Soil Water Balance in the Sudano-Sahelian Zone (Proceedings of the Niamey Workshop, February 1991). IAHS Publ. no. 199, 1991.

A risk-probability map for millet production in southwest Niger

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Abstract Soil water studies for millet (*Pennisetum americanum* L.) were carried out at the ICRISAT Sahelian Center at Sadoré, Niger, in the 1986, 1987 and 1988 growing seasons. The soil water model SWATRER was calibrated using soil and plant data for millet under typical field conditions for West Africa. Soil profile matric potential and water content were measured twice a week. The soil hydraulic conductivity and the moisture retention characteristics of the test field were also determined. Actual soil evaporation was measured after several rains. Stomatal conductances were measured and actual transpiration was calculated using the Penman-Monteith equation. Dry matter and leaf area index were determined throughout the growing season. Good agreement was obtained between measured and simulated soil water data. Long-term crop water balance simulations were carried out with use of the calibrated model for Gao in Mali and for Tillaberi, Niamey and Gaya in Niger. As a measure of plant water stress, the ratio between the yearly actual transpiration CT_a and yearly potential transpiration CT_p was considered. A threshold index for this ratio was used ($CT_a/CT_p = 0.9$) to construct a risk-probability map for millet production in southwest Niger.

INTRODUCTION

In southwest Niger drought is considered as a major reason for the low and erratic yield of millet, but the exact interrelationships between drought and millet yield are still not fully understood. This lack of understanding results mainly from an unsatisfactory description of drought . In southwest Niger, as in other regions of the Sahel zone, the mean evaporative demand of the atmosphere exceeds the mean annual rainfall. The ratio of both quantities has been used as an index of drought. However, this index is not strongly correlated with crop yield. A better correlation is obtained when only the growing season is considered. Also in this case some measure of evaporative demand must be defined. Reference crop evapotranspiration, pan evaporation and Piche evaporation have been used in this respect and also the actual crop water requirement has been proposed, but none of these quantities is entirely satisfactory, since only one value for the entire growing season is given (Dancette & Hall, 1979). Similarly, one single value for the amount of precipitation during the growing season usually does not allow conclusions about the rainfall distribution and efficiency. Soil water models, with a high resolution in time, allow a better estimation of the adequacy of rainfall in satisfying crop water needs, especially when long term synoptic weather data are analysed (Dancette & Hall, 1979). These authors show a crop water supply probability map for millet in Senegal, that is based on such considerations. For regional water and crop management purposes such maps are highly valuable.

The objective of our research in southwest Niger was to prepare a similar map. To this end soil water studies with millet on the widespread luvic Arenosols in southwest Niger were carried out. The field data were used to calibrate the soil water simulation model SWATRER (Dierckx *et al.*, 1986; Raes *et al.*, 1986), which is a further development of previous work, described by Feddes *et al.* (1978) and by Belmans *et al.* (1983). The model SWATRER has been used for example by Dierckx *et al.* (1988) to simulate the soil water dynamics of irrigated corn. The calibrated model was used to simulate the soil water dynamics for millet at different locations in southwest Niger using long-term daily weather data. From the simulation results a risk probability map for the production of millet in southwest Niger was prepared. The procedure, as well as the results, will briefly be discussed in the next sections.

MODEL DESCRIPTION

The model has been described in great detail by Feddes *et al.* (1978). Additional information may be found in Belmans *et al.* (1983) and Dierckx *et al.* (1986). Therefore, in the present paper only a brief overview will be given. The central part of the model is the soil water flow equation to which a sink term is added to describe root water extraction. This equation in one dimensional space can be given as:

$$\partial\theta/\partial t = \partial(K\partial H/\partial z)/\partial z - S(z,t) \qquad (1)$$

in which expression $\partial\theta/\partial t$ is the change of soil water content at depth z as a function of time, K is the soil hydraulic conductivity, H is the total potential of the soil water and $S(z,t)$ is the rate of soil water extraction by roots. To use equation (1), the soil hydraulic characteristics (conductivity and retention) must be known and the strength of the sink term $S(z,t)$ must be specified. The strength of this sink term is usually described as a function of the evaporative demand of the atmosphere above the canopy, of the root distribution of the crop and of the soil dryness in the rooting zone (see Belmans *et al.*, 1983). In SWATRER, the evaporative demand of the atmosphere is estimated with use of an expression proposed by Doorenbos & Pruitt (1977). These authors describe the daily potential evapotranspiration ET_0 of a well-watered short grass surface as:

