Equation [S-19] is valid only when cumulative rainfall and sprinkler irrigation (CUMSR) exceed 10 mm.

As precipitation accumulates the loose material mass slowly decreases as (Zobeck and Popham, 1992; Potter, 1990)

$$\begin{aligned} SM_{los} &= SMX_{los}(1 - 0.005 \text{ CUMSR}), \\ &10 < \text{CUMSR} < 180 \text{ mm} \end{aligned} \quad (20)$$

where

$$\begin{aligned} SM_{los} &= \text{loose mass on surface crust (kg/m}^2\text{), and} \\ \text{CUMSR} &= \text{cumulative sprinkler irrigation and rainfall (mm).} \end{aligned}$$

An estimating equation for the maximum, loose cover is (Zobeck and Popham, 1992)

$$SFX_{los} = 0.14 + 0.001 \text{ CUMSR}, \quad \text{CUMSR} > 10\text{mm} \quad (21)$$

where

$$SFX_{los} = \text{maximum loose soil cover on crust.}$$

A process which acts to consolidate loose material is snowmelt. Snow does not melt uniformly over the field, so about 10 mm of melt may be required to fully consolidate the loose material. An approximation for this process is:

$$\frac{SM_{los}}{SMAX_{los}} = \text{EXP}\left(\frac{-HG_{snom}}{k3_{los}}\right) \quad (22)$$

where

$$\begin{aligned} HG_{snom} &= \text{snowmelt, and} \\ k3_{los} &= \text{a coefficient, approximate value 5.} \end{aligned}$$

Loose soil fraction is decreased linearly with loose soil mass as:

$$SF_{\text{los}} = SF X_{\text{los}} \frac{SM_{\text{los}}}{SMX_{\text{los}}} \quad (23)$$

DRY AGGREGATE STABILITY

Experimental results show abrasion coefficients are linearly related to natural log of dry aggregate crushing energy (Hagen, Skidmore, and Saleh, 1992). Because it is practical to measure from small field samples, the Ln of crushing energy will be used as the measure of dry aggregate stability in WEPS. From sampling 10 soils periodically over 3 years (Skidmore and Layton, 1992), the mean aggregate stability was:

$$(SE_{\text{ag}})_{\text{mean}} = 0.83 + 15.7 SF_{\text{cla}} - 23.8 SF_{\text{cla}}^2 \quad (24)$$

where

$$(SE_{\text{ag}})_{\text{mean}} = \text{mean of natural log aggregate crushing energies, Ln(J/kg)}.$$

The mean coefficient of variation (CV) averaged over all soils was 0.16.

Several processes affect the aggregate stability including freeze/thaw, freeze/dry, wet/dry, overburden pressure, and biological (glue). Moreover, these processes may cause increases or decreases in stability depending upon soil and process conditions. We describe an approximate method to estimate dry aggregate stability. First, determine a maximum and a minimum aggregate stability for each soil as follows:

$$SEMAX_{\text{ag}} = (SE_{\text{ag}})_{\text{mean}} + 2 * 0.16 * (SE_{\text{ag}})_{\text{mean}} \quad (25)$$

$$SEMIN_{\text{ag}} = (SE_{\text{ag}})_{\text{mean}} - 2 * 0.16 * (SE_{\text{ag}})_{\text{mean}} \quad (26)$$

Next, we model the decrease in stability using a simple exponential function:

$$\frac{(SE_{\text{ag}} - SEMIN_{\text{ag}})}{(SEMAX_{\text{ag}} - SEMIN_{\text{ag}})} = \text{EXP} \left(\frac{-N_{\text{cj}}}{K4_{\text{j}}} \right) \quad (27)$$

where

$$\begin{aligned} N_{\text{cj}} &= \text{the number of 'cycles' of the jth process, and} \\ K4_{\text{j}} &= \text{a coefficient reflecting the important variables of the jth process.} \end{aligned}$$

To calculate the corresponding number of "cycles" of a certain process knowing the present aggregate stability we use,

$$N_{cj} = -K_{4j} * \text{Ln} \left(\frac{SE_{ag} - SEMIN_{ag}}{SEMAX_{ag} - SEMIN_{ag}} \right) \quad (28)$$

For simulation under field conditions, one must also assign the effects of a 'cycle' for each process. For freeze/thaw process/cycle, the decrease in stability likely manifests itself upon thawing. Hence, it seems appropriate to assign the effects on stability of a freeze/thaw cycle when the daily soil state moves from frozen to thawed. In the case of freeze/dry, any daily decrease in moisture content of a frozen soil will be termed a 'cycle'. In the case of wet/dry, the decrease in stability seems to occur upon wetting. Hence, for wet/dry, any daily increase in layer water content will be termed a 'cycle'. At this point overburden pressure will not be considered a separate process, but one of the variables, like water content, which affects the response magnitude of a 'cycle'.

From lab and field data, one needs to determine values for K_{4j} .

For freeze/thaw at the surface (and possibly for all tilled layers) Layton (unpublished) found for 2 soils ($R^2=0.66$)

$$K_{4ft} = \frac{1}{0.0346 W - 0.0417} \quad (29)$$

and

$K_{4ft}=100$ when W is less than 1.5,

where

W = ratio of moisture content at freezing to -1500 kPa moisture content.

For the wet/dry process where the process causes aggregation below about 30 mm, one should add a damping term to the K_{4j} to negate the effect below the surface layer. For example, an estimate is:

$$K_{4wd} = 2 \frac{HR_{awc}}{HR_{wc} - HR_{wp}} + 4F_{clay} + \left(\frac{SZ_{mpt}}{5} \right)^{3.6} \quad (30)$$

where

SZ_{mpt} = depth to midpoint of soil layer (mm),
 HR_{awc} = available soil water content on a mass basis (kg/kg),
 HR_{wc} = soil water content on a mass basis (kg/kg), and
 HR_{wp} = wilting point (kg/kg).

A crude estimate for the freeze/dry process is:

$$K4_{fd} = \frac{HR_{awc}}{HR_{wc} - HR_{wp}} \quad (31)$$

Some processes increase aggregate stability. For example, with super-saturation, the structure may collapse and then reform with increased aggregate stability. Below the surface, pressure often combined with wet/dry cycles increases aggregate stability. These processes can be treated as the mathematical compliment to the deaggregation processes:

$$\frac{SE_{ag} - SEMIN_{ag}}{SEMAX_{ag} - SEMIN_{AG}} = 1 - \text{EXP}\left(\frac{-N_c}{K5_{wd}}\right) \quad (32)$$

and, if needed, one can obtain the number of wet/dry cycles corresponding to a certain SE_{ag} from:

$$N_c = -K5_{wd} \text{Ln} \left[\frac{SEMAX_{ag} - SE_{ag}}{SEMAX_{ag} - SEMIN_{ag}} \right] \quad (33)$$

for HR_{wc} greater than HR_{awc}

$$K5_{wd} = \frac{HR_{awc}}{HR_{wc} - HR_{wp}} \quad (34)$$

and for $(HR_{wc} - HR_{wp})$ less than HR_{awc} ,

$$K5_{wd} = \frac{HR_{awc}}{HR_{wc} - HR_{wp}} + \frac{(\text{midpoint depth of bottom layer})}{SZ_{mpt}} \quad (35)$$

For decreasing HR_{wc} , assume no change in SE_{ag} .

AGGREGATE SIZE DISTRIBUTION - ASD

Among the variables in the soil submodel, ASD is one of the most important. It is important, because it has strong influence on predictions of erosion (as in WEQ), and it varies widely in response to various processes. In addition to updating surface ASD, the SOIL submodel must also update ASD in all other soil layers in the tillage zone. It is important that the SOIL submodel include aggregation processes which increase ASD in the tillage zone. Otherwise, after few iterations the deaggregation processes in the SOIL and MANAGEMENT submodels only return a minimum value of ASD to the EROSION submodel.

The aggregate size distribution of field soils in the most general case fits an abnormal log-normal distribution, which is defined by four parameters - a geometric mean diameter (SL_{agm}) and geometric standard deviation (SO_{ags}), coupled with upper (SL_{agx}) and lower (SL_{agn}) limit parameters. The upper limit is also updated by the MANAGEMENT submodel. The lower limit is about 0.015 mm, and will vary slightly as a function of soil intrinsic properties. The SOIL submodel must update the SL_{agm} , SO_{ags} , and SL_{agx} in response to the driving forces.

Similar to our model for aggregate stability, the deaggregation processes affecting aggregate size distribution are simulated as follows:

$$SL_{agm} = (SL_{agmo} - GMDMIN) * \exp\left(\frac{-N_c}{K_6}\right) + GMDMIN \quad (36)$$

The factor K_6 is different for different processes and layers, e.g. rainfall and sprinkler irrigation affect only the first layer, and for that (partly from Zobeck notes, Oct. 1991):

$$K_6 = \left[\frac{SL_{agmo} - GMDMIN}{0.004(SD_{bk})(SL_{agmo})} + 50 SF_{cla} \left[\frac{1}{1.01 - BF_{cov}} \right] \right] \quad (37)$$

where

N_c	=	amount of rainfall and sprinkler irrigation when dealing with the top layer and it means the number of cycles for a process when we deal with all layers,
SL_{agmo}	=	geometric mean diameter after last tillage (mm),
SD_{bk}	=	soil bulk density (Mg/m^3),
$GMDMIN$	=	minimum GMD, about 1.5 mm for rainfall, and
BF_{cov}	=	biomass fraction of cover

Wet/dry, freeze/thaw and freeze/dry affect ASD in all layers. The corresponding factors to these cycles are:

$$K_{6_{wd}} = \left[20 + 50 F_{clay} + \left(\frac{SZ_{mpt}}{5} \right)^{3.6} \right] \frac{HR_{awc}}{HR_{wc} - HR_{wp}} \quad (38)$$

$$K_{6_{ft}} = \left[20 + 50 SF_{cla} \right] \frac{HR_{awc}}{HR_{wc} - HR_{wp}} \quad (39)$$

For a freeze/dry process for any layer:

$$K6_{fd} = [2 + 5 SF_{cla}] \frac{HR_{awc}}{(HR_{wc} - HR_{wp})} \quad (40)$$

The companion equation to (S-35) is given by

$$N_C = -K6 \ln \left(\frac{SL_{agm} - GMDMIN}{SL_{agmo} - GMDMIN} \right) \quad (41)$$

For aggregation caused by a wet/dry process

$$SL_{agm} = SL_{agxo} \left[1 - \exp \left(\frac{-N_c}{K7_{wd}} \right) \right] \quad (42)$$

$$N_C = -K7_{wd} \ln \left(1 - \frac{SL_{agm}}{SL_{agxo}} \right) \quad (43)$$

$$K7_{wd} = \frac{HR_{awc}}{HR_{wc} - HR_{wp}} + \frac{\text{midpoint depth of bottom layer}}{SZ_{mpt}} \quad (44)$$

where

SL_{agxo} = maximum diameter after last tillage (mm).

at present, the $S0_{ags}$ will be linked to SL_{agm} as

$$S0_{ags} = \left(\frac{SL_{agm}}{0.3} \right)^{0.73} \quad (45)$$

Finally, SL_{agx} also will be linked to SL_{agm} as

$$SL_{agx} = SL_{agm} \frac{SL_{agxo}}{SL_{agmo}} \quad (46)$$

where

SL_{agmo} = geometric mean diameter after last tillage (mm).

