SOMOMOD

A COMPUTERIZED PROCEDURE FOR RATING THE LAND QUALITY ADEQUACY OF WATER SUPPLY TO ANNUAL CROPS UNDER RAINFED CONDITIONS

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ABSTRACT: The land quality "adequacy of water supply to annual crops under rainfed conditions" can be rated with SOMOMOD. This software package uses a compartmentalized water balance model to calculate the probability that a particular annual crop will produce good yields during a particular time period on a specific land unit, under the assumption that other physical factors are not limiting for the considered use. SOMOMOD is an interactive programme; the user has to specify the critical limits for the input-variables. Crop zoning studies are feasible with SOMOMOD as is illustrated by several test cases for Jamaica. Results generated with the model should be validated against field observations. The SOMOMOD module is incorporated in version 3.0 of the computerized Jamaica Physical Land Evaluation System (JAMPLES).

Key words: water balance, crop water requirements, available water capacity, land quality, Jamaica.

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CONTENTS

1. INTRODUCTION

A minimum supply of water is needed to ensure satisfactory crop growth and production. For a given crop variety, the value of this 'threshold' varies with the stage and rate of development, the soil conditions and the climate which determine the potential water use of the crop. The availability of water with respect both to time and amount, soil properties and management factors determine the actual water use of the crop.

The importance of a reliable water supply - soil moisture reserve and its recharge by rainfall - for rainfed agriculture is emphasized in the computerized Jamaica Physical Land Evaluation System (Batjes et al., 1987). The "75%-dependable growing period", as determined with the existing system of agro-climatic zoning, does not account for the effect of the water holding properties of the soil. This is seen as a shortcoming, particularly for shallow rooting annual crops (SSU, 1988a & b). For the latter crops it is important to study the adequacy of soil moisture supply in relation to crop water requirements during critical periods of development. A computerized soil moisture module (SOMOMOD) allowing for this type of studies is discussed in this paper.

Following a short review of crop water requirements (Section 2) and crop-extractable soil water (Section 3) the simulation model is discussed in Section 4. Subsequently, the rating system for the land quality under study is applied to a number of test cases (Section 5). Finally, comments are made as to the applicability of the SOMOMOD model in land evaluation studies (Section 6).

2. CROP WATER REQUIREMENTS

Crop water requirements are normally expressed by the rate of evapo-transpiration which is related to the evaporative demand of the atmosphere. They can be expressed as a function of the potential evapo-transpiration (PET) that is the rate of evapo-transpiration of an extended surface of an 8-15 cm tall green grass cover, actively growing, completely shading the ground and not short of water (see FAO, 1979).

Empirically determined crop coefficients (kc) can be used to relate PET to the maximum crop evapo-transpiration (ETm) when the water supply fully meets the water requirements of the crop. For a given climatic region, crop variety and crop development stage (i) the maximum evapotranspiration of a crop is:

[1] $ETm(i) = kc(i) \times PET(i)$

During the initial stages of development of annual crops the consumptive water demand is generally low (exception: rice). The water supply -i.e. the rainfall distribution under rainfed conditions- during this stage must be reliable in view of the seedling's shallow rooting depth; limited use can be made of the soil water reserve. The consumptive water demand of the crop increases as the leaf area increases, reaches its peak during flowering and rapidly decreases again during ripening (see FAO, 1979).

Following a good rain shower the actual evapo-transpiration of a crop (ETa) will be equal to its potential evapotranspiration rate (ETm) for as long as the surface soil is sufficiently wet to satisfy ETm requirements. As the soil dries out, it gradually becomes more difficult for the crop to extract water from the soil so that ETa will drop below ETm (Section 3).

In areas with one or two distinct dry and wet seasons monthly PET rates will change markedly from one year to the other, particularly in the transition period, depending on whether the showers arrive early or late. This variability can only be quantified in areas with fully equiped meteorological stations, of which there are 11 throughout Jamaica (JMS, 1973; IICA, 1983). In view of this low density of observations mean monthly PET rates, determined according to the Priestley & Taylor method, are calculated through linear regression (IICA, 1983). The effect of the earlier described interannual variability of PET on potential water requirements of crops therefore cannot be quantified in this study. The year to year variability in monthly rainfall totals, however, can be considered in view of the availability of an extensive, manuscript data base of monthly rainfall data for Jamaica.

3. CROP-EXTRACTABLE SOIL WATER

Plant roots can extract water from a soil by exterting a suction that exceeds the water potential of the soil (e.g. Russel, 1980). The lower limit of the crop available part of the soil moisture reserve is called field moisture capacity. It is defined as the quantity of water that remains after gravitational water has drained away. At the Soil Survey Unit the field moisture capacity (FMC) is considered to correspond with a matric suction of 100 cm water (pF= log(100)= 2) irrespective of the soil type (e.g. SSU, 1986). In practice, however, the water potential corresponding with conditions of "field moisture capacity" will differ from one soil type to the other (e.g. Russel, 1980).

By convention it is assumed that most plants will die when the matric suction of the soil reaches 15,000 cm water (pF 4.2; about 15 bar), i.e. at the "permanent wilting point" (PWP). For most types of crops water supply and production are already impaired before PWP is reached . The matric suction at which the decrease in crop growth/production begins has been termed "critical soil suction". The value of the latter suction varies with the type and development stage of the crop, the evaporative demand of the atmosphere and the soil type. For a large number of crops irrigation experts have established which fraction of the total available water capacity (TAWC, see below) can be taken up freely by a particular crop at a given value of ETm (FAO, 1977 & 1979). Some of these results are summarized in Table 1. These figures should be validated for Jamaica through field experiments.

