1481

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WATERMAN: an operational soil water balance model compatible with IBSNAT data files

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Abstract The CERES crop growth simulation models for sorghum, maize and millet, and other models like SOYGRO and PNUTGRO, are becoming widely used for various applications in agriculture. These models use data files whose structure was developed by IBSNAT. As the use of these models becomes more widespread the amount of data coded in the IBSNAT format will become more readily available. There is, therefore, an advantage in having an operational, dedicated, soil water balance model compatible with the IBSNAT data format so that water balance analyses can be done without reformatting the data. WATERMAN is a model developed to achieve this objective. The program obtains the required weather, soil and crop information from the EXP.DIR and WTH.DIR files. All required soil profile variables of the chosen soil type are then input from the SPROFILE.* file. The user can select several applications, such as daily or periodic soil water balance, daily water contents of various layers and irrigation scheduling with or without consideration of rainfall probabilities. Test runs at Samaru, Nigeria, gave acceptable results.

INTRODUCTION

Several dedicated soil water balance models exist, e.g. Thornthwaite & Mather (1955); Stockle & Campbell (1985); Ritchie (1972); Reddy (1983); and Campbell & Diaz (1988). Each model, however, has its own data requirements and structures of input files. There is no standard data format. If one's data exists in a format for an application, say a crop growth model, it has to be reformatted for use by the chosen soil water balance model.

The problem is that no model is used widely enough in agriculture for its input file structure to be used as a standard by other models. This is despite the fact that most models require the same key weather, crop and soil variables as input data. Recently, however, the CERES group of crop simulation models for sorghum, maize, millet and wheat; and other models like SOYGRO and PNUTGRO are becoming widely used for various applications in agriculture. These models use the same data files whose structure was designed by the International Benchmark Sites Network for

Agrotechnology Transfer (IBSNAT) (Boote *et al.*, 1987). As the use of the models becomes more widespread so the amount of data coded in the IBSNAT input file structure will increase. This data structure may become a standard for other programmes.

Although the CERES models have a soil water balance module, the models cannot be used for water balance applications beyond those they were designed for. There is, therefore, a need for a dedicated soil water balance model that uses the CERES models' file structures. Several applications can be designed and performed without reformatting the data. A model called WATERMAN, reported here, was designed to achieve this objective.

THE BASIC MODEL

The model is based on a simple water balance equation for a layered soil profile given as:

$$WC_{n,j} = WC_{n-1,j} + INF_j + D_{j-1} - ETA_j - D_j \qquad (1)$$

where $WC_{n,j}$ is the water content of layer j on day n and INF_j, ETA_j and D_j are infiltration, evapotranspiration (*ET*) and drainage, respectively. The components of the equation are computed for each layer on a daily basis.

Infiltration and drainage

Infiltration is calculated with a bucket type approach. Runoff is assumed to occur only if the amount of rainfall (*R*) plus irrigation (*I*) on day *n* is greater than the total profile water deficit (*WD*). For each layer the upper limit of water storage (*UL*) is assumed to be the saturation water content (*SWC*). If $WC_{n,j}$ is greater than the water content at field capacity (FC_j) the difference is assumed to drain to the layer below within one day. If the amount of rainfall is not enough to re-fill the profile, it is assumed distributed to successive layers below the surface. After redistribution all layers that receive infiltrate are assumed to arrive at a uniform water content with the restriction that no layer loses water after the redistribution process.

Evapotranspiration

Daily crop evapotranspiration is calculated using the crop coefficient approach given by the equation

$$ETA_n = K_c\,(ETo_n) \qquad (2)$$

where ETA_n and ETo_n are actual and grass reference crop evapotranspiration on day *n* respectively and K_c is the crop coefficient. *ETo* is calculated with the radiation method given by the FAO (Doorenbos & Pruitt, 1977). Crop coefficient curves compatible with the grass reference procedure have been developed for several crops of the Sudano-Sahelian zone by Abdulmumin (1988) and Abdulmumin & Misari (1990). Curves for some of the crops are given in Fig. 1.