BULK DENSITY

In the SOIL submodel, the 'settled' bulk density in any layer of mineral soil will be estimated at a 300 mm. depth, and below, using the intrinsic properties of the soil layer as inputs to Rawls' (1983) prediction diagram.

In layers above the 300 mm. depth, the settled bulk density will be modified by the following equation:

$$SD_{bk} = SD_{bko}(0.72 + 0.00092SZ_{mpt}) \quad (47)$$

where

$$\begin{aligned} SD_{bk} &= \text{settled bulk density of layer (Mg/m}^3\text{),} \\ SD_{bko} &= \text{settled bulk density at 300 mm. depth based on sand, clay, and organic} \\ &\quad \text{matter for the current layer (Mg/m}^3\text{), and} \\ SZ_{mpt} &= \text{depth to soil layer midpoint (mm).} \end{aligned}$$

There are two further modifications to bulk density: First, if layer bulk density is greater than SD_{bk} , perhaps caused by tillage or other initial conditions, the layer bulk density will remain unchanged in SOIL (this step may be modified at a later time as we learn more about effects of processes on bulk density). Second, if layer bulk density is less than SD_{bk} , then it is assumed that the layer will approach SD_{bk} as a result of wetting. An approximation is

$$\frac{SD_{bki} - SD_{mn}}{SD_{li} - SD_{mn}} = 1 - \exp \left(- \frac{\left(\frac{HR_{wc}}{HR_{awc}} \right)}{K8_{li}} \right) \quad (48)$$

then, for increasing HR_{wc} , the reverse equation to equation (S-47) is

$$(HRWC - HRWP) = -HRAWC * K8_{bk} \text{Ln} \left(1 - \frac{SK_{bki} - SD_{mn}}{SD_{6k} - SD_{mn}} \right) \quad (49)$$

where the subscript I refers to the ith layer.

For decreasing HR_{wc} , let the change in settled bulk density = 0.

Where

$$\begin{aligned} &HR_{wc} \text{ and } HR_{awc} \text{ were defined earlier,} \\ SD_{bki} &= \text{current bulk density for the soil (Mg/m}^3\text{),} \\ SD_{mn} &= \text{minimum soil bulk density (Mg/m}^3\text{),} \end{aligned}$$

$K8_{bk}$ = a coefficient, approximate value 0.6,
and

$$SD_{bk} - SD_{mn} = 0.6 \quad (50)$$

CRUST AND AGGREGATE DENSITY

Based on data of Skidmore and Layton (unpublished),

$$SD_{ag} = SD_{bko} \quad (51)$$

where

SD_{ag} = Soil aggregate density (Mg/m^3).

As suggested by Zobeck (October 1991), the following equation will be used for crust density:

$$SD_{cr} = 0.576 + 0.603 SD_{bko}. \quad (52)$$

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LIST OF SYMBOLS, DEFINITIONS, AND UNITS

SYMBOL	DESCRIPTION	UNIT
A_{cr}, B_{cr}	regression coefficients	---
A_{rr}, C_{rr}	regression coefficients	---
BF_{cov}	fraction of growing plant and residue biomass cover	m^2/m^2
BF_{cov}	biomass fraction of cover	---
$CF2_{cov}$	correction factor for biomass cover	---
$CR1_{rg}$	correction factor for ridge scale	---
CUMP	cumulative depth of snowmelt, rainfall and sprinkler irrigation water	mm
CUMSR	cumulative sprinkler irrigation and rainfall	mm
GMDMIN	minimum GMD, about 1.5 mm for rainfall	---
HG_{snom}	snowmelt	mm
HR_{awc}	available soil water content	kg/kg
HR_{wc}	soil water content	kg/kg
HR_{wp}	soil water content at -1500 kPa	kg/kg
$K4_j$	coefficient reflecting the important variables of the jth process	---
$K8_{bk}$	coefficient, approximate value 0.6	---
KG_{los}	a coefficient, approximate value 5	---
N_c	amount of rainfall and sprinkler irrigation when dealing with the top layer and it means the number of cycles	mm
N_{cj}	number of 'cycles' of the jth process	---
SD_{ag}	soil aggregate density	Mg/m^3
SD_{bk}	settled bulk density of layer	Mg/m^3
SD_{bk}	soil bulk density	Mg/m^3

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SD_{bki}	current bulk density for the soil	Mg/m ³
SD_{bko}	settled bulk density at 300 mm, depth based on sand, clay, and organic matter for the current layer	---
SD_{mn}	minimum soil bulk density	Mg/m ³
SE_{ag}	aggregate stability crushing energy	ln(J/kg)
SE_{cr}	crust stability crushing energy	ln(J/kg)
$(SE_{ag})_{mean}$	mean of natural log aggregate crushing energies	ln(J/kg)
SF_{cce}	soil fraction calcium carbonate equivalent	kg/kg
SF_{cla}	soil fraction clay in first layer	kg/kg
SF_{cr}	soil fraction crust cover	m ² /m ²
SF_{om}	soil fraction organic matter	kg/kg
SF_{san}	soil fraction sand in first layer	kg/kg
SF_{sil}	soil fraction silt in first layer	kg/kg
SFX_{los}	maximum loose soil cover on crust	m ² /m ²
SL_{agmo}	geometric mean diameter after last tillage	mm
SL_{agxo}	maximum diameter after last tillage	mm
SM_{los}	loose, erodible mass on surface crust	kg/m ²
SMX_{los}	maximum loose, erodible mass on crust	kg/m ²
SZ_{cr}	crust thickness	mm
SZ_{mpt}	depth to soil layer midpoint	mm
SZ_{rg}	current ridge height	mm
SZ_{rgo}	initial ridge height after tillage	mm
SZ_{rr}, SZ_{rro}	current and initial (after tillage) random roughness	mm
W	ratio of moisture content at freezing to -1500 kPa moisture content	kg/kg
ΔX_j	increment of the jth driving force	---

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SOIL SUBMODEL

WEPS

X_j	an independent driving variable of the jth process	---
X_{i_j}	current value of the jth process variable	---
X_{rg}	ridge spacing	mm
Y	a dependent soil temporal variable	---

Table S-1. Soil Submodel State Variable and Process Matrix.

Soil Temporal Variables	Surface Processes			Layer Processes			
	Rain Sprinkler Irrigation	Furrow Irrigation	Snow Melt	Wet/Dry	Freeze/Thaw	Freeze/Dry	Glue
Roughness:							
Ridge Height	X		X				
Dike Height	X		X				
Random	X		X				
Crust:							
Depth	X		X				
Cover Fraction	X		X				
Density	X		X				
Stability	X		X	X	X	X	
Loose Mass	X		X				
Loose Cover	X		X				
Aggregate:							
Size Distribution	X		X	X	X	X	
Stability	X		X	X	X	X	
Density	X		X				
Bulk Density	X		X				

CROP SUBMODEL



CROP SUBMODEL

A. Retta and D. V. Armbrust

ABSTRACT

A crop growth submodel (dubbed CROP) was developed for the wind erosion prediction system (WEPS). The model calculates daily production of masses of roots, leaves, stems, and reproductive organs and of leaf and stem areas. Crop growth variables can be adjusted for suboptimal temperature conditions or lack of adequate supplies of water and nutrients to meet crop needs. The model was tested on data from several crops. Agreement between measured and simulated values was good, with r^2 values ranging from 0.72 to 0.87, with slopes close to 1, and intercepts close to 0, indicating that the model reasonably simulates crop biomass and leaf and stem area growth.

INTRODUCTION

The crop growth model (CROP) is one of the submodels in the Wind Erosion Prediction System (WEPS). The presence of live biomass on the soil surface influences the quantity of soil that can be removed by wind erosion. Biomass growth needs to be estimated throughout the growing season to account for live biomass cover. At harvest, an estimate of the amount of dead biomass remaining on the cropped surface is required for use by the DECOMPOSITION and other submodels of WEPS.

CROP was adapted from the Erosion Productivity Impact Calculator (EPIC) crop growth model (Williams et. al., 1989). EPIC simulates growth of many types of crops and other plant communities and has been validated for many different crops at locations around the world. Additional capabilities and modifications have been developed and incorporated into CROP to meet the need for predicting effects of a growing crop on wind erosion. Some of the factors that affect wind erosion are the flexibility and arrangement of individual plant parts, distribution of plant parts by height, and number of plants per unit area (Shaw and Periera, 1982). Leaves and stems have to be accounted for separately for several reasons. (1) on a per-unit-area basis, stems of young seedlings are roughly 10 times more effective than leaves in

depleting wind energy, with the effectiveness of leaves increasing with crop growth (Hagen, 1991; Armbrust and Bilbro, personal communication). (2) Leaves are more sensitive to sandblast damage than are stems. (3) Leaves and stems decompose at different rates. Thus, one of the requirements of the CROP submodel is to give daily estimates of leaf and stem growth. In EPIC, leaf area index (LAI) is calculated directly, and no adjustments are made for differences in plant populations. The CROP submodel calculates leaf area per plant, and, thus, differences in plant cover resulting from differences in the number of live seedlings and the effects on wind erosion can be properly evaluated.

Harvesting of grain crops removes the grain and returns the nongrain portion of the reproductive mass to the soil surface. In order to maintain an accurate mass balance, an estimate of the biomass (other than leaves and stems) that is left on the soil surface is needed. The CROP submodel is designed to estimate daily biomass production; partition biomass into root, leaf, stem, and reproductive parts; obtain estimates of leaf and stem area growth; and, at physiological maturity, calculate economic (grain or other yield) and noneconomic (chaff) parts. The objective of this technical paper is to give a brief description of the methods and approaches used in the CROP submodel to calculate crop-plant state variables. Where a method of calculation different than that in EPIC was used, the reason for doing so is discussed briefly.

MODEL DESCRIPTION:

Crop Parameters:

Crop parameters are critical parts of the CROP submodel and are considered to be constant for a given crop. Many of the crop parameters were taken from EPIC (Williams et al., 1990b). Parameters for calculating leaf and stem areas and for partitioning aboveground biomass into leaf, stem, and reproductive masses were developed for soybean, corn, grainsorghum, winter wheat, oats, and rice (Retta and Armbrust, 1995; Retta et al., 1995). Specific leaf area values for several crops are from van Keulen (1986). For crops for which measured parameters were lacking, default values were assigned and will be replaced as soon as measured data are available.

The crop parameter data file also contains stress- and nutrient-related parameters from the EPIC crop data file, several of which are given as composite numbers, such as the 's-curve' frost damage parameter value for corn of 5.01, which were replaced by the two separate parameters; -5.0 °C for the temperature and 0.01 as the stress factor.

Phenological development

Phenological development of the crop is based on growing-degree-day (GDD) accumulation. The crop parameter file for CROP contains, for each crop, the potential GDDs from planting to physiological maturity and the relative GDDs from planting to emergence, to the start of the reproductive phase, and to the start of leaf senescence. CROP uses the same procedures as EPIC for simulating annual or perennial plants, and winter or summer crops. Annual plants 'grow' from planting to the date when the accumulated GDDs equal the potential GDDs for the crop. For annual winter crops, such as wheat, GDD accumulation (therefore growth) does not occur during the period of dormancy. Perennial crops maintain their root systems throughout the year, although the plant may become dormant after a frost. After the end of dormancy, plants start growing when the average daily air temperature exceeds the base temperature of the plant. For established alfalfa, a value of the average GDD between consecutive cuts is needed. Procedures described in the ALMANAC model (Kiniry, et al., 1992) for simulating concurrent growth of two plant species (forage mixtures, range grass mixtures, weeds and crops, etc.) or removal of live biomass by grazing have not been incorporated into CROP at this time.