Table 1. Soil water depletion factor [DEP(i)] for selected crop groups and ETm values.

crop group	ETm (mm/day)				
	2	3	4	5	6
1 onion, pepper, potato	0.50	0.43	0.35	0.30	0.25
2 cabbage, pea, tomato	0.68	0.58	0.48	0.40	0.35
3 bean, groundnut, water melon	0.80	0.70	0.60	0.50	0.45
4 cotton, maize, sorghum, soybean, tobacco	0.88	0.80	0.70	0.60	0.50

Adapted from FAO (1979 p.28)

The amount of water (TAWC) considered potentially extractable from the rooted soil zone (RD) by a crop is:

[2] $TAWC(i,j) = RD(i) \times (WCfmc - WCpwp)$

with:

RD(i) the effective rooting depth of the crop in the soil under study at the end of month-i (j= year).

WCfmc the volume of water held in the soil at field moisture capacity (assumed to correspond with pF=2.0)

WCpwp the volume of water held in the soil at the permanent wilting point (assumed to correspond with pF=4.2)

The amount of water readily available to the crop is termed RAWC:

[3] $RAWC(i,j) = DEP(i) \times TAWC(i,j)$

with:

DEP(i) a factor expressing the fraction of the total available water capacity that can be extracted by a particular crop without depressing its evapo-transpiration and/or growth rate (ETa = ETm).

Equations [2] and [3] are commonly used in soil water balance modelling eventhough there is no "universal" field moisture capacity nor permanent wilting point for all soils (see e.g. Driessen, 1986; Dent & Cook, 1987). In cases where these points are known for a particular combination of soil and crop they can be entered into SOMOMOD as user-defined variables (see Appendix I).

It is assumed that soil-water is extracted by the crop according to a linear uptake pattern and that such a relationship also holds for the infiltration of rainfall into the soil. This assumption will not be justified for soils featuring pronounced hysteresis (e.g. Vertisols).

4. THE SOIL WATER BALANCE MODEL

The axis of SOMOMOD is a water balance model that takes into account the fact that the amount of water that can be extracted by a specific crop from a particular soil will vary with:

a) the development stage of the crop

b) the evaporative demand of the atmosphere,

c) soil characteristics, and

d) rainfall supply

SOMOMOD does not account for water inputs resulting from runoff from adjacent sloping areas nor for capillary water transport in soils with a shallow ground-water table [Equation 4]. SOMOMOD should not be used where such processes play an important role.

In view of the resolution level of our climatic data base (dt= 30 days) a simple procedure has been developed to approximate the decrease in crop water use with an increasing degree of soil moisture deficit (Appendix II). ETa drops below ETm once the amount of readily crop-available water has been used (See CSP in Figure 1). After this point water deficits start to occur; crop yields will gradually decrease until the PWP is reached. During this period the actual rate of evapotranspiration is considered to decrease at a rate of FAC x ETm, where FAC is characterized by a square root function (see Appendix II). The process of water use by the crop continues until the critical level for ETa, as determined by the pre-selected target yield, is reached (ETa < FACcr x ETm). Beyond this point, the water potential of the soil is considered to be limiting for economic production of the crop.

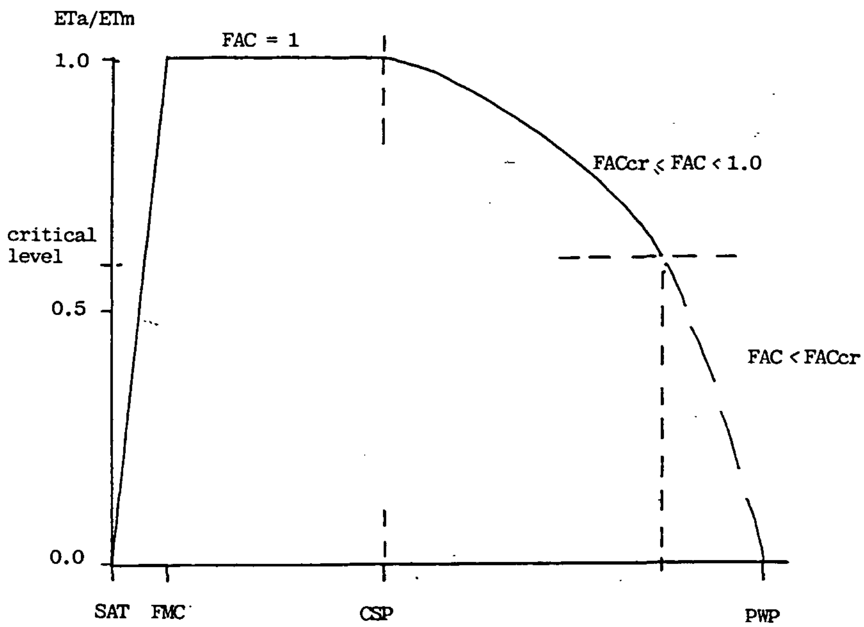

Figure 1: Relationship between the soil water supply and ETa as modelled in SOMOMOD.
[SAT= saturation point; FMC= field moisture capacity;
CSP= critical suction point; PWP= permanent wilting point]

Monthly fluctuations in the crop-extractable soil water reserve during time period (i,j) are calculated as follows:

[4] $SSW(i,j) = SSW(i-1,j) + R(i,j) - ETa(i)$

with:

SSW(i,j) the simulated amount of readily crop-extractable water stored in the root zone at the end of month-i of year-j.

R(i,j) the effective rainfall for the ith month of year j.

ETa(i) the estimated actual evapotranspiration rate of the crop in the ith month.