$$ET_0 = c\left\{\frac{\Delta}{\Delta + \gamma} R_n + \left[1 - \frac{\Delta}{\Delta + \gamma}\right] f(u) \left[e_s - e_a\right]\right\} \tag{2}$$

where Δ = rate of change of saturated vapour pressure with temperature, γ = psychrometic constant, R_n = the (equivalent) net radiation, $f(u)$ = a wind function and $(e_s - e_a)$ = the mean daily vapour pressure deficit of the atmosphere above the canopy. The quantity c in equation (2), denotes the site specific matching factor, see Doorenbos & Pruitt (1977). The same authors propose for $f(u)$ the expression:

$$f(u) = a + bu \tag{3}$$

where a (= 0.27) and b (= 0.0027) are constants and u = wind speed at 2 m height. In SWATRER this function, originally derived for short grass, is also used.

The daily potential crop evapotranspiration, ET_c, is calculated from ET_0 of equation (2) as:

$$ET_c = K_c ET_0 \tag{4}$$

where K_c = the crop coefficient which depends on the growth stage of the crop. The values of K_c varied from 1.0 during the first stage, 1.1 in the third stage, to 0.25 at the end of the fourth stage.

Since millet, especially during the early part of the growing season, only partly covers the soil, a distinction between evaporation and transpiration is appropriate. The daily potential soil evaporation E_p in SWATRER is estimated as:

$$E_p = l\, e^{-m\,\mathrm{LAI}} ET_c \tag{5}$$

where l and m are crop specific coefficients that can be determined using regression analysis, LAI = leaf area index, and ET_c is given by equation (4). The values used for l and m were l = 1.0 and m = 0.6.

The daily potential transpiration T_p is calculated from ET_c and E_p as:

$$T_p = ET_c - E_p \tag{6}$$

After daily values for T_p and E_p are thus calculated, estimates for the actual values of transpiration T_a and evaporation E_a are needed. In this respect SWATRER follows work by Hoogland *et al.* (1981) and by Ritchie (1972). For further model information the reader is referred to the original publications mentioned earlier, or to Bley (1990). For the model calibration soil, crop and weather data were obtained from the following field experiments.

MATERIALS AND METHODS

Field experiments

In 1986, 1987 and 1988 soil water studies for millet were carried out at the ICRISAT Sahelian Center at Sadoré, 45 km south of Niamey, Niger. In 1986 preliminary experiments were conducted, whereas in 1987 and 1988 systematic soil water studies were carried out under typical West African field conditions (Bley, 1990). The deep sandy soil is described as a psammentic Paleustalf (West *et al.*, 1984) (or luvic Arenosol, FAO Class.) and is particularly well suited for soil water studies. The soil surface on the ICRISAT Sahelian Center is horizontal and thus runoff was assumed to be negligible. The crop studied was millet (*Pennisetum americanum* L. cv. CIVT) with a growing period of 100 days. The planting density was 10 000 pockets per hectare, with approximately three plants per pocket. No fertilizer was applied but crop residues from the previous year were left on the field.

The soil water studies were conducted in a field that was subdivided into plots of 10 m × 10 m. In each plot there was one neutron probe access tube (of 260 cm length) and six tensiometers (at depths 15, 45, 75, 105, 135 and 165 cm). In total there were four replicates. Soil moisture measurements (at 13 depths) and soil matric potential measurements were made twice every week during the growing season. Soil evaporation was measured with microlysimeters, as described by Boast (1986), on 28 days in 1987 and on 25 days in 1988. On each day the lysimeters were weighed up to six times in three replicates.

The leaf area index LAI was determined at 40, 60 and 75 days after sowing in 1987, and at 42, 65 and 80 days after sowing in 1988. Percent plant cover was measured three times in 1987 (41, 53 and 77 days after sowing) and once in 1988 (68 days after sowing). Crop height was measured 13 times in 1987 and nine times in 1988. In 1987 as well as in 1988 the root distribution of the millet crop was determined a number of times in an accompanying research programme (Mr H. Hafner, University of Hohenheim). Total dry matter production and grain yield were determined at harvest. Diurnal measurements of stomatal conductance were made using a diffusion porometer on six days during 1987 and 1988. Measurements were taken every 2 h from dawn to dusk on both leaf surfaces of every second leaf beginning with the flag leaf. The sensor was shaded, as recommended by Azam-Ali (1983).