Relative growing degree days (GDD_r) is calculated daily using equation [1] and compared to the input values in the crop parameter file. A phenological event is reached when the calculated value of GDD_r reaches or exceeds the required GDD_r .

$$GDD_r = \frac{\sum_{i=1}^k \left(\frac{T_{\max} + T_{\min}}{2} - T_{\text{bas}} \right)}{GDD_p} \quad [C-1]$$

where:

T_{\max} = daily maximum temperature (°C),

T_{\min} = daily minimum temperature (°C),

T_{bas} = base temperature (°C),

GDD_r = relative GDD (ratio of cumulated GDDs at any time to the total GDDs at physiological maturity),

GDD_p = total GDDs from planting to physiological maturity.

k = number of days after planting

Note: GDD is accumulated if $(T_{\max} + T_{\min})/2 \geq T_{\text{bas}}$.

Day length

Dormancy for fall-planted crops such as winter wheat or perennial crops such as alfalfa is a function of daylength. Winter dormancy occurs during the period when the daylength is less than one hr greater than the minimum daylength for the location. Accumulation of GDD (and therefore growth) does not occur during the winter dormancy period. Daylength is calculated as follows:

$$SD = 0.4102 \sin\left(\frac{2\pi}{365}\right)(JD - 80.25) \quad [C-2]$$

$$HRLT = 7.64 \cos^{-1}\left[-\tan\left(\frac{2\pi XLAT}{365}\right) \tan(SD)\right] \quad [C-3]$$

Where:

XLAT = latitude of location (degrees, negative for southern hemisphere),

HRLT = daylength (hr),

$\pi = 3.14159$,

SD = the sun's declination angle (rad.),

JD = day of year since January 1.

Emergence

Emergence occurs when the GDD accumulation from date of planting equals 6% of the seasonal GDD. CROP does not account for effects of soil temperature, soil water, soil crusting, soil strength, seeding depth, soil removal or deposition caused by wind erosion, which can influence germination, seedling emergence, survival, and growth.

Biomass production

Shortwave radiation at the top of the canopy is multiplied by the factor C to estimate the amount of photosynthetically active radiation (PAR). Intercepted PAR is calculated using the exponential function (Beer's law) for distribution of light within a canopy. The potential biomass produced daily is calculated by multiplying the intercepted light by the radiation use efficiency factor (BE). These relationships are shown in equation [C-4]. A value of 0.65 for the extinction coefficient is used in EPIC for all crops. In CROP, the extinction coefficient is crop dependent.

$$PDDM = 0.001 (C) (RA) (BE) [1 - \exp(-K_c * LAI)] \quad [C-4]$$

where,

PDDM = potential daily biomass production (t/ha),

BE = radiation use efficiency (kg/MJ),
 RA = solar radiation (MJ/m²),
 C = fraction of shortwave solar irradiance that is photosynthetically active (C=0.5),
 K_c = radiation extinction coefficient,
 LAI = leaf area index.

The radiation use efficiency factor (BE) is adjusted for elevated CO₂ levels or high vapor pressure deficits using the same algorithm given in EPIC and described by Stockle et al. (1992a).

Partitioning of biomass

Daily produced biomass is partitioned to roots and aboveground plant parts. The root mass partitioning ratio (P_{rt}) is calculated using equation [C-5]. Equation [C-5] was taken from EPIC.

$$P_{rt} = 0.4 - 0.2 * GDD_r \quad (5)$$

Where:

P_{rt} = root mass partitioning ratio.

New root mass is calculated as a product of daily converted biomass and P_{rt}. The balance is aboveground biomass, which is subdivided further into leaf, stem, and reproductive masses. The leaf mass partitioning is calculated using equation [C-6]. The reproductive mass partitioning fraction also is calculated using equation [C-6] by replacing the leaf parameters (A_{lf}, B_{lf}, C_{lf}, D_{lf}) with reproductive parameters. The stem partitioning ratio is obtained by subtraction, because, by definition, the sum of leaf, stem, and reproductive partitioning ratios must equal 1.0. Before the onset of the reproductive phase, aboveground biomass is partitioned only to leaf and stem masses. After about 80% (depending on the crop) of the season has elapsed, no biomass is allocated to leaves and stems.

$$P_{lf} = A_{lf} + \frac{B_{lf}}{\left[1 + \text{EXP} \left(\frac{-(GDD_r - C_{lf})}{D_{lf}} \right) \right]} \quad (6)$$

where:

P_{lf} = leaf mass partitioning ratio,
 A_{lf}, B_{lf}, C_{lf}, D_{lf} are leaf partitioning parameters.

At physiological maturity, economic yield is calculated using relationship [7]. The non-economic (chaff) part left on the soil surface is estimated by subtracting the economic yield from the total reproductive mass. However, if growing conditions during the latter part of the growing season are poor, calculated economic yields could exceed total reproductive mass resulting in negative value for chaff. Under these conditions the reproductive mass is assumed to be the economic yield, and therefore chaff will have a value of zero.

$$YLD = (HI) (DMAG) \quad (7)$$

where:

YLD = economic yield (t/ha),

HI = harvest index,

DMAG = aboveground biomass (t/ha).

Leaf and stem area growth

Leaf area per plant is calculated as a product of leaf mass and the specific leaf area (SLA) of the crop. Leaf area index (LAI) then is computed as shown in equation [C-8]. Stem area index (SAI) is calculated in the same way as LAI. Although the leaf area and leaf weight relationship is linear for most crops, the stem area and stem weight relationship is linear for some crops but nonlinear for other crops (Retta and Armbrust, 1995).

$$LAI = \frac{(BM_{lf}) (SLA)}{PAREA} \quad (8)$$

where:

LAI = leaf area index,

BM_{lf} = leaf mass (kg/plant),

SLA = specific leaf area (m^2/kg),

PAREA = ground area ($m^2/plant$).

Leaf area index decline

During the leaf senescence period (triggered when GDD_r equals about 0.8 for most crops), LAI is estimated using equation [C-9].

$$LAI = LAI_s \left[\frac{1 - GDD_r}{1 - GDD_{rs}} \right]^{rlad} \quad (9)$$

where:

GDD_{rs} = relative growing degree days to the start of leaf senescence.

LAI_s = LAI when leaf senescence begins,

rlad = green leaf area decline rate parameter.

Plant height

Plant height is estimated using the sigmoid function [C-10]. The parameters C_{ht} and D_{ht} were obtained from fitting plant height data to the 2-parameter sigmoid function. The plant height function in EPIC was not adequate.

$$PCHT = \frac{HMX}{\left[1 + \text{EXP} \left(\frac{GDD_r - C_{ht}}{D_{ht}} \right) \right]} \quad (10)$$

where:

PCHT = potential crop height (m),
 HMX = maximum crop height (m),
 C_{ht} , D_{ht} : height parameters.

Root mass distribution algorithms in the EPIC source code were difficult to interpret. Therefore, a relationship given by Jones et al. (1991) was used to distribute root mass in each soil layer.

$$RWT_i = RWT_i + DRW \frac{\left(1 - \frac{ZA_i}{3} \right)^{wgc}}{\sum_{i=1}^{i=ir} \left(1 - \frac{ZA_i}{3} \right)^{wgc}} \quad (11)$$

Where:

RWT_i = root mass in a layer (t/ha),
 DRW = daily increase in root mass (t/ha),
 ZA_i = depth to the middle of the i^{th} soil layer that has roots (m),
 wgc = genotype-specific rooting coefficient,
 ir = deepest layer to which roots have penetrated.

GROWTH CONSTRAINTS

Potential growth and yield seldom are achieved, because of stress caused by suboptimal conditions. The CROP submodel adjusts daily biomass and area growth for water, temperature, and nutrient stresses. Water, temperature, and nutrient stress factors range from 0, where no growth will occur, to 1 for no limitation in growth. For any simulation day, the

minimum value of the water, nutrient, or temperature stress factor adjusts daily produced biomass.

Water stress

The water stress factor is calculated as a ratio of actual to potential transpiration. These calculations are made in the HYDROLOGY submodel.

Temperature stress

Temperature stress is estimated using equation [C-12]. This equation is the same as given in EPIC, except that the soil surface temperature was replaced with average air temperature, because soil temperatures are not readily available. This function produces a symmetrical temperature stress factor about the optimum temperature.

$$T_s = \sin\left(\frac{\pi}{2} \cdot \frac{T_{av} - T_{bas}}{T_{opt} - T_{bas}}\right) \quad (12)$$

where:

T_{av} = average air temperature,

T_{bas} = base temperature (°C)

T_{opt} = optimum temperature (°C).

T_s = temperature stress factor

Frost damage is assessed using equation [C-13]. Frost stress is applied primarily to winter crops, but can be applied to summer crops, if freezing temperatures occur before the crop reaches physiological maturity. Calculation of frost damage stress is triggered whenever the minimum temperature is at or below -1.0 °C.

$$F_s = \frac{|T_{min}|}{|T_{min}| - \text{EXP}(A_f + B_f T_{min})} \quad (13)$$

where:

F_s = frost damage factor,

T_{min} = daily minimum air temperature (°C),

A_f, B_f = parameters in the frost damage 's-curve'.

Nutrient stress

Nitrogen and phosphorous supply, demand, uptake and stress algorithms of EPIC, with some minor modifications, were incorporated into CROP. These equations are described in the EPIC model documentation manual (Williams et al., 1990a).

VALIDATION

Materials and methods

Data for soybean, corn, grain sorghum, winter wheat, and oats were used to test the accuracy of the CROP submodel in simulating biomass and organ growth of crop plants. All data contained detailed measurements of plant state variables taken at approximately weekly intervals. Data were obtained from experimental plots located in Manhattan, Kansas. Details of site and growth conditions for each crop are described elsewhere (Retta and Armbrust, 1995). We had two seasons of data for each crop, except sorghum, which had 1 year of data. We obtained additional data for grain sorghum, which consisted of dry weights of leaves, stems, reproductive, and aboveground masses, and leaf area per plant. These data were measured every 5 days from emergence to physiological maturity by Reeves (1971) for three grain sorghum hybrids (representing three maturity groups) over a 2-year period. However, Reeves' data did not contain measurements of stem area.

A stand-alone version of the CROP submodel was used for the simulations. This version of the CROP submodel was not interfaced with the HYDROLOGY submodel of WEPS at the time when the analyses were performed. To calculate crop water use, a simple water balance subroutine was constructed in which potential evapotranspiration was calculated using Hargraves' formula as described by Samani and Pessarakli (1986).