Depending on the choice of the user the simulation procedure [4] is either carried out for one particular time period, with length equal to the period required by the crop from sowing/planting to harvesting, or repeated for several combinations of time periods. Generally, it is only meanignful to carry out analyses for time periods falling within the so-called "75%-dependable growing period" (see SSU, 1988a).

Each simulation run is started by calculating the initial soil water content at the beginning of the envisaged month of sowing/planting. This is done under the assumption that the soil was in fallow in the preceding month and that evapo-transpirative water losses amounted to 0.3xPET at that time.

A compartmentalized approach to water storage in a soil is used in equation [4]. In the month of sowing/planting (month No.1) the effective precipitation first recharges the uppermost soil layer. The depth of this layer corresponds with the average effective rooting depth of the crop at the end of the first month [RD(1)]. The maximum amount of water that can be stored in crop-extractable form in the first soil layer is equal to TAWC(1). Any water surplus will be available for deep percolation to the next soil layer, the depth of which corresponds with the effective rooting depth at the end of month No.2 [RD(2)]. If the rainfall surplus in month-1 exceeds TAWC(2) the remaining excess is considered lost from the system as a 'sink' term.

The above procedure is repeated for the successive months of each potential growing period. If the simulation shows that there is a marked water deficit in month i of year j, i.e. when SSW(i,j)<0, the simulation run for the year under consideration is stopped. The model subsequently proceeds with the simulation run for the next year. This operation is repeated for all the years covered by the rainfall data base. During this process, the model keeps track of the number of years during which the moisture supply - soil moisture reserve and its recharge by rainfall - fulfilled the water requirement for good crop growth/production and the total number of simulation runs. Yearly rainfall records with missing values are automatically excluded from the simulation procedure.

5. ADEQUACY OF WATER SUPPLY TO ANNUAL CROPS

5.1 The rating system

The probability of obtaining good yields of a particular crop in a specific area, characterized by its climate (monthly rainfall and PET) and the physical characteristics of its soils, forms the basis for the rating system in Table 2. In order to obtain "good" yields in a particular time period the water supply should be sufficiently high to allow the crop to utilize water at a rate of FAC x ETm (see Appendix II and Figure 1).

Table 2. Key to suitability classes determined with SOMOMOD for specific combinations of climatic conditions (rainfall and PET), soils and crops.

Probability	suitability class
75 - 100%	highly suitable
50 - 74%	moderately suitable
25 - 49%	marginally suitable
0 - 24%	not suitable

The land quality "adequacy of moisture supply to annual crops under rainfed conditions" is rated on the basis of Table 2. In accordance with the rating system used for the "other" land qualities (SSU, 1987a) three possible degrees of limitations are proposed, viz:

0 - no constraints (Prob.> 75%)
1 - moderate constraints (50% <Prob.<= 75%)
2 - strong constraints (Prob.=<50%)

5.2 Application to test cases

Two distinctly different rainfall stations are used for the test cases, Bernard Lodge and Linstead which receive total rainfall in excess of 1365 mm and 537 mm respectively in 75% of the years. According to the agro-climatic module (RAINSTAT) the "75%-dependable growing period" extends from October to November at Bernard Lodge and from May to December at Linstead (SSU, 1987b). At Bernard Lodge there is one moist month (M), during which rainfall ranges from 0.5xPET to 1.0xPET in 75% of the years, while there are five at Linstead. At Linstead there is a rainfall surplus (Rain/PET>1.0) in September and October in 75% of the years; such period have been termed humid (H). There are no humid months at Bernard Lodge.

RAINSTAT analyses monthly rainfall totals as "individual" events, whereas SOMOMOD takes into consideration the chronological sequence of rainfall events. SOMOMOD further accounts for the water holding characteristics of the soil whereas only a broadly defined period of water utilization (U) has been considered in RAINSTAT.

Figures 2 and 3 are based on results of simulation runs for Linstead (maize) and Bernard Lodge (millet). In both examples the size of the soil's TAWC is varied whereas the kc factor, percent effective rainfall (90%) and rooting depth are considered constant for a particular crop in a particular development stage. Figures 2 and 3 reflect the fact that for a particular crop the relative importance of the size of TAWC on the length of the growing period increases as the area becomes drier.

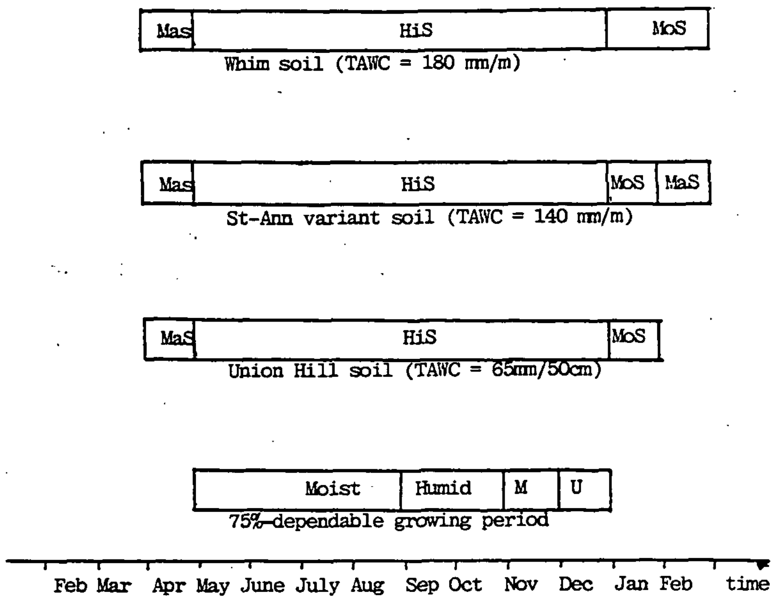

Figure 2. The effect of the TAWC of Whim, St-Ann variant and Union-Hill soils on the adequacy of seasonal water supply to maize in the Linstead area as compared with the length of the 75%-dependable growing period.