The soil hydraulic properties were also determined, in the field as well as in the laboratory. The laboratory determinations were carried out with standard methods. In the field the hydraulic conductivity was measured with a procedure described by Hillel *et al.* (1972), and the moisture retention characteristics with the use of neutron probe data and tensiometer readings. Finally, relevant weather data were collected by the ICRISAT Sahelian Center weather unit, and by an automatic weather station run by the Institute of Hydrology, Wallingford, UK, which was located near the experimental field.

Model calibrations

The collected field data from 1987 and 1988 were used to calibrate SWATRER. The field determined soil hydraulic properties as well as the laboratory determined ones were used in the model to simulate soil water content, soil evaporation and crop transpiration. Calculated values were compared with measured data until a satisfactory agreement was obtained. The measured transpiration data were derived using the Penman-Monteith equation:

$$\lambda E = \{ \Delta R_n + \rho c_p (e_s - e_a)\, GA \} / \{ \Delta + c_p / \gamma\, (1 + GA/GS) \} \qquad (7)$$

where λE = instantaneous transpiration rate, ρ = density of the air above the canopy, c_p = specific heat of the air, GA = aerodynamic conductance of the air over the canopy and GS = canopy conductance for water vapour transport. The other symbols used in equation (7) have been explained previously.

The net radiation R_n in equation (7) was calculated as:

$$R_n = R_0 - R_s \qquad (8)$$

where R_0 = net radiation over the canopy and R_s = net radiation at the soil surface. The quantity R_s was estimated as:

$$R_s = \mathrm{R}_0\, \mathrm{e}^{-M\,\mathrm{LAI}} \qquad (9)$$

with M = the extinction coefficient of the crop. Following Wallace *et al.* (1986) the value M = 0.5 was taken.

The aerodynamic conductance GA in equation (7) was calculated as the reciprocal of the aerodynamic resistance r_{av}, which was estimated according to Wallace *et al.* (1984) as:

$$r_{av} = r_{am} + r_b \qquad (10)$$

where r_{am} = aerodynamic resistance to momentum transfer and r_b = excess resistance. The quantities r_{am} and r_b were calculated as:

$$r_{am} = \ln^2 \{ (z - d)/z_0 \} / k^2 u \qquad (11)$$

and

$$r_b = 1.5 \ln \{ (z - d) / z_0 \} / k^2 u \qquad (12)$$

The quantities d and z_0 in equations (11) and (12) were approximated as d = $0.63h$ and z_0 = $0.13h$ (Monteith, 1975) with h being the crop height. In equations (11) and (12) k = von Kármánn's constant (= 0.41) and u = wind speed at height z.

The canopy conductance GS, finally, was calculated following Grace, (1983) as:

$$GS = (gs_u + gs_1)\ \mathrm{LAI} \tag{13}$$

where gs_u and gs_1 = stomatal conductances of the upper and lower sides of the leaves respectively.

Long-term simulations

With the calibrated SWATRER model, soil water simulations for millet, grown on deep luvic Arenosols in other parts of southwest Niger and Mali, were carried out. Simulations were conducted for Gao (Mali, 16.16°N, 0.03°W), Tillaberi (14.07°N, 1.3°E), Niamey (13.3°N, 2.08°E) and Gaya (11.59° N, 3.3°E). The period of simulation for Gao was 28 years, for Tillaberi 26 years and Niamey 29 years between 1950 and 1978. For Gaya weather data were available for only two years (1976 and 1977). Simulations always started on the first day after 1 May with at least 20 mm of rainfall and with additional rainfall within the next two weeks. Rain water prior to this date was stored as soil moisture. The length of the growing season was set equal to 100 days. Simulations were terminated at the end of the calendar year. For each year and location the ratio of cumulative actual transpiration CT_a and potential transpiration CT_p was calculated as a measure of water stress. At the end of all simulations such values were evaluated statistically. These data were then used in conjunction with other climatic data from southwest Niger (Sivakumar, 1986a,b; Sivakumar *et al.*, 1979) to prepare a risk probability map for millet production in southwest Niger.

RESULTS AND DISCUSSION

Figure 1 shows growing season rainfall and comparisons of calculated and measured soil water data at Sadoré for 1987 and 1988. There was good agreement between simulated and measured soil water content at 60 cm and 200 cm depth. A similar agreement between measured and simulated soil water values for other depths was obtained.