Results and Discussion

Measured and simulated leaf, stem, reproductive, and aboveground masses and leaf and stem areas were compared (Fig. 1). Measured and simulated values showed high linear correlation (r^2 ranged from 0.72 for leaf area index to 0.87 for aboveground biomass). In most cases, the slopes and intercepts were significantly different from 1 and 0, respectively (table 1). Overall, the model showed a tendency to overestimate LAI and leaf mass, underestimate SAI and stem mass, and gave reasonably accurate estimates of reproductive and aboveground masses. Based on this limited test, model performance was comparable to that of EPIC.

Part of the data used in the validation tests also was used to derive equations for partitioning aboveground biomass into leaf, stem, and reproductive masses (Retta et al., 1995), and all the data (except Reeves' sorghum data) were used to derive the specific leaf and stem area values

for each crop. Thus, there is some concern as to the validity of these tests, because an unbiased test of model accuracy can be obtained only by using data that were not used to develop model parameters. However, these tests may be less biased than they appear at first glance. The primary parameter for generating biomass in the model is the biomass conversion efficiency factor (radiation use efficiency, RUE), which was obtained from the EPIC data base for each crop and not developed using these data. The partitioning and specific area parameters were applied to model-generated aboveground biomass, which was entirely independent of the data, and not on measured biomass. Thus, the bias, if any, may be considered of minor consequence. Therefore, these tests indicate that the model can give reasonable estimates of organ growth in mass and area on a daily basis.

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LIST OF SYMBOLS

Symbol	Description	Unit
A_f, B_f	parameters in the frost damage 's-curve'	
$A_{lf}, B_{lf}, C_{lf}, D_{lf}$	leaf partitioning parameters	
BE	radiation use efficiency	kg/MJ
BM_{lf}	leaf mass	kg/plant
C	fraction of shortwave solar radiation that is photosynthetically active (C=0.5)	MJ/MJ
C_{ht}, D_{ht}	plant height parameters	
DMAG	Aboveground biomass	t/ha
DRW	daily increase in root mass	t/ha
F_s	frost damage factor	
GDD_p	total GDDs from planting to physiological maturity	°Cd
GDD_r	relative GDD (ratio of cumulated GDDs at any time to the total GDDs at physiological maturity)	°Cd/°Cd
GDD_{rs}	relative growing degree days to the start of leaf senescence	°Cd/°Cd
HMX	maximum plant height	m
HRLT	daylength	hr
JD	day of year since January 1	d
K_e	radiation extinction coefficient	
LAI	leaf area index	m ² /m ²
LAI_s	LAI when leaf senescence begins	m ² /m ²
PAREA	ground area	m ² /plant
PCHT	plant height	m
PDDM	potential dailt biomass production	t/ha

Symbol	Description	Unit
P_{lf}	leaf mass partitioning ratio	t/t
P_{rt}	root mass partitioning ratio	t/t
RA	solar radiation	MJ/m ²
rlad	green leaf area decline rate parameter	
RWT_i	root mass in a layer	t/ha
SD	the sun's declination angle	rad
SLA	specific leaf area	m ² /kg
SSA	specific stem area	m ² /kg
T_{av}	average air temperature	°C
T_{bas}	base temperature	°C
T_{max}	daily maximum temperature	°C
T_{min}	daily minimum temperature	°C
T_{opt}	optimum temperature	°C
T_s	temperature stress factor	
wcg	rooting coefficient	
XLAT	latitude of location (negative for southern hemisphere)	deg
YLD	economic yield	t/ha
ZA_i	depth to the middle of the i^{th} soil layer that has roots	m

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Figure C-1. Comparison of simulated versus measured data for soybeans, corn, grain sorghum, winter wheat, and oats.

Table C-1. Parameters of linear regression of measured on simulated plant variables

Plant variable	Slope	Intercept	r ²	n
LAI	0.99	0.94**	0.72	270
SAI	0.40**	0.15**	0.75	115
Leaf mass	1.09*	0.29**	0.73	270
Stem mass	0.63**	0.60**	0.74	270
Reprod. mass	0.83**	0.56**	0.83	167
Aboveground mass	0.86**	1.00**	0.87	270

* & ** indicate significance at 0.05 and 0.01 levels.

RESIDUE DECOMPOSITION SUBMODEL



RESIDUE DECOMPOSITION SUBMODEL

Jean L. Steiner, Harry H. Schomberg, and Paul W. Unger

MODEL OVERVIEW

The DECOMPOSITION submodel simulates the decrease in crop residue biomass due to microbial activity. The decomposition process is modeled as a first order reaction with temperature and moisture as driving variables. The total quantities of biomass remaining after harvest are partitioned between standing (DMSBM), surface (DMFBM), buried (DMGBM), and root (DMRBM) pools. Below ground biomass decomposition is calculated for each soil layer.

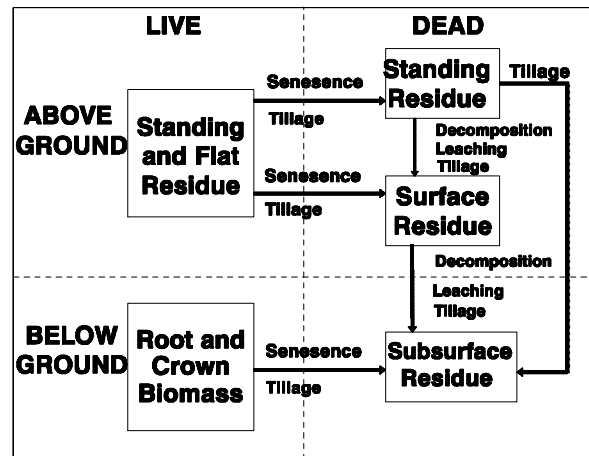


Figure D-1. Biomass distribution and transfer between residue pools.

Since residue decomposition can require a long period of time, crop residue biomass from sequential harvests are accounted for in separate data pools using an indexing variable (IAGE). Standing, surface, buried, and root biomass from the most recently harvested crop will be indexed IAGE = 1, biomass from the penultimate crop IAGE = 2, and for surface biomass a third pool will be accounted for as IAGE = 3. On a day of harvest, any biomass remaining from a previous crop is moved into the older age pools and residue from the current crop are indexed IAGE = 1. Decomposition rates for biomass pools one and two will be appropriate for the specific crops while biomass pool three will have a decomposition rate that reflects a slow rate of decomposition.

The variables DECOMPOSITION requires from other models are given in Table D-1 along with an indication of what information that variable provides. The variables used for DECOMPOSITION are given in Table D-2.

DECOMPOSITION

The general decomposition equation is a simple first order rate loss equation:

$$M_t = M_o * \exp^{-k \text{CUMDD}} \quad (1)$$

where M_t is the present quantity of biomass (kg m^{-2}) in the standing, surface, buried, or root pools; M_o is the initial biomass (kg m^{-2}); k is a crop specific rate constant used to calculate residue biomass changes (day^{-1}); and CUMDD is a weighted-time variable calculated from functions of temperature (TCF) and moisture (WCF). Optimum moisture and temperature conditions result in the accumulation of 1 decomposition day for each day of the simulation. When moisture or temperature limit the rate of decomposition, the minimum of the moisture or temperature functions is used to accumulate a fraction of a decomposition day.

In the DECOMPOSITION SUBMODEL biomass loss is actually calculated using the numeric form of equation [D-1] as follows;

$$M_t = M_{t-1} * (1 - k * \text{MIN}(\text{TCF}, \text{WCF})). \quad (2)$$

Functions for TCF and WCF are adjusted depending on residue placement (standing, surface and below ground). The moisture function for standing residues,

$$\text{WCF}_s = \frac{\text{RAIN}}{4} \quad (3)$$

is based on the rainfall depth in mm, RAIN, with 4 mm of rainfall considered to saturate the standing residues. Greater than 4 mm rainfall results in WCF_s being set to 1. Residual moisture in the residues is considered to decrease by 60 % each day following the wetting event.

Both precipitation and soil moisture influence the moisture of surface residues. The maximum of either the above estimate of WCF_s or a function WCF_f that considers the surface residues to be in equilibrium with the upper soil layer Θ_1 is used. WCF_f is calculated from the soil water content (Θ_1) and the optimum water content Θ_{optimum} .

$$\text{WCF}_f = \frac{\Theta_1}{\Theta_{\text{optimum}}} \quad (4)$$

The moisture function for buried residues and roots is,

$$WCF_g(NZS) = \frac{\Theta_{NZS}}{\Theta_{optimum}} \quad (5)$$

where NZS is the soil layer and Θ_{NZS} is the water content of layer NZS and $\Theta_{optimum}$ is the optimum soil water content for each layer (HRWCFC(NZS)).

The function to calculate TCF is similar to one describing the influence of temperature on photosynthesis (Taylor and Sexton, 1972) and used by Stroo et al. (1989) for decomposition,

$$WCF_g(NZS) = \frac{2(T_{avg} + A)^2 (T_{opt} + A)^2 - (T_{avg} + A)^4}{(T_{opt} + A)^4} \quad (6)$$

where T_{avg} is average daily temperature ($^{\circ}C$), T_{opt} is the optimum temperature for decomposition ($32^{\circ}C$) and A is a constant (0). Average air temperature is used for standing and flat residues and average soil temperature by layer is used for below ground residues.

Future plans are to include an indexing variable for nutrient availability.

CHANGES IN STANDING RESIDUE BIOMASS AND POPULATION

Standing residue losses occur from both microbial and physical actions. Physical transfers of crop residues from the standing biomass pool will reduce both the population size and biomass. When the changes occur due to physical forces such as wind, snow, gravity, or wheel traffic the transfer is to the surface pool. Tillage may result in redistribution to both the surface and buried pools. A daily estimate of the standing population is required in order to evaluate stem area index (SAI) and its influence on aerodynamic resistance.

The change in stem number is calculated similar to the loss in biomass (Eqn. [D-2]),

$$STMNO_t = STMNO_{t-1} * (1 - k * MIN(TCF, WCF)) \quad (7)$$

where $STMNO_t$ is the number of stems standing on day t, $STMNO_{t-1}$ is the number of stems standing yesterday, and TCF and WCF are the temperature and water functions for standing residues (Steiner et al, 1994). The transfer of biomass from the standing component is then calculated from the change in stem number as follows,

$$DMSBMY = DMSBM \quad (8)$$

$$DMSBM = DMSBM * (STMNO_t / STMNO_{t-1}) \quad (9)$$

$$DMFBM = DMFBM + (DMSBMY - DMSBM) \quad (10)$$

where DMSBMY is a variable set equal to the current standing biomass, DMSBM is the standing biomass, and DMFBM is the flat biomass.

PERCENT SOIL COVER FROM STANDING AND SURFACE RESIDUES

Both the standing and surface crop residues provide cover to the soil surface. The percent soil cover from the two standing residue pools is estimated each day as follows,

$$STAREA(J) = \pi * (STMDIAM(J)/2)^2 * STMNO(J) \quad (11)$$

$$STCOV = (STAREA(1) + STAREA(2)) / TOTAR \quad (12)$$

where STAREA(J) is the estimated stem area (m²) for pool J, STMDIAM(J), is the stem diameter for pool J, and STMNO(J) is the number of stems in pool J. The cover is converted to area / unit area by dividing by the unit area TOTAR (m²).

The equation used to predict residue cover from flat residue is from Gregory (1982):

$$COVF(J) = 1 - \exp^{-COVFACT(J) * DMFBM(J)} \quad (13)$$

where COVF(J) is the flat residue cover (0 - 1) in pool J, DMFBM(J) is the flat residue mass (kg m⁻²), and COVFACT(J) is a coefficient used to calculate flat residue cover. The flat cover from the pools are summed to give total flat cover (FLCOV).