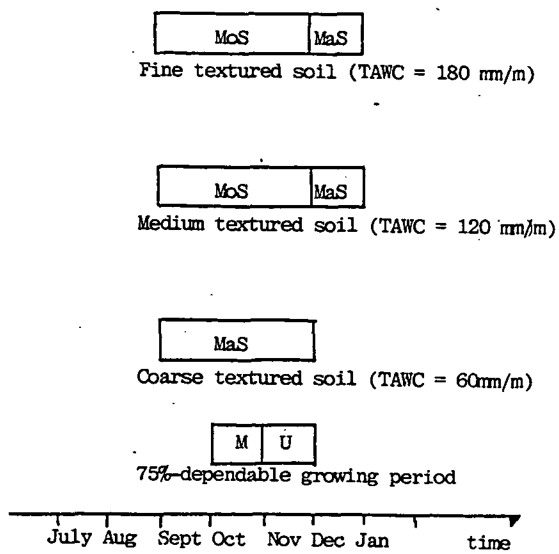

Figure 3. The effect of the TAWC of three fictitious soils (coarse, medium and fine textured) on the adequacy of seasonal water supply to millet at Bernard Lodge as compared with the length of the 75%-dependable growing period.

Results generated with SOMOMOD can also be used for crop zoning studies (Figures 4 and 5). At Bernard Lodge, Whim soils are moderately suitable for producing Millet in the September-November (S N) period, while they are at best marginally suitable for Maize under rainfed conditions.

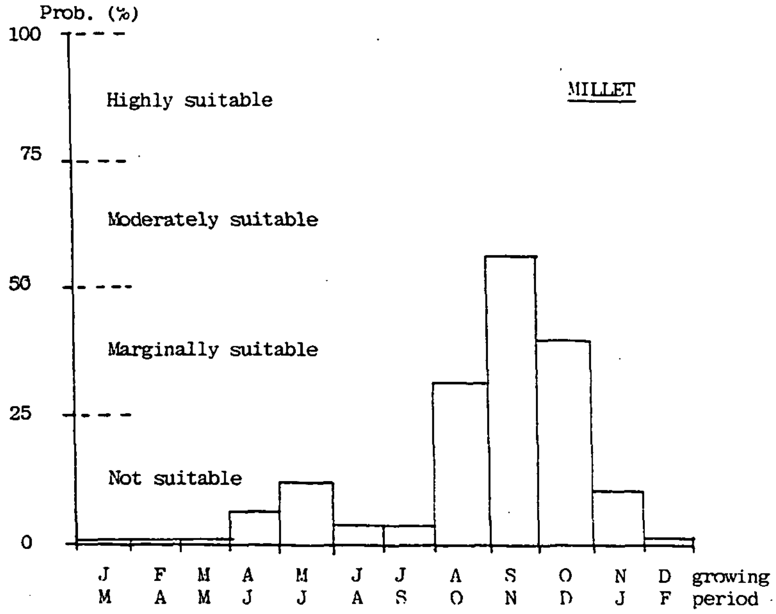

Figure 4. Probability of obtaining good yields of rainfed millet during pre-selected time periods on Whim soils at Bernard Lodge and suitability assessment (e.g. J M = January-March)

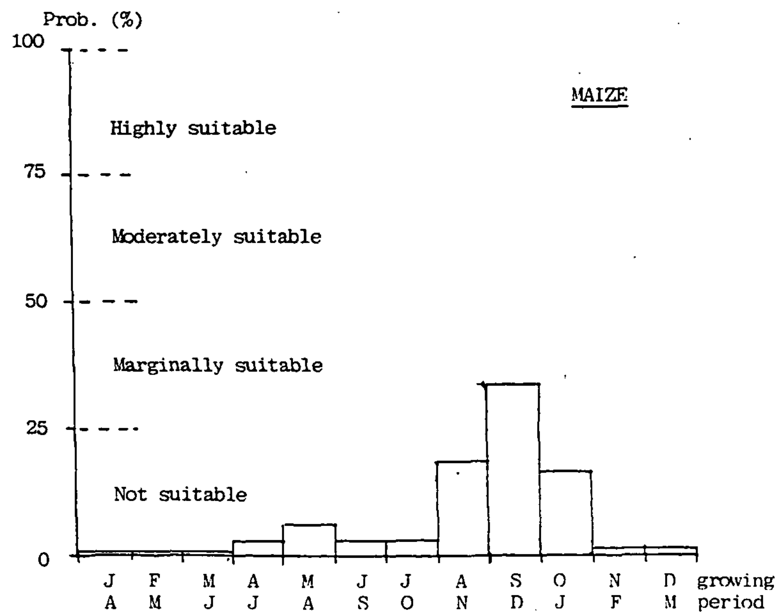

Figure 5. Probability of obtaining good yields of rainfed maize during pre-selected time periods on Whim soils at Bernard Lodge and suitability assessment.

6. DISCUSSION

Accurate modelling of soil-water-crop relationships is complex and data-hungry (e.g. Dent & Cook, 1987; Keulen & Wolf, 1988). SOMOMOD uses assumptions that are in line with the level of resolution of the climatic (dt= 30 days) and soil data bases. Results of agricultural research and/or data from literature should be used to determine the relevant regional-threshold values for the state-variables in SOMOMOD. Further experience in model testing and use will continue to contribute to improvements of the model.