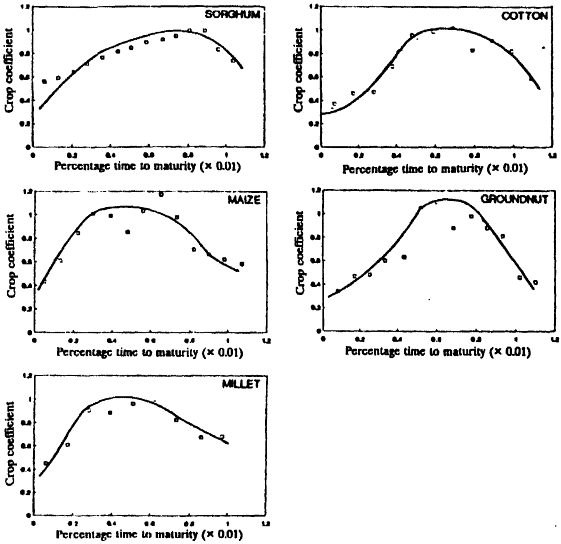

Fig. 1 Crop coefficient (K_c) curves of some crops of the Sudano-Sahelian zone (after Abdulmumin & Misari, 1990).

Each day total canopy ETA_n is partitioned to the various layers to which roots have extended based on estimated rooting density within the layer. Daily increase in root depth is related to the K_c curve using a procedure similar to that given by Fereres *et al.* (1980). Root density within each layer is assumed to increase linearly from zero at the time the root front arrives at the layer to a maximum value depending on the observed rooting habit of the crop. Details of the *ETA* partitioning procedure are given by Abdulmumin (1989).

INPUT DATA FILES

The program is designed to obtain all the required crop, soil and weather information from relevant files designed for the IBSNAT versions of models such as PNUTGRO, CERES-Maize and CERES-Sorghum. In addition there are three files unique to WATERMAN, two of which are optional.

IBSNAT files

Details of the structures and variables of the IBSNAT files are given by Boote *et al.* (1987). The user first indicates the crop model for which the data base was designed. The program then reads the XXEXP.DIR file (XX represents a two letter prefix, such as PN for PNUTGRO and SG for CERES-Sorghum) and presents the user with a choice of experiments, just like the crop model does. The choice of experiment enables the program to select the correct weather, SPROFILE.XX2, agronomy and irrigation data files.

The program obtains crop related variables from the agronomy file (usually with extension .XX8). These variables are soil profile number, cultivar number, planting date, seeding depth and allowable depletion. Allowable depletion is the percentage of profile soil water the crop is allowed to extract before irrigation becomes necessary.

The soil profile number read from the agronomy file is used to identify the relevant soil profile in the SPROFILE.XX2 file. For each layer the variables read from the soil profile data are: thickness of the layer (*ZJ*); water contents (volume %) at wilting point (*WP*), field capacity (*FC*), saturation (*SWC*) and at planting (*WCI*); and a weighting factor for calculating the proportion of roots in the layer.

Details of irrigations within the season are obtained from the irrigation file (with extension .XX6); the file provides for each irrigation the day and depth of irrigation water.

The weather file provides daily minimum and maximum temperature, solar radiation, and rainfall. The program uses the planting date read from the agronomy file as the starting date of simulation.

WATERMAN files

Three input files have been created which are unique to WATERMAN. The first contains digitized crop coefficient data and the length of the crop's growing season in days. The second contains long term monthly mean wind speed and relative humidity for the location, which are needed by the FAO radiation method for *ETo* computations. This file is optional in cases where adjustment of *ETo* estimates to local conditions is not necessary. The third is an optional file containing weekly initial and conditional probabilities of rainfall at the location. This file is only needed for analysis of supplementary irrigation requiring considerations of rainfall probabilities as described later. The probability estimates are obtained separately using the method described by Virmani *et al.* (1978).

APPLICATIONS

At the moment the program has three main applications: (a) daily and periodic soil water balance, (b) monitoring of daily water contents in various layers and (c) irrigation or supplementary irrigation scheduling, with or without considerations of rainfall probabilities.

The first two applications are straight forward water balance computations. The third is an application of water balance in irrigation or supplementary irrigation scheduling. The program schedules irrigations when an amount of water equal to the percentage allowable depletion (read from the agronomy file) has been extracted in chosen layers of the soil profile. The day and amount of irrigation water (equivalent to the total profile soil moisture deficit) are indicated. If the rainfall probability option is chosen, irrigation is indicated only when the probability of rainfall during the week, equal to or greater than the soil moisture deficit, is below a chosen percentage (for example 70%).

MODEL TESTS

Test locations are limited to those where experimentally measured soil water data exists for comparison with model estimates. Kowal (1968b) made detailed soil water measurements on experimental plots of several crops at Samaru, Nigeria (latitude 11°11'N, longitude 7°38'E) The site has ferruginous tropical soils with high proportions of fine sand (Lawes, 1962). Water holding characteristics of the profile reported by Kowal (1968a) are given in Table 1.