Total residue cover is computed from:

$$DCOVER = FLCOV + STCOV \quad (14)$$

where DCOVER is the total residue cover (0-1).

RESIDUE DISTRIBUTION BY HEIGHT

The standing residues provide a vertical area that has a direct influence on wind speed. The vertical surface area is estimated by

$$DASAI = STMNO * STMHT * STMDIAM \quad (15)$$

where DASAI is the vertical stem area index. This area is divided into five equal increments (SAI) of the stubble height, STMHT for use by the EROSION model.

$$\text{SAI} = \text{DASAI} / 5 \quad (16)$$

MODIFYING VARIABLES DUE TO TILLAGE OPERATIONS

On a day of tillage, the distribution of residues will change between standing, flat and buried components depending on the tillage implement being used. The MANAGEMENT submodel will need to update the current biomass for each position (standing, surface, buried, and root) in each of the three age pools (1, 2, 3). Soil surface cover is then updated from the amount of biomass remaining in the surface and standing pools. (See Table D-3.)

CROP RESIDUE DECOMPOSITION SUBMODEL SUMMARY

1. Initialize decomposition variables for standing, surface, buried, and root biomass. Initialize decomposition rate constants for old residues.
2. At harvest:
 - a. Transfer residue biomass, stem numbers, decomposition days, decomposition rates and cover factors from younger to older age pools.
 - b. Check MANAGEMENT to see if the harvest process buried residues.
 - c. Put mass and stem information for harvested crop into IAGE = 1 pools.
 - d. Initialize decomposition rates (DKORATEA) and cover factor (COVFACT) variables for harvested crop.
3. Daily:
 - a. Test for harvest or tillage date.
 - b. Calculate temperature and moisture functions and accumulate decomposition days.
 - c. Calculate change in biomass for residue pools

- standing residue mass (DMSBM)
 - surface residue mass (DMFBM)
 - below ground residue mass (DMGBM)
 - root residue mass (DMRBM)
- d. Calculate transfer of standing residue mass to surface residue mass and update standing and surface biomass.
- e. Compute vertical and horizontal residue cover.

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Table D-1. Required Inputs From Other Submodels.

<u>Variable description</u>	<u>Local Variable</u>
Air temperature daily average.	WT
Combine height	TZCUT
Crop above ground biomass at harvest	CMSBM
Crop height at harvest	CZ
Crop yield	CMYLD
Current crop species	ICROP
Number of soil layers	NZS
Plant population	CNPOP
Precipitation -daily	WZPPT
Root biomass at harvest	CMBG(NZS)
Soil temperature by depth	ST(NZS)
Soil water content VOLUMETRIC	HRVWC(NZS)
Soil water holding capacity	HRWCFC(NZS)

Table D-2. Decomposition Variable List.

<u>Variable Description</u>	<u>Local Variable Name</u>
Sorted by Variable Name	
Mass to cover conversion coefficient fresh residue (crop specific table value)	CF1
Mass to cover conversion coefficient old residue (crop specific table value)	CF2
Mass to cover conversion coefficient	COVFACT(pool)
Horizontal cover from standing residue in pool iage	COVF(iage)
Cumulative decomposition days for standing pool	CUMDDF(iage)
Cumulative decomposition days for below ground	CUMDDG(iage)
Cumulative decomposition days for standing pool	CUMDDS(iage)
Vertical surface area from stems in standing pool iage	DASAI(iage)
Vertical surface area from all standing stems	DASAIT
Horizontal surface cover from all aboveground residue	DCOVER
Min. of water and temperature factors for flat	DIENVF
Min. of water and temperature factors below ground	DIENVG(ISZ)
Min. of water and temperature factors for standing	DIENVS
May add coeff. for soil & fertilization effects	DINUTRC=1
Temperature factor for above ground biomass	DITCA
Temperature factor for below ground biomass	DITCG(ISZ)
Water factor for flat biomass, 0 to 1.0	DIWCF
Water factor for below ground biomass, 0 to 1.0	DIWCG(ISZ)
Water factor for standing biomass, 0 to 1.0	DIWCS
Water factor for yesterday standing biomass	DIWCSY
Water factor for standing biomass on initial wetting day	DIWCSI
Decomposition rate constant (using pool id)	DKORATEA(pool,iage)
Decomposition constant (species specific) leaves and stems	DKRATE(IDRES)
Decomposition constant (species specific) roots	DKRATER(IDRES)
Decomposition constant for stem number (species specific)	DKRATESN(IDRES)
Flat biomass	DMFBM(iage)
Yesterdays flat biomass (internal bookkeeping variable)	DMFBMY
Buried biomass	DMGBM(iage,ISZ)
Yesterdays buried biomass (internal bookkeeping)	DMGBMY(SZ)
Root biomass	DMRBM(iage,ISZ)
Yesterdays root biomass (internal bookkeeping)	DMRBMYSZ)
Standing biomass	DMSBM(iage)
Yesterdays standing biomass (internal variable)	DMSBMY
Counter for days following a wetting event (4 to 1)	DWETI
Horizontal cover from all flat material	FLCOV
Age of residue	IAGE
Species ID of most recent harvest	IDRES
Species ID of the penultimate harvest	IDRESO
Stem area index by height	SAI(I)
Stem area of standing stems (iage) for estimate of horizontal cover	STAREA(iage)
Horizontal cover due to all standing stems	STCOV
Stem diameter	STMDIAM(iage)
Stem height	STMHT(iage)
Stem number current	STMNO(iage)
Stem number yesterday (internal variable)	STMNOY
Temperature function 0 to 1.0	TC(T)

Table D-2. continued.

<u>Sort by Descriptive Term</u>	<u>Local Variable Name</u>
<u>Variable Description</u>	
Age of residue	IAGE
Buried biomass	DMGBM(iage,ISZ)
Counter for days following a wetting event (4 to 1)	DWETI
Cumulative decomposition days for standing pool	CUMDDS(iage)
Cumulative decomposition days for below ground	CUMDDG(iage)
Cumulative decomposition days for standing pool	CUMDDF(iage)
Decomposition rate constant (using pool id)	DKORATEA(pool,iage)
Decomposition constant (species specific) roots	DKRATER(IDRES)
Decomposition constant for stem number (species specific)	DKRATESN(IDRES)
Decomposition constant (species specific) leaves and stems	DKRATE(IDRES)
Flat biomass	DMFBM(iage)
Horizontal cover due to all standing stems	STCOV
Horizontal cover from standing residue in pool iage	COVF(iage)
Horizontal cover from all flat material	FLCOV
Horizontal surface cover from all above ground residue	DCOVER
Mass to cover conversion coefficient fresh residue (crop specific table value)	CF1
Mass to cover conversion coefficient old residue (crop specific table value)	CF2
Mass to cover conversion coefficient	COVFACT(pool)
May add coeff. for soil & fertilization effects	DINUTRC=1
Min. of water and temperature factors below ground	DIENVG(ISZ)
Min. of water and temperature factors for flat	DIENVF
Min. of water and temperature factors for standing	DIENVS
Root biomass	DMRBM(iage,ISZ)
Species ID of the penultimate harvest	IDRESO
Species ID of most recent harvest	IDRES
Standing biomass	DMSBM(iage)
Stem area of standing stems (iage) for estimate of horizontal cover	STAREA(iage)
Stem area index by height	SAI(I)
Stem number current	STMNO(iage)
Stem height	STMHT(iage)
Stem number yesterday (internal variable)	STMNOY
Stem diameter	STMDIAM(iage)
Temperature function 0 to 1.0	TC(T)
Temperature factor for above ground biomass	DITCA
Temperature factor for below ground biomass	DITCG(ISZ)
Vertical surface area from all standing stems	DASAIT
Vertical surface area from stems in standing pool iage	DASAI(iage)
Water factor for flat biomass, 0 to 1.0	DIWCF
Water factor for yesterday standing biomass	DIWCSY
Water factor for standing biomass, 0 to 1.0	DIWCS
Water factor for below ground biomass, 0 to 1.0	DIWCG(ISZ)
Water factor for standing biomass on initial wetting day	DIWCSI
Yesterdays flat biomass (internal bookkeeping variable)	DMFBMY
Yesterdays root biomass (internal bookkeeping)	DMRBMYSZ)
Yesterdays buried biomass (internal bookkeeping)	DMGBMYSZ)
Yesterdays standing biomass (internal variable)	DMSBMY

Table D-3. Variables That MANAGEMENT Must Modify.

Standing to flat or below ground

DMSBM(IAGE=1) --> DMFBM(1) or DMGBM(1,ISZ)
 DMSBM(2) --> DMFBM(2) or DMGBM(2,ISZ)

STMNO(1) & STMNO(2) may also be reduced and will need adjustment.

Flat to below ground

DMFBM(1) --> DMGBM(1,ISZ)
 DMFBM(2) --> DMGBM(2,ISZ)
 DMFBM(3) --> DMGBM(2,ISZ)

Below ground to Flat

DMGBM(1,ISZ) DMFBM(3)
 DMGBM(2,ISZ) DMFBM(3)

(only mass in layers above the tillage depth need to be modified)

Root to ????

DMRBM(1,ISZ) --> DMRBM(1,ISZ)
 DMRBM(2,ISZ) --> DMRBM(2,ISZ)

APPENDICES



APPENDIX AA: WEPS-RELATED LITERATURE

PAPERS BY THE WEPS CORE TEAM MEMBERS

Ambe, N.M. and L.E. Wagner

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Appendix BB: Variable Naming Conventions and Global Variable List

WEPS VARIABLE CONVENTIONS

As with any program of the size and complexity of WEPS, a full understanding of the model structure and conventions is imperative from the outset of the project. This is necessary so that software development, maintenance, and support can be achieved with the utmost ease and efficiency. Furthermore, the original programmers are often not available to help with

program maintenance. Thus, a set of defined conventions to be followed when working with variables will allow for efficient development, maintenance, and support of WEPS.

VARIABLE USAGE

State variables are those that describe the state of the WEPS system at any point in time. A state variable is global to the whole WEPS model (i.e., it can be recognized anywhere in the model if needed) and, thus, must have only one definition. It can be used by any of the submodels. Examples of state variables would be percent sand or dew point temperature. These state variable names will be termed 'primary'.

State variables also may have a 'secondary' name. These are variables passed through call statements where there is no need to carry the last index in an array. For example, soil bulk density is a two-dimensional array (layer,subregion) as maintained by MAIN. When passed by a call statement to the SOIL submodel, however, it appears as a one-dimensional array (layer) within the submodel statement. Not all state variables have a secondary name.

State variables with primary and secondary names need to be explicitly defined and unique within WEPS. Primary state variables are the only ones that will be maintained in a variable list by the MAIN program coordinator. These variables are either passed through call statements or are available to submodels through \$INCLUDE files.

Variables that are local only to a submodel are not considered to be state variables. Some local variables may appear to be the same as those in other submodels and may even have the same definition as those in other submodels, but they must not be considered to be the same from submodel to submodel. These variables must be initialized within the submodels where they are used.