Preliminary validation studies of SOMOMOD have indicated that the land quality "adequacy of water supply to rainfed crops" can succesfully be rated for crops requiring a relatively short growing season (up to 6 months). Test simulations for some deep rooting perennial crops, however, have given unsensical results. The latter type of studies are more complicated because some tree crops (e.g. citrus and mango) require a marked dry period for good production, whereas yields of e.g. banana and cocoa decrease already with moderate water deficits. In the case of perennial crops, the adequacy of rainfall supply can therefore best be rated with the existing method (SSU, 1988a & b). This system considers both the length of the "75%-dependable growing period" and the amount of annual rainfall surpassed in 75% of the years. The preliminary version for the rating system of the "adequacy of water supply to crops" as described in SSU (1987a) can be refined/updated on the basis of the present study (SSU, 1989).

In SOMOMOD it is assumed that rainfall conditions recorded in the 'near-past' are representative for rainfall conditions in the 'near-future'. Analyses with SOMOMOD should be based on data records covering long time periods in view of the cyclic pattern of years with "low" and "high" rainfall totals in Jamaica (JMS, 1973). A minimum of 20 years of observations is recommended.

Parallel to rating the "adequacy of moisture supply to rainfed crops" the land evaluator should asses whether the "other" land qualities of a particular land unit, as considered in SSU (1987a), will be limiting for particular form of land use. This type of integrated study can be performed with MATMOD and LANDEV, two modules of the Jamaica Physical Land Evaluation System (SSU, 1989)

REFERENCES

Batjes, N.H., Bouwman, A.F & K.M. Sinclair, 1987. Jamaica Physical Land Evaluation System. In Beek et al. (Eds). Quantified Land Evaluation Procedures, ITC Publication No.6, Enschede. p. 39-43

Dent, D.L. & H. Cook, 1987. Soil water sufficiency levels: data needs and error bars of a soil water potential model. In: Beek et al. (Eds): Quantified Land Evaluation Procedures, ITC Publication No. 6, Enschede. p. 111-118.

Driessen, P.M., 1986. Soil data, a matter of concern. Annual Report 1986, International Soil Reference and Information Centre, Wageningen. p. 43-47

FAO, 1977. Crop water requirements. Irrigation and drainage paper No. 24, Food and Agricultural Organization of the United Nations, Rome, Italy.

FAO, 1979. Yield response to water. Irrigation and Drainage Paper No. 33, Food and Agricultural Organization of the United Nations, Rome, Italy.

IICA, 1983. Agro-climatic study of Jamaica. L'Homme, J-P. and M. Eldin, Interamerican Institute for Cooperation on Agriculture/ORSTOM, San Jose, Costa Rica.

JMS, 1973. The climate of Jamaica (First Edition). The Meteorological Service, Kingston, Jamaica.

Keulen, H. van & J. Wolf (Eds), 1988. Modelling of agricultural production: weather, soils and crops. Simulation Monograph, PUDOC, Wageningen. pp. 479

Russel, E.W., 1980. Soil conditions and plant growth. Longman, London. pp. 849

SSU, 1986. Soil and Land Use Survey of the St. Catherine Plains. Campbell, V.A., A.T.L.M. Commissaris & H.A. de Wit, Soil Survey Report No.1, Soil Survey Unit, RPPD, Jamaica.

SSU, 1987a. List of ratings for land qualities used in the Jamaica Physical Land Evaluation System (2nd Approximation). Batjes, N.H., Technical Soils Bulletin No.10, Soil Survey Unit, RPPD, Jamaica.

SSU, 1987b. An analysis of rainfall variability in St. Catherine for agricultural planning. Batjes, N.H., Miscellaneous Paper No.4, Soil Survey Unit, RPPD, Jamaica.

SSU, 1988a. Review of agro-climatic software modules of JAMPLES. N.H. Batjes, Technical Soils Bulletin No.13, Soil Survey Unit, RPPD, Jamaica.

SSU, 1988b. Agro-climatic characterization of the parish of Clarendon, Jamaica. Batjes, N.H., Technical Soils Bulletin No. 6, Soil Survey Unit, RPPD, Jamaica

SSU, 1989 (In prep.). JAMPLES User's Guide (Version 3.0). Batjes, N.H., Technical Soils Bulletin No. 16, SSU/RPPD, Jamaica.

APPENDIX I: Application of the SOMOMOD module to a number of climatic regions, soils and crops.

In this test case the SOMOMOD module is used to determine whether particular crops (e.g. maize and millet) can produce satisfactorily under rainfed conditions in the Bernard Lodge and Linstead area respectively.

First, it is shown how the user-defined state-variables can be calculated for a simulation run for maize and how these variables can be processed with SOMOMOD. Results of some test cases can be found at the end of this Appendix.

Stage-1: User-defined variables

Growing season: The length required from sowing to harvesting is 120 days for maize (grain).

TAWC: The maize crop is grown on deep, well structured and freely drained Whim soils that are formed over recent alluvium. Whim soils classify as fine-loamy, mixed, isohyperthermic members of Udic Haplustolls and show little or no soil-limitations for maize (SSU, 1986). Table A shows the total available water capacity (TAWC) in a representative Whim soil as a function of soil depth.

Table A. Total available water capacity soil layer in a Whim soil.

depth	moisture content (vol%) pF2.0	pF4.2	total available water for plants per soil layer (vol.%)
0-20cm	45.3	23.1	22.2
20-50cm	35.5	26.2	18.0
50-75cm	35.4	16.5	18.9
75-100cm	38.8	25.9	12.9

The estimated rooting depth of maize at the end of each month is shown in Table B. Note that Whim soils show no limitations to root development (SSU, 1986).