Some applications of the model were tested at Samaru and compared to the data of Kowal (1968b). Figures 2 and 3 show a comparison of model simulated and measured soil moisture under sorghum and groundnuts, respectively. Observations were taken for only the second half of the season.

Table 1 Some water holding characteristicsof the soil at Samaru, Nigeria (from the data of Kowal, 1968a)

Depth (cm)	*Field capacity (volume %)*	*Wilting point (volume %)*	*Available water (volume %)*
0-8	*25.4*	*6.2*	*19.2*
8-20	*25.9*	*10.4*	*15.5*
20-50	*27.2*	*18.0*	*9.2*
50-74	*29.5*	*14.2*	*15.3*
74-88	*29.3*	*10.2*	*19.1*
88-120	*29.4*	*5.8*	*23.6*

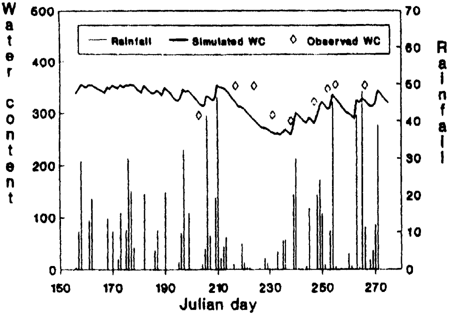

Fig. 2 Water content (WC in mm) of a 120 cm soil profile under sorghum, planted on day 156, 1967, at Samaru, Nigeria. Rainfall (mm) is also shown.

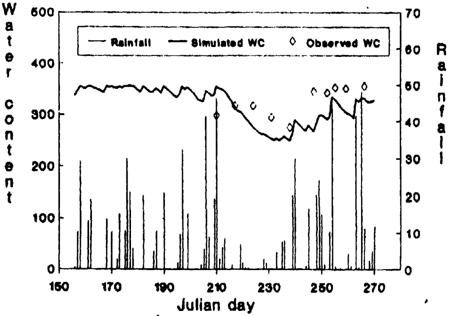

Fig. 3 Water content (WC, in mm) of a 120 cm soil profile under groundnut, planted on day 156, 1967, at Samaru, Nigeria. Rainfall (mm) is also shown.

The model tends to underestimate the observed data. This may be accounted for by the fact that horizontal runoff was not allowed as part of the treatments of Kowal (1968b). All water was made to percolate down the profile. In his report Kowal (1968b) acknowledged that observed vertical drainage was slower than expected. However, the model simulation broadly agrees with trends in soil water contents.

Model output of 10 day totals of water balance components for groundnuts are given in Table 2. The deficit *ET* figures refer to shortfalls in *ETA* caused by insufficient soil moisture. Unfortunately there are no experimentally measured data to compare with the estimates.

Table 2 A WATERMAN output of periodic water balance (a period is 10 days long, but period 12 was only 5 days)

Location: Samaru *Year: 1967*
Soil type: Samaru Alfisol *Planting day: 156*
Crop: Groundnut

Whole profile water balance components (mm):

Period	Potential ET	Actual ET	Deficit ET	Rain	Irrigation	Runoff + percolation	Change in soil moisture storage
1	80.7	24.0	1.4	72.4	0.0	35.4	12.9
2	78.5	26.4	3.9	52.6	0.0	8.7	17.5
3	77.1	36.9	1.4	77.2	0.0	32.9	7.4
4	78.7	43.6	4.5	38.6	0.0	2.0	- 7.1
5	78.0	54.4	5.2	64.1	0.0	3.3	6.4
6	78.5	72.9	2.5	134.0	0.0	15.7	45.4
7	79.1	71.1	15.3	11.2	0.0	0.0	-59.9
8	76.2	35.4	49.6	18.1	0.0	0.0	-17.3
9	76.8	50.5	31.6	76.1	0.0	0.0	25.6
10	80.9	55.8	19.8	116.7	0.0	0.0	60.9
11	79.8	56.5	4.2	95.8	0.0	0.0	39.3
12	38.1	22.4	1.1	69.8	0.0	0.0	47.4
Totals	902.4	550.0	140.6	826.6	0.0	98.0	178.6

CONCLUSIONS

The data format used by the CERES crop models and the IBSNAT models such as PNUTGRO may become a standard for models in agriculture. This is probably the first attempt to write a water balance model compatible with this format. The advantage envisaged is of wider use as the use of the CERES models increases. Tests of the model with data from Samaru show that soil moisture contents are well simulated. A disadvantage is the use of optional files beyond those of the CERES models. However, these are only necessary for applications that go beyond simple water balance, such as irrigation scheduling with the consideration of rainfall probabilities.

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