Some named constants will be defined in parameter statements and used to define the maximum size of an array (e.g., subregion index). This will provide the advantage that, in order to change array dimensions of all variables with a given index, only one line of code must be modified. Other constants will be used to set the current value of array indexes. Again, only one line of code will need to be modified to change all values of this array index. See examples below under constants.

VARIABLE NAMES

Variable naming must comply with the following conventions.

State Variables

first letter - use the letter "a" to designate a state variable primary name.
- use the letter 'b' to designate a variable secondary name, if one exists.

second letter - submodel/subject

- m - main,
- h - hydrology,
- t - management,
- s - soil,
- c - crop,
- d - decomposition,
- b - biomass,
- w - weather.

third letter - indication of units

- 0 - (zero) unitless or unknown,
- a - angle,
- c - concentration,
- d - density,
- e - energy,
- f - fraction (0.0 - 1.0),
- l - length,
- m - mass,
- n - number (e.g., of days)
- r - ratio (can be greater than 1.0),
- t - temperature,
- u - wind speed,
- x - horizontal length,
- z - vertical length, depth, or height,

fourth - sixth letters - use mnemonic descriptors.

Note: Primary and secondary names for state variables will be distinguished by first letter (a or b).

Exception: The only exceptions to the above naming conventions occur for the maximum value used on indexed variables in WEPS. In these cases the first letter is "n" followed by a mnemonic descriptor. For example, the maximum number of subregions in a WEPS run is "nsubr" and the maximum number of soil layers is "nslay". See "Example of Code Using Constants" below.

Example: asdbk(l,s) for primary and bsdbk(l) for secondary names for soil bulk density.

Local Variables

Programmers' choice.

Parameters

- first letter

- use m for those that designate the maximum size of an array index (e.g., 'mnsz' for maximum number of soil layers or 'mnsb' for maximum number of subregions).

- other letters

- programmers, choice.

See "Example of Code Using Constants" below.

Example of Code Using Constants

```
parameter (mnsz = 10, mnsb = 4)
.
.
.
real aspsan(mnsz,mnsb)
real asdbk(mnsz,mnsb)
.
.
.
integer nslay
integer nsubr
.
.
.
nslay = 5
nsubr = 2
.
.
.
do 10 i = 1, nslay
do 20 j = 1, nsubr
.
.
.
```

WEPS Common Blocks

fname*	common	typ	class	size	stat	value	units	short description
mlsubr	mlsubr	N	B	-	SG	-	-	subregion information
mlsim	mlsim	N	B	-	SG	-	-	simulation run information
mlgeo	mlgeo	N	B	-	SG	-	-	simulation region geometry
mlflag	mlflag	N	B	-	SG	-	-	flags for initialization and output
sllayr	sllayr	N	B	-	SG	-	-	soil layer information
slsurf	slsurf	N	B	-	SG	-	-	soil temporal properties (surface)
slphys	slphys	N	B	-	SG	-	-	soil temporal properties (physical)
slagg	slagg	N	B	-	SG	-	-	soil temporal properties (aggregate)
slnutr	slnutr	N	B	-	SG	-	-	soil temporal properties (nutrients)
sldbh	sldbh	N	B	-	SG	-	-	soil intrinsic properties (hydrology)
sldbc	sldbc	N	B	-	SG	-	-	soil intrinsic properties (chemical)
slgen	slgen	C	B	-	SG	-	-	general soil information
sllayd	sllayd	N	B	-	DG	-	-	other soil layer information
slsgeo	slsgeo	N	B	-	SG	-	-	soil surface geometric properties
slpsd	slpsd	N	B	-	DG	-	-	soil layer particle size distr. parameters
clinfo	clinfo	C	B	-	SG	-	-	general crop information
clgen	clgen	N	B	-	SG	-	-	crop input parameters
clglob	clglob	N	B	-	SG	-	-	crop properties
cldb1	cldb1	N	B	-	SG	-	-	crop database variables
cldb2	cldb2	N	B	-	SG	-	-	crop database variables
cldb3	cldb3	N	B	-	SG	-	-	crop database variables
cldb4	cldb4	N	B	-	SG	-	-	crop database variables
cldb5	cldb5	N	B	-	SG	-	-	crop database variables
clmass	clmass	N	B	-	DG	-	-	crop mass properties by height
clgeom	clgeom	N	B	-	DG	-	-	crop geometric properties by height
dlgen	dlgen	C	B	-	SG	-	-	general decomp biomass information
dlglob	dlglob	N	B	-	SG	-	-	decomp biomass information
dldb	dldb	N	B	-	SG	-	-	decomp biomass database variables
dlmass	dlmass	N	B	-	DG	-	-	decomp biomass mass properties by height
dlgeom	dlgeom	N	B	-	DG	-	-	decomp biomass geometric properties by height
blglob	blglob	N	B	-	DG	-	-	total biomass information
blmass	blmass	N	B	-	DG	-	-	total biomass mass properties by height
blgeom	blgeom	N	B	-	DG	-	-	total biomass geometric properties by height
blcovr	blcovr	N	B	-	DG	-	-	total biomass cover
wlinfo	wlinfo	C	B	-	SG	-	-	weather generator inputs and other info.
wclig	wclig	N	B	-	SG	-	-	daily cligen weather variables
wlwind	wlwind	N	B	-	SG	-	-	daily wind weather variables
wlpavg	wlpavg	N	B	-	SG	-	-	average weather parameters for period
hlet	hlet	N	B	-	SG	-	-	evapotranspiration parameters
hlhydro	hlhydro	N	B	-	SG	-	-	soil hydrologic parameters
hidb1	hidb1	N	B	-	SG	-	-	soil water holding parameters
hlscs	hlscs	N	B	-	SG	-	-	SCS runoff curve numbers
hltemp	hltemp	N	B	-	DG	-	-	Soil temperature

WEPS Fortran Parameters

fname*	common	typ	class	size	stat	value	units	short description
mnsz	plwerm	I	P	1	-	10	-	maximum number of soil layers
mnspt	plwerm	I	P	1	-	2	-	max. # of points describing simulation region
mnsbr	plwerm	I	P	1	-	4	-	maximum number of subregions
mnsrpt	plwerm	I	P	1	-	2	-	max. number of points describing a subregion
mnrar	plwerm	I	P	1	-	4	-	maximum number of accounting regions
mnrarpt	plwerm	I	P	1	-	2	-	max # of pnts describing an accounting region
mnrbr	plwerm	I	P	1	-	4	-	maximum number of barriers per subregions
mnrbrpt	plwerm	I	P	1	-	2	-	maximum number of points describing a barrier
mncz	plwerm	I	P	1	-	5	-	maximum number of crop height sections
mnrtime	plwerm	I	P	1	-	96	-	maximum number of time steps
mnrpls	plwerm	I	P	1	-	4	-	maximum number of biomass pools

mfname	plstrlen	I	P	1	-	30	-	maximum length of file names
mwsta	plstrlen	I	P	1	-	30	-	maximum length of weather station names
mloc	plstrlen	I	P	1	-	10	-	maximum length of location information
mdate	plstrlen	I	P	1	-	10	-	maximum length of date strings
pi	plconst	R	P	1	-	3.14159	radians	PI constant
anemht	plconst	R	P	1	-	10.0	m	anemometer height
awzz0	plconst	R	P	1	-	20.0	mm	?
awzgr	plconst	R	P	1	-	9.816	m/s^2	acceleration due to gravity
mtomm	plunconv	R	P	1	-	1000.0	m/mm	unit conversion: m/mm
hrday	plunconv	I	P	1	-	24	hrs/day	conversion constant: number of hours/day
co2	plcrop	R	P	1	-	330.0	ppm	concentration of CO ₂ in the atmosphere
hix1	plcrop	R	P	1	-	0.50		ratio - actual to pot. ET (x1 in HI s-curve)
hix2	plcrop	R	P	1	-	0.95		ratio - actual to pot. ET (x2 in HI s-curve)
hiy1	plcrop	R	P	1	-	0.10		fraction of reduction in harvest index (y1)
hiy2	plcrop	R	P	1	-	0.95		fraction of reduction in harvest index (y2)
sllx1	plcrop	R	P	1	-	5.00	ppm	soil labile P concentration (x1 on s-curve)
sllx2	plcrop	R	P	1	-	20.00	ppm	soil labile P concentration (x2 on s-curve)
sllx1	plcrop	R	P	1	-	0.01		P uptake restriction factor (y1 on s-curve)
sllx2	plcrop	R	P	1	-	0.90		P uptake restriction factor (y2 on s-curve)
s8x1	plcrop	R	P	1	-	20.00		scaled ratio of actual to pot. N or P (y1)
s8x2	plcrop	R	P	1	-	80.00		scaled ratio of actual to pot. N or P (y2)
s8y1	plcrop	R	P	1	-	0.50		N or P stress factor (y1)
s8y2	plcrop	R	P	1	-	0.95		N or P stress factor (y2)

WEPS Global Variables

VARIABLES - MAIN

fname*	common	typ	class	size	stat	value	units	short description
nsubr	mlsubr	I	1D	-	SG	-	-	number of subregions
amrslp	mlsubr	R	1D (sr)	-	SG	-	m/m	subregion slope
am0csr	mlsubr	I	1D	-	SG	-	-	current subregion
am0irr	mlsubr	I	1D (sr)	-	SG	-	-	irrig. flag (0=none, 1=sprinkler, 2=furrow)
ntstep	mlsim	I	S	-	SG	-	-	# of time steps per day erosion is calculated
am0jd	mlsim	I	S	-	SG	-	-	current Julian day of simulation run
amalat	mlsim	R	S	-	SG	-	degrees	latitude of the simulation site
amalon	mlsim	R	S	-	SG	-	degrees	longitude of the simulation site
amzele	mlsim	R	1D	-	SG	-	m	site elevation above sea level
nacctr	mlgeo	I	S	-	SG	-	-	number of accounting regions
nbar	mlgeo	I	1D (sr)	-	SG	-	-	number of barriers per subregion
amasim	mlgeo	R	S	-	SG	-	degrees	field angle (clockwise from true north)
amxsim	mlgeo	R	2D (xy,pt)	-	SG	-	m	coordinate of simulation region
amxar	mlgeo	R	3D (xy,pt,ar)	-	SG	-	m	coordinate of accounting region
amxsr	mlgeo	R	3D (xy,pt,sr)	-	SG	-	m	coordinate of subregion
amxbar	mlgeo	R	4D(xy,pt,b,sr)	-	SG	-	m	coordinate of subregion barrier
am0eif	mlflag	L	S	-	SG	-	-	flag to run erosion initialization
am0cif	mlflag	L	S	-	SG	-	-	flag to initialize crop at start and plant
am0dif	mlflag	L	S	-	SG	-	-	flag to initialize decomp at start + harvest
am0cgf	mlflag	L	S	-	SG	-	-	flag to call crop growth between plant + harv
am0ifl	mlflag	L	S	-	SG	-	-	flag to run submodel initialization
am0hfl	mlflag	I	S	-	SG	-	-	flag to print hydrology submodel output
am0sfl	mlflag	I	S	-	SG	-	-	flag to print soil submodel output
am0tfl	mlflag	I	S	-	SG	-	-	flag to print tillage submodel output
am0cfl	mlflag	I	S	-	SG	-	-	flag to print crop submodel output
am0dfl	mlflag	I	S	-	SG	-	-	flag to print decomposition submodel output
am0efl	mlflag	I	S	-	SG	-	-	flag to print erosion submodel output
am0hdb	mldebug	I	S	-	SG	-	-	flag to print vars. pre and post hydro call
am0sdb	mldebug	I	S	-	SG	-	-	flag to print vars. pre and post soil call
am0tdb	mldebug	I	S	-	SG	-	-	flag to print vars. pre and post tillage call
am0cdb	mldebug	I	S	-	SG	-	-	flag to print vars. pre and post crop call
am0ddb	mldebug	I	S	-	SG	-	-	flag to print vars. pre and post decomp call
am0edb	mldebug	I	S	-	SG	-	-	flag to print vars. pre and post erosion call