Table B. Average rooted soil depth (RD) for maize at the end of the subsequent months of the growing season and cumulated total available water capacity for the successive soil layers (TAWC).

month-i	maize (grain)	
	RD(i)	TAWC(i)
1	0-30 cm	52 mm
2	0-50 cm	98 mm
3	0-75 cm	146 mm*
4	0-100cm	178 mm

* 146 = 0.222x200 + 0.18x300 + 0.189x250 (mm, rounded-off figures)

<u>kc</u>: The weighed monthly crop coefficients for maize are derived from FAO (1979, pp. 101-104). Ideally, field trials should indicate whether these coefficients can be used succesfully with the Priestley & Taylor method of calculating PET.

Table C. Approximate crop coefficients for the crop development stages of maize.

development stage	time (days)	kc
initial stage	20	0.40
crop development stage	35	0.75
mid-season stage	40	1.05
late season stage	25	0.75

In this example the maize crop is sown at the beginning of a particular month. However, it is also possible to "plant" the crop in e.g. the middle of a month in which case a kc of 0.3 can be used for the period that the soil remains in "fallow".

The average monthly crop coefficients are calculated as follows:

<u>maize (grain)</u>:
month-1: kc= (20x0.40 + 10x0.75)/30 = 0.52
month-2: kc= (25x0.75 + 5x1.05)/30 = 0.80
month-3: kc= (30x1.05)/30 = 1.05
month-4: kc= (5x1.05 + 25x0.75)/30 = 0.80

The mean minimum seasonal water requirement (MWR) of the maize crop during a particular time period can now be calculated. For the August-November period in the Linstead area this is done as follows:

$$MWR = Sum[kc(i) \times PET(i)]$$
$$= 0.52 \times 144 + 0.80 \times 124 + 1.05 \times 122 + 0.80 \times 104 = 382 \text{ mm}$$

DEP(i): Indicative values for DEP(i) as a function of the crop type and prevailing conditions of ETm are shown in Table 1 (see also FAO, 1977 & 1979). Note that the tolerable range of depletion (DEP) of the "total available water capacity" is narrow for crops where the fresh part is harvested (e.g. lettuce) and relatively wide for crops grown for their dry parts (e.g. cereals). The tolerable level of depletion varies greatly with the crop development stage (FAO, 1979 p.36). This temporal variability in crop tolerance to water deficits can be studied with SOMOMOD provided adequate field observations are available. Until such studies are made, it is recommended to identify the highest possible value for mean seasonal ETm and to use the corresponding average value for DEP (Table 1). By doing this the potentially most limiting conditions are studied; results should therefore be conservative.

Stage-2: Model execution:

Now that the state variables have been quantified they can be entered into the model. First, the climatic data file for the study area is accessed; it contains the monthly rainfall and mean monthly PET data. Next, the user specifies the name of the crop, the length of the growing season (sowing-harvesting) in months and the soil type.

For each crop development stage - monthly period - the computer console prompts the user for the following input:
- kc
- TAWC of the root zone (mm)
- Maximum allowable depletion level (DEP(i)) as a function of ETm.

Subsequently, the user specifies:
- The percentage of total rainfall that is considered effective (the proposed default value is 90%).
- The first and last month of the 75%-dependable growing period as determined with RAINSTAT (SSU, 1988a). [For illustrative purposes simulations for the 'whole' year are presented in this paper.]

The programme subsequently calculates the actual probability of having conditions of rainfall and PET that allow for good growth of the crop on the specified soil under the assumption that the "other" land qualities are not limiting. Matching of the "other" land qualities with crop requirements is done separately using the MATMOD and LANDEV modules of JAMPLES (see SSU, 1989).

Results:

Results of 5 simulations are shown in self-explanatory Tables that should be studied in conjunction with the assumptions listed below the main table.

Table 1': Probability of rainfall meeting the water requirements for satisfactory growth of Maize grown under rainfed conditions on Whim soils in the Linstead area during pre-selected time periods. [See second table for the assumptions].

Time period	MWR	Nt	Ne	Prob.	interpretation for Maize
Jan.-Apr.	399	25	1	4	not-suitable
Feb.-May	436	25	3	12	not-suitable
Mar.-June	459	25	4	16	not-suitable
Apr.-July	470	25	12	48	marginally suitable
May-Aug.	471	25	20	80	highly suitable
June-Sep.	449	25	22	88	highly suitable
July-Oct.	424	25	22	88	highly suitable
Aug.-Nov.	386	25	24	96	highly suitable
Sep.-Dec.	354	25	24	96	highly suitable
Oct.-Jan.	338	25	20	80	highly suitable
Nov.-Feb.	332	25	13	52	moderately suitable
Dec.-Mar.	361	25	3	12	not-suitable

Assumptions used in the multiple-root zone soil water balance model.

Crop:Maize   Soil name: Whim

Month after sowing	1	2	3	4
kc	0.52	0.80	1.05	0.80
TAWC (mm/RDi)	52	98	146	178
DEP	0.60	0.60	0.60	0.70
RAWC (mm/RDi)	31	58	87	124

TAWC= total available water capacity of root zone in month i (RDi).
RAWC= readily available water capacity of root zone in month i, with RAWC= DEP*TAWC.
Nt= total number of years covered by the rainfall record (Period: 1952 - 1976).
Ne= number of years during which crop water requirements for satisfactory growth were met during a particular time period (annual crops only)
Prob.= probability of reaching at least satisfactory crop yields during a particular time period (Prob.= (Ne/Nt)*100 %).
MWR= Minimum Water Requirement for satisfactory growth of crop i.e. MWR= sum[ETm].
Effective rainfall is considered to be equal to 90 % of total monthly fall.

Table 2: Probability of rainfall meeting the water requirements for satisfactory growth of Maize grown under rainfed conditions on St-Ann variant soils in the Linstead area during pre-selected time periods. [See second table for the assumptions].

Time period	MWR	Nt	Ne	Prob.	interpretation for Maize
Jan.-Apr.	399	25	1	4	not-suitable
Feb.-May	436	25	2	8	not-suitable
Mar.-June	459	25	3	12	not-suitable
Apr.-July	470	25	11	44	marginally suitable
May-Aug.	471	25	19	76	highly suitable
June-Sep.	449	25	21	84	highly suitable
July-Oct.	424	25	22	88	highly suitable
Aug.-Nov.	386	25	24	96	highly suitable
Sep.-Dec.	354	25	24	96	highly suitable
Oct.-Jan.	338	25	18	72	moderately suitable
Nov.-Feb.	332	25	8	32	marginally suitable
Dec.-Mar.	361	25	3	12	not-suitable

Assumptions used in the multiple-root zone soil water balance model.

Crop:Maize   Soil name: St-Ann variant

Month after sowing	1	2	3	4
kc	0.52	0.80	1.05	0.80
TAWC (mm/RDi)	35	70	103	140
DEP	0.60	0.60	0.60	0.70
RAWC (mm/RDi)	21	42	61	98

TAWC= total available water capacity of root zone in month i (RDi).
RAWC= readily available water capacity of root zone in month i, with RAWC= DEP*TAWC.
Nt= total number of years covered by the rainfall record (Period: 1952 - 1976).
Ne= number of years during which crop water requirements for satisfactory growth were met during a particular time period (annual crops only)
Prob.= probability of reaching at least satisfactory crop yields during a particular time period (Prob.= (Ne/Nt)*100 %).
MWR= Minimum Water Requirement for satisfactory growth of crop i.e. MWR= sum[ETm].
Effective rainfall is considered to be equal to 90 % of total monthly fall.

Table 3: Probability of rainfall meeting the water requirements for satisfactory growth of Maize grown under rainfed conditions on Union Hill soils in the Linstead area during pre-selected time periods. [See second table for the assumptions].

Time period	MWR	Nt	Ne	Prob.	interpretation for Maize
Jan.-Apr.	399	25	0	0	not-suitable
Feb.-May	436	25	1	4	not-suitable
Mar.-June	459	25	3	12	not-suitable
Apr.-July	470	25	11	44	marginally suitable
May-Aug.	471	25	19	76	highly suitable
June-Sep.	449	25	20	80	highly suitable
July-Oct.	424	25	22	88	highly suitable
Aug.-Nov.	386	25	24	96	highly suitable
Sep.-Dec.	354	25	20	80	highly suitable
Oct.-Jan.	338	25	14	56	moderately suitable
Nov.-Feb.	332	25	5	20	not-suitable
Dec.-Mar.	361	25	2	8	not-suitable

Assumptions used in the multiple-root zone soil water balance model.

Crop: Maize   Soil name: Union Hill

Month after sowing	1	2	3	4
kc	0.52	0.80	1.05	0.80
TAWC (mm/RDi)	30	65	65	65
DEP	0.60	0.60	0.60	0.70
RAWC (mm/RDi)	18	39	39	45

TAWC= total available water capacity of root zone in month i (RDi).
RAWC= readily available water capacity of root zone in month i, with RAWC= DEP*TAWC.
Nt= total number of years covered by the rainfall record (Period: 1952 - 1976).
Ne= number of years during which crop water requirements for satisfactory growth were met during a particular time period (annual crops only)
Prob.= probability of reaching at least satisfactory crop yields during a particular time period (Prob.= (Ne/Nt)*100 %).
MWR= Minimum Water Requirement for satisfactory growth of crop i.e. MWR= sum[ETm].
Effective rainfall is considered to be equal to 90 % of total monthly fall.

Table 4: Probability of rainfall meeting the water requirements for satisfactory growth of Maize grown under rainfed conditions on Whim soils in the Bernard Lodge area during pre-selected time periods. [See second table for the assumptions].

Time period	MWR	Nt	Ne	Prob.	interpretation for Maize
Jan.-Apr.	409	31	0	0	not-suitable
Feb.-May	448	32	0	0	not-suitable
Mar.-June	470	32	0	0	not-suitable
Apr.-July	480	33	1	3	not-suitable
May-Aug.	481	33	2	6	not-suitable
June-Sep.	458	32	1	3	not-suitable
July-Oct.	432	31	1	3	not-suitable
Aug.-Nov.	394	33	6	18	not-suitable
Sep.-Dec.	362	30	10	33	marginally suitable
Oct.-Jan.	345	30	5	16	not-suitable
Nov.-Feb.	339	29	0	0	not-suitable
Dec.-Mar.	369	27	0	0	not-suitable

Assumptions used in the multiple-root zone soil water balance model.

Crop:Maize   Soil name: Whim

Month after sowing	1	2	3	4
kc	0.52	0.80	1.05	0.80
TAWC (mm/RDi)	52	98	146	178
DEP	0.60	0.60	0.60	0.70
RAWC (mm/RDi)	31	58	87	124

TAWC= total available water capacity of root zone in month i (RDi).
RAWC= readily available water capacity of root zone in month i. with RAWC= DEP*TAWC.
Nt= total number of years covered by the rainfall record (Period: 1951 - 1984).
Ne= number of years during which crop water requirements for satisfactory growth were met during a particular time period (annual crops only)
Prob.= probability of reaching at least satisfactory crop yields during a particular time period (Prob.= (Ne/Nt)*100 %).
MWR= Minimum Water Requirement for satisfactory growth of crop i.e. MWR= sum[ETm].
Effective rainfall is considered to be equal to 90 % of total monthly fall.