VARIABLES - BIOMASS

fname*	common	typ	class	size	stat	value	units	short description
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abzht	blglob	R	1D	(s)	DG	-	m	total biomass height
abzrtd	blglob	R	1D	(s)	DG	-	m	total biomass root depth
abma	blmass	R	1D	(0:h,s)	DG	-	kg/m ²	total biomass above ground by ht. (0th=flat)
abmb	blmass	R	1D	(1,s)	DG	-	kg/m ²	total biomass below ground by layer
abrsai	blgeom	R	1D	(s)	DG	-	m ² /m ²	total biomass stem area index
abrlai	blgeom	R	1D	(s)	DG	-	m ² /m ²	total biomass leaf area index
abffcv	blcovr	R	1D	(s)	DG	-	m ² /m ²	total biomass cover (flat)
abfscv	blcovr	R	1D	(s)	DG	-	m ² /m ²	total biomass cover (standing)

VARIABLES - CROP

fname*	common	typ	class	size	stat	value	units	short description
ac0nam	clinfo	C	S	(s)	SG	-	-	crop name
ac0idc	clinfo	I	S	(s)	SG	-	-	crop type (annual, perennial, . . .)
acxrow	clgen	R	1D	(s)	SG	-	m	crop row spacing
acdpop	clgen	R	1D	(s)	SG	-	p/m ²	crop seeding density
ac0rg	clgen	I	1D	(s)	SG	-	-	crop seeding location in relation to ridge
acrcn	cldb1	R	1D	(s)	SG	-	-	crop C:N ratio
ac0id	cldb1	I	1D	(s)	SG	-	-	crop id number
acrhi	cldb1	R	1D	(s)	SG	-	kg/kg	crop harvest index (yield/above gnd biomass)
acrmhi	cldb1	R	1D	(s)	SG	-	kg/kg	minimum crop harvest index under drought
acephu	cldb1	R	1D	(s)	SG	-	-	heat units from planting to maturity
acehu0	cldb1	R	1D	(s)	SG	-	-	heat units when senescence starts
aczmrt	cldb1	R	1D	(s)	SG	-	m	maximum root depth
aczmxc	cldb1	R	1D	(s)	SG	-	m	maximum crop height
acrla	cldb1	R	1D	(s)	SG	-	-	maximum leaf area index
acrbe	cldb1	R	1D	(s)	SG	-	kg/ha*MJ	biomass / energy ratio
acrbed	cldb1	R	1D	(s)	SG	-	-	biomass / energy decline rate
ac0lad	cldb1	R	2D	(h,s)	SG	-	-	leaf area distr. (5 parts) 1-bottom/5-top
ac0sad	cldb1	R	2D	(h,s)	SG	-	-	stem area distr. (5 parts) 1-bottom/5-top
ac0bev	cldb1	S	1D	(s)	SG	-	-	vapor press. to biomass conversion efficiency
acrbe1	cldb1	R	1D	(2,s)	SG	-	-	x, y point on CO ₂ concentration curve
acrbe2	cldb1	R	1D	(2,s)	SG	-	-	x, y point on biomass conversion curve
actopt	cldb2	R	1D	(s)	SG	-	deg C	optimal temperature for plant growth
actmin	cldb2	R	1D	(s)	SG	-	deg C	minimum temperature for plant growth
acfd1a	cldb2	R	1D	(s)	SG	-	-	fract. of grow season when LAI decline starts
acrd1a	cldb2	R	1D	(s)	SG	-	-	Leaf Area Index (LAI) decline rate
ac0caf	cldb2	R	1D	(s)	SG	-	-	critical aeration factor
ac0ck	cldb2	R	1D	(s)	SG	-	-	extinction coefficient
ac0psf	cldb2	R	1D	(s)	SG	-	-	pest stress factor
ac0alt	cldb2	R	1D	(s)	SG	-	-	aluminum tolerance index
ac0pt1	cldb2	R	2D	(2,s)	SG	-	%?	x & y coord. for 1st pt. on optimal LAI curve
ac0pt2	cldb2	R	2D	(2,s)	SG	-	%?	x & y coord. for 2nd pt. on optimal LAI curve
ac0fd1	cldb2	R	2D	(2,s)	SG	-	deg C	x & y coord. for 1st point on frost damage "
ac0fd2	cldb2	R	2D	(2,s)	SG	-	deg C	x & y coord. for 2st point on frost damage "
ac0bn1	cldb3	R	1D	(s)	SG	-	-	N uptake parameter - N fraction at emergence
ac0bn2	cldb3	R	1D	(s)	SG	-	-	N uptake param. - N fraction at 0.5 maturity
ac0bn3	cldb3	R	1D	(s)	SG	-	-	N uptake parameter - N fraction at maturity
ac0bp1	cldb3	R	1D	(s)	SG	-	-	P uptake parameter - P fraction at emergence
ac0bp2	cldb3	R	1D	(s)	SG	-	-	P uptake param. - P fraction at .5 maturity
ac0bp3	cldb3	R	1D	(s)	SG	-	-	P uptake parameter - P fraction at maturity
acfnny	cldb3	R	1D	(s)	SG	-	-	fraction of nitrogen in yield
acfpny	cldb3	R	1D	(s)	SG	-	-	fraction of phosphorous in yield
acfwy	cldb3	R	1D	(s)	SG	-	-	fraction of water in yield
ac0hta	cldb4	R	1D	(s)	SG	-	-	ht. "a" for LAIZ/SAIZ/LAI/canopy estimation
ac0htb	cldb4	R	1D	(s)	SG	-	-	ht. "b" for LAIZ/SAIZ/LAI/canopy estimation
ac0lza	cldb4	R	1D	(s)	SG	-	-	leaf area "a" for LAIZ estimation
ac0lzb	cldb4	R	1D	(s)	SG	-	-	leaf area "b" for LAIZ estimation
ac0saa	cldb4	R	1D	(s)	SG	-	-	stem area "a" for SAIZ estimation
ac0sab	cldb4	R	1D	(s)	SG	-	-	stem area "b" for SAIZ estimation
ac0laa	cldb4	R	1D	(s)	SG	-	-	leaf area index "a" for LAI estimation
ac0lab	cldb4	R	1D	(s)	SG	-	-	leaf area index "b" for LAI estimation
ac0cca	cldb4	R	1D	(s)	SG	-	-	canopy cover "a" for canopy cover estimation
ac0ccb	cldb4	R	1D	(s)	SG	-	-	canopy cover "b" for canopy cover estimation
ac0bw1	cldb5	R	1D	(s)	SG	-	-	wind erosion factor for standing live
ac0bw2	cldb5	R	1D	(s)	SG	-	-	wind erosion factor for standing dead
ac0bw3	cldb5	R	1D	(s)	SG	-	-	wind erosion factor for flat residue
ac0cmn	cldb5	R	1D	(s)	SG	-	-	minimum value of C factor for water erosion

acz	clglob	R	1D	(s)	SG	-	m	crop height
aczrtd	clglob	R	1D	(s)	SG	-	m	crop root depth
acmst	clglob	R	1D	(s)	SG	-	kg	standing crop mass (above ground)
acmrt	clglob	R	1D	(s)	SG	-	kg	crop root mass
acrahi	clglob	R	1D	(s)	SG	-	kg/kg	adjusted crop harvest index
acragr	clmass	R	1D	(0:h+1)	DG	-	kg/m^2	crop mass above gnd./ht. (0th=flat,h+1=total)
acrbgr	clmass	R	1D	(l)	DG	-	kg/m^2	crop mass below ground by layer
acmyld	clmass	R	S	1	DG	-	kg/m^2	crop yield
acrsai	clgeom	R	1D	(s)	DG	-	m^2/m^2	crop stem area index
acrlai	clgeom	R	1D	(s)	DG	-	m^2/m^2	crop leaf area index
acrsaz	clgeom	R	2D	(h,s)	DG	-	1/m	crop stem area index by height
acrlaz	clgeom	R	2D	(h,s)	DG	-	1/m	crop leaf area index by height
acffcv	clgeom	R	1D	(s)	DG	-	m^2/m^2	crop biomass cover (flat)
acfscv	clgeom	R	1D	(s)	DG	-	m^2/m^2	crop biomass cover (standing)
acftcv	clgeom	R	1D	(s)	DG	-	m^2/m^2	crop biomass cover (total)

VARIABLES - DECOMPOSITION

fname*	common	typ	class	size	stat	value	units	short description
ad0nam	dlgen	R	2D	(b,s)	SG	-	-	decomp biomass pool name
ad0cn	dlgen	R	2D	(b,s)	SG	-	-	decomp biomass pool C:N ratio
adxrow	dlgen	R	2D	(b,s)	SG	-	m	decomp biomass pool row spacing
addpop	dlgen	R	2D	(b,s)	SG	-	p/m^2	decomp biomass pool seeding density
adzrtd	dlglob	R	1D	(s)	SG	-	m	total decomposition biomass root depth
admst	dlglob	R	2D	(b,s)	SG	-	kg	decomposition biomass pool standing mass
admfv	dlglob	R	2D	(b,s)	SG	-	kg	decomposition biomass pool flat mass
admtrt	dlglob	R	1D	(s)	SG	-	kg	total decomposition biomass root mass
adzght	dlglob	R	2D	(b,s)	SG	-	m	harvest height
addstm	dlglob	R	2D	(b,s)	SG	-	#/m^2	stem number
adma	dlmass	R	2D	(0:h,b,s)	DG	-	kg/m^2	decomp. biomass pools above ground/ht(0=flat)
admb	dlmass	R	1D	(b,l,s)	DG	-	kg/m^2	total decomp. biomass below ground/layer
admr	dlmass	R	1D	(b,l,s)	DG	-	kg/m^2	total decomp. root biomass below ground/layer
admres	dlmass	R	1D	(s)	DG	-	kg/ha	plant residue on soil surface
adrsai	dlgeom	R	1D	(s)	DG	-	m^2/m^2	total decomposition biomass stem area index
adrlai	dlgeom	R	1D	(s)	DG	-	m^2/m^2	total decomposition biomass leaf area index
adrsaz	dlgeom	R	2D	(h,s)	DG	-	1/m	total decomp. biomass stem area index by ht.
adrlaz	dlgeom	R	2D	(h,s)	DG	-	1/m	total decomp. biomass leaf area index by ht.
adffcv	dlgeom	R	1D	(s)	DG	-	m^2/m^2	total decomposition biomass cover (flat)
adfscv	dlgeom	R	1D	(s)	DG	-	m^2/m^2	total decomposition biomass cover (standing)

VARIABLES - HYDROLOGY

fname*	common	typ	class	size	stat	value	units	short description
ahzea	hlet	R	S	1	DG	-	mm/day	actual bare soil evaporation
ahzep	hlet	R	S	1	DG	-	mm/day	potential bare soil evaporation
ahzeta	hlet	R	S	1	DG	-	mm/day	actual evapotranspiration
ahzstp	hlet	R	S	1	DG	-	mm/day	potential evapotranspiration
ahzpta	hlet	R	S	1	DG	-	mm/day	actual plant transpiration
ahzptp	hlet	R	S	1	DG	-	mm/day	potential plant transpiration
ahrwc	hlhydro	R	2D	(l,s)	SG	-	kg/kg	soil water content - mass basis
aheaep	hlhydro	R	2D	(l,s)	SG	-	J/kg	soil air entry potential
ahrsk	hlhydro	R	2D	(l,s)	SG	-	m/s	saturated soil hydraulic conductivity
ah0cb	hlhydro	R	2D	(l,s)	SG	-	-	power of water release curve
ahfwsf	hlhydro	R	1D	(s)	SG	-	-	crop water stress factor
ahzsno	hlhydro	R	1D	(s)	SG	-	mm	initial water content in snow
ahzsmt	hlhydro	R	1D	(s)	SG	-	mm/day	snow melt
ahzirr	hlhydro	R	1D	(s)	SG	-	mm/day	irrigation water applied
ahzper	hlhydro	R	1D	(s)	SG	-	mm/day	cumulative daily deep percolation
ahzrun	hlhydro	R	1D	(s)	SG	-	mm/day	cumulative daily surface runoff
ah0cng	hlscs	R	1D	(s)	SG	-	-	SCS runoff curve number (good)
ah0cnp	hlscs	R	1D	(s)	SG	-	-	SCS runoff curve number (poor)
ahrwc0	hlhdl	R	2D	(time,s)	SG	-	kg/kg	hourly surface soil water content (grav.)
ahrwcw	hlhdl	R	2D	(l,s)	SG	-	kg/kg	15 bar soil water content (grav.)
ahrwcf	hlhdl	R	2D	(l,s)	SG	-	kg/kg	1/3 bar soil water content (grav.)
ahrwca	hlhdl	R	2D	(l,s)	DG	-	kg/kg	available soil water content (grav.)
ahrwcs	hlhdl	R	2D	(l,s)	DG	-	kg/kg	saturation soil water content (grav.)

ahtsav	hltemp	R	2D	(1,s)	DG	-	deg C	average soil temperature at layer midpoint
ahtsmx	hltemp	R	2D	(1,s)	DG	-	deg C	maximum soil temperature at layer midpoint
ahtsmn	hltemp	R	2D	(1,s)	DG	-	deg C	minimum soil temperature at layer midpoint

VARIABLES - SOIL

fname*	common	typ	class	size	stat	value	units	short description
nslay	sllayr	I	1D	(s)	SG	-	-	number of soil layers used in a subregion
aszlyt	sllayr	R	2D	(1,s)	SG	-	mm	soil layer thickness
asdbl	slphys	R	2D	(0:1,s)	SG	-	Mg/m ³	soil layer (+ surface) bulk density
asfsan	sldbh	R	2D	(1,s)	SG	-	kg/kg	fraction sand (layer)
asfsil	sldbh	R	2D	(1,s)	SG	-	kg/kg	fraction silt (layer)
asfcla	sldbh	R	2D	(1,s)	SG	-	kg/kg	fraction clay (layer)
as0ph	sldb	R	2D	(1,s)	SG	-	-	pH (layer)
ascmg	sldb	R	2D	(1,s)	SG	-	cmol/kg	magnesium ion concentration (layer)
ascna	sldb	R	2D	(1,s)	SG	-	cmol/kg	sodium ion concentration (layer)
asfcce	sldb	R	2D	(1,s)	SG	-	dec	fraction calcium carbonate equiv. (layer)
asfcec	sldb	R	2D	(1,s)	SG	-	cmol/kg	cation exchange capacity (layer)
asfesp	sldb	R	2D	(1,s)	SG	-	dec	exchangeable sodium percentage (layer)
asfom	sldb	R	2D	(0:1,s)	SG	-	kg/kg	fraction organic matter (layer + surface)
asfnoh	sldb	R	2D	(1,s)	SG	-	mg/kg	organic N concentration of humus
asfpoh	sldb	R	2D	(1,s)	SG	-	mg/kg	organic P concentration of humus
asfpp	sldb	R	2D	(1,s)	SG	-	dec	fraction of fertilizer P that is labile
asfsm	sldb	R	2D	(1,s)	SG	-	cmol/kg	sum of bases
asftap	sldb	R	2D	(1,s)	SG	-	kg/ha	total available P by layer from all sources
asftan	sldb	R	2D	(1,s)	SG	-	kg/ha	total available N by layer from all sources
asmno3	sldb	R	2D	(s)	SG	-	kg/ha	amount of NO ₃ applied
asdagd	slagg	R	2D	(0:1,s)	SG	-	Mg/m ³	aggregate density (layer + surface)
aseags	slagg	R	2D	(0:1,s)	SG	-	ln(J/m ²)	dry aggregate stability (layer + surface)
aslagm	slagg	R	2D	(0:1,s)	SG	-	mm	aggr. size geom. mean dia. (layer + surface)
as0ags	slagg	R	2D	(0:1,s)	SG	-	-	aggr. size geom. mean std. dev. (layer+surf)
aslagx	slagg	R	2D	(0:1,s)	SG	-	mm	max aggregate size of each layer (layer+surf)
aslagm	slagg	R	2D	(0:1,s)	SG	-	mm	min aggregate size of each layer (layer+surf)
aszcr	slsurf	R	1D	(s)	SG	-	mm	soil crust thickness
asfcr	slsurf	R	1D	(s)	SG	-	m ² /m ²	fraction of soil covered by crust
asmls	slsurf	R	1D	(s)	SG	-	Mg/m ²	loose material on crusted surface
asflos	slsurf	R	1D	(s)	SG	-	m ² /m ²	fraction of loose material on soil surface
asdcr	slsurf	R	1D	(s)	SG	-	Mg/m ³	crust density
asecr	slsurf	R	1D	(s)	SG	-	ln(J/m ²)	crust stability
asfald	slsurf	R	1D	(s)	SG	-	-	dry soil albedo
asfalw	slsurf	R	1D	(s)	SG	-	-	wet soil albedo
aszlyd	sllayd	R	1D	(1,s)	DG	-	mm	depth to bottom of each soil layer
aszlym	sllayd	R	1D	(1)	DG	-	m	depth to midpoint each soil layer
aszmp	sllayd	R	1D	(1)	DG	-	m	distance between midpoints of soil layers
asdsbk	sllayd	R	2D	(1,s)	DG	-	Mg/m ³	soil layer settled bulk density
aszrgh	slsgeo	R	1D	(s)	DG	-	mm	ridge height
asxrgw	slsgeo	R	1D	(s)	DG	-	mm	ridge width
asxrsg	slsgeo	R	1D	(s)	DG	-	mm	ridge spacing
asargo	slsgeo	R	1D	(s)	DG	-	degrees	ridge orientation (clockwise from true north)
asxdks	slsgeo	R	1D	(s)	DG	-	mm	dike spacing
as0rrk	slsgeo	R	1D	(s)	DG	-	-	K (shape) random roughness parameter
aslrck	slsgeo	R	1D	(s)	DG	-	degrees	C (scale) random roughness parameter
aslsgm	alpsd	R	2D	(1,s)	DG	-	mm	soil layer particle geometric mean diameter
as0sgs	alpsd	R	2D	(1,s)	DG	-	-	soil layer particle geom. standard deviation

VARIABLES - WEATHER

fname*	common	typ	class	size	stat	value	units	short description
awtdmx	wlclig	R	S	1	SG	-	deg C	air temperature (daily maximum)
awtdmn	wlclig	R	S	1	SG	-	deg C	air temperature (daily minimum)
awtdav	wlclig	R	S	1	SG	-	deg C	air temperature (daily average)
awtyav	wlclig	R	S	1	SG	-	deg C	air temperature (yearly average)
awtdpt	wlclig	R	S	1	SG	-	deg C	dew point temperature (daily)
aweirr	wlclig	R	S	1	SG	-	MJ/m ²	global radiation
awzdpt	wlclig	R	S	1	SG	-	mm	daily precipitation
awrrh	wlclig	R	S	1	SG	-	-	relative humidity

awadir	wlwind	R	S	1	SG	-	degrees	wind direction from North
awrmxn	wlwind	R	S	1	SG	-	-	ratio of maximum/minimum daily wind speed
awhrmx	wlwind	R	S	1	SG	-	hr	hour of day maximum wind speed occurs
awudmx	wlwind	R	S	1	SG	-	m/s	wind velocity (daily maximum)
awudmn	wlwind	R	S	1	SG	-	m/s	wind velocity (daily minimum)
awudav	wlwind	R	S	1	DG	-	m/s	wind velocity (daily average)
awu	wlwind	R	S	(time)	DG	-	m/s	wind velocity (sub-daily averages)
aw0dif	wlinfo	C	S	(15)	SG	-	-	daily weather data input file name
aw0hif	wlinfo	C	S	(15)	SG	-	-	hourly weather (wind) data input file name
aw0cst	wlinfo	C	S	(30)	SG	-	-	cligen weather station (name)
aw0wst	wlinfo	C	S	(30)	SG	-	-	wind generator weather station (name)
aw0sd	wlinfo	C	S	(10)	SG	-	-	weather data file (starting date)
aw0ed	wlinfo	C	S	(10)	SG	-	-	weather data file (ending date)
aw0clt	wlinfo	R	S	1	SG	-	-	cligen weather station location (latitude)
aw0cln	wlinfo	R	S	1	SG	-	-	cligen weather station location (longitude)
aw0wlt	wlinfo	R	S	1	SG	-	-	wind weather station location (latitude)
aw0wln	wlinfo	R	S	1	SG	-	-	wind weather station location (longitude)
awtmmx	wlpavg	R	S	1	DG	-	m/s	air temperature (monthly maximum average)
awtmmn	wlpavg	R	S	1	DG	-	m/s	air temperature (monthly minimum average)
awdair	wlpavg	R	S	1	DG	-	kg/m ³	air density (monthly average)
awztpt	wlpavg	R	S	1	DG	-	mm	total precipitation (period)
awtpav	wlpavg	R	S	1	DG	-	deg C	average period temperature
awepir	wlpavg	R	S	1	DG	-	MJ/m ²	average daily incoming radiation for period
awupav	wlpavg	R	S	1	DG	-	m/s	average daily wind speed
awnuet	wlpavg	R	S	1	DG	-	days	number of days wind speed exceeded threshold
aweuet	wlpavg	R	S	1	DG	-	MJ	total wind energy exceeding threshold

*fname = fortran name

common = common block name

typ = type N = named common
 C = character
 I = integer
 R = real

class P = parameter
 B = block
 S = scaler
 1D = 1 dimensional
 2D = 2 dimensional

size l = layer
 s = subregion
 h = height
 b = biomass pool
 l = scaler quantity
 time = time step

stat = status where, SG = state global
 DS = dependent global

value = current values for parameters