Table 5: Probability of rainfall meeting the water requirements for satisfactory growth of Millet grown under rainfed conditions on Whim soils in the Bernard Lodge area during pre-selected time periods. [See second table for the assumptions].

Time period	MWR	Nt	Ne	Prob.	interpretation for Millet
Jan.-Mar.	272	31	0	0	not-suitable
Feb.-Apr.	310	32	0	0	not-suitable
Mar.-May	333	32	0	0	not-suitable
Apr.-June	338	32	2	6	not-suitable
May-July	343	33	4	12	not-suitable
June-Aug.	342	32	1	3	not-suitable
July-Sep.	318	32	1	3	not-suitable
Aug.-Oct.	291	32	8	25	marginally suitable
Sep.-Nov.	267	30	17	56	moderately suitable
Oct.-Dec.	246	30	12	40	marginally suitable
Nov.-Jan.	237	28	3	10	not-suitable
Dec.-Feb.	241	27	0	0	not-suitable

Assumptions used in the multiple-root zone soil water balance model.

Crop:Millet   Soil name: Whim

Month after sowing	1	2	3
kc	0.40	1.05	0.80
TAWC (mm/RDi)	52	100	150
DEP	0.70	0.70	0.80
RAWC (mm/RDi)	36	70	120

TAWC= total available water capacity of root zone in month i (RDi).
RAWC= readily available water capacity of root zone in month i, with RAWC= DEP*TAWC.
Nt= total number of years covered by the rainfall record (Period: 1951 - 1984).
Ne= number of years during which crop water requirements for satisfactory growth were met during a particular time period (annual crops only)
Prob.= probability of reaching at least satisfactory crop yields during a particular time period (Prob.= (Ne/Nt)*100 %).
MWR= Minimum Water Requirement for satisfactory growth of crop i.e. MWR= sum[ETm].
Effective rainfall is considered to be equal to 90 % of total monthly fall.

APPENDIX II: Methodology used to approximate the actual rate of crop evapotranspiration (ETa) as a function of the soil-water supply (SSW).

Under the assumption that rainfall is evenly distributed the following steps are used to calculate the actual rate of evapotranspiration (ETa) of the crop in the ith month of year j:

Step 1:

Calculate the soil water deficit index (SWDI) which indicates the degree to which the crop's water requirement for good growth would be met if ETa was equal to ETm:

$$SWDI(i,j) = SSW(i-1,j) + R(i,j) - kc(i) \times PET(i)$$

(See Section 4 of the report for key to abbreviations)

Step 2:

a) IF $(1-DEP(i)) \times TAWC(i,j) <= SWDI(i,j) <= TAWC(i,j)$ THEN there is no water deficit.
   $ETa(i,j) = ETm(i) \times FAC(i,j)$ with $FAC(i,j) = 1$
   Proceed with step 4.

b) IF $SWDI(i,j) < (1-DEP(i)) \times TAWC(i,j)$ THEN there is some degree of water deficit.
   $ETa(i,j) = ETm(i) \times FAC(i,j)$ with $0 <= FAC(i,j) < 1$
   Proceed with step 3.

Step 3:

For the considered time period calculate the factor FAC(i,j) which reflects that soil moisture becomes less readily available to plants as the soil moisture reserve is gradually depleted. A curvilinear relationship (square root function) is assumed for this relationship (see Figure 1).

$$FAC(i,j) = [SWDI(i,j) \ / \ (1-DEP(i)) \times TAWC(i,j)]^{1/2}$$

The response of yield to water supply is quantified through the yield response factor (ky) which relates relative yield decrease (1-Ya/Ym) to relative evapotranspiration deficit (1-ETa/ETm) (FAO, 1979). The decrease in yield is proportionally less with the increase in water deficit for those crops that have ky<1 than for those with ky>1.

For a "sensitive" crop such as maize - most stringent condition- the above relationship can be used to approximate the minimum value permissible for FAC(i,j), in the relationship ETa = FAC x

ETm, required to ensure satisfactory production. In the case of maize the yield response factor over the whole growing season is about 1.25 (FAO, 1979). Under the general assumption that economic conditions for crop production become less than optimal when the relative yield (Ya/Ym) of the crop falls below 80% in a preselected number of years (probability level) the critical value for FAC can be calculated:

$$(1-Ya/Ym) = 1 - 0.8 = 1.25 \times (1-ETa/ETm)$$
$$ETa = 0.84 \times ETm$$

For sorghum, a crop relatively tolerant of drought, the ky factor for the total growing period is about 0.9 (FAO, 1979). Using the above assumption it follows that:

$$(1-Ya/Ym) = 1 - 0.8 = 0.9 \times (1-ETa/ETm)$$
$$ETa = 0.77 \times ETm$$

The critical limit for FACcr has been set at 0.8 in our model; this is considered to be a stringent condition.

<u>Step 4</u>:

The soil water supply - soil moisture reserve and its recharge by rainfall - in a particular month (i) in a given year (j) is approximated with the following equation:

$$SWS(i,j) = SSW(i-1,j) + R(i) - FAC(i) \times KC(i) \times PET(i)$$

with $FACcr \le FAC(i) \le 1.0$