Figure 2 shows daily values of T_p at Sadoré as calculated with SWATRER. Except for one period in 1987 (shaded in Fig. 2) the daily actual evapotranspiration T_a was always equal to T_p. Also shown in Fig. 2 are values for the transpiration, as calculated with the Penman-Monteith equation. In 1987 there was sometimes reasonable agreement between the results from SWATRER an the Penman-Monteith equation, but in 1988 the Penman-Monteith values were lower.

In view of the good agreement between calculated and measured soil water content, and the fair agreement between simulated and measured transpiration, the calibration of SWATRER was considered as adequate. The model was then used to simulate the soil water dynamics for a farmer's millet field at Gao (Mali), Tillaberi, Niamey and Gaya. Results from these simulation runs are shown in Figs 3 and 4. Since only two years of data were available for Gaya in south Niger, only data for Gao (Mali), Tillaberi

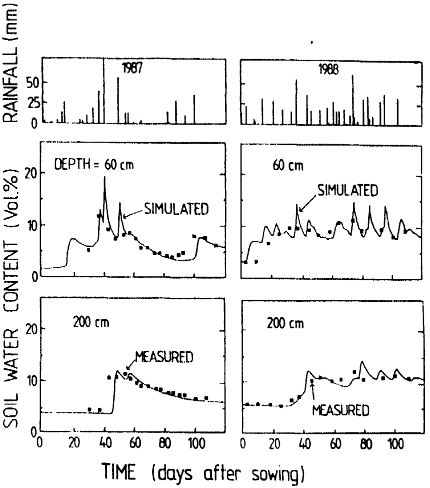

Fig. 1 Comparison of measured (■) and calculated (--------) soil water content at 60 and 200 cm depth for 1987 (left) and 1988 (right).

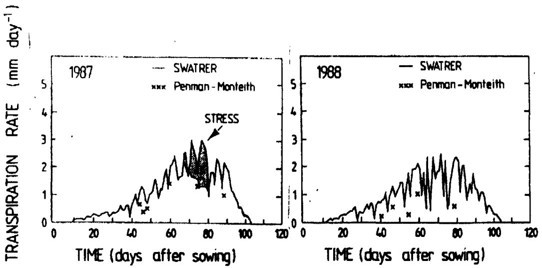

***Fig. 2** Potential and actual transpiration as estimated with SWATRER and as calculated with the Penman-Monteith equation; 1987 (left) and 1988 (right).*

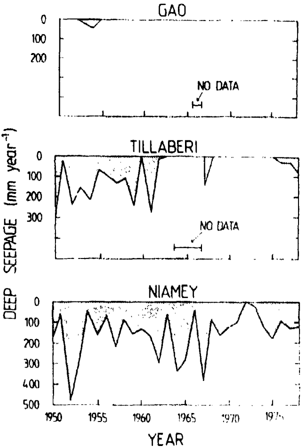

Fig. 3 The annual deep seepage during the period 1950–1978 as estimated with SWATRER for Gao, Tillaberi and Niamey.

and Niamey will be shown.

In Fig. 3 the yearly amount of calculated deep seepage (at 270 cm depth) at the three locations is shown. The figure shows for Niamey a mean amount of deep seepage of nearly 200 mm per year. Hence, in the southern part of Niger a considerable amount of groundwater recharge appears to occur. At the same time however, there is a risk, that plant nutrients are leached from soils that are already low in nutrients (Bley, 1990).

Additional model results are shown in Fig. 4. For the period 1950–1978 the yearly ratio of actual to potential transpiration is shown. With a few exceptions (drought years 1968–1972) this ratio for Niamey and Tillabery is close to 1.0; for Gao however, the mean value is only 0.5. It appears that in southern Niger an insufficient water supply is not the main cause for low productivity. According to Bley (1990) a considerable increase in crop yield is possible when fertilizers are applied and crop residues are left on the field.

A summary of simulation results is given in Table 1. Shown are mean values for various components of the soil water balance for millet in southwest Niger and Mali. The data pertain to the period 1950–1978 and are, with the exception of rainfall, calculated with SWATRER. It should be noted that Table 1 refers to a 100 day growing period.

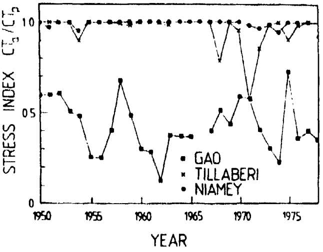

Fig. 4 The annual ratio of cumulative actual CT_a and potential CT_p transpiration as estimated with SWATRER during the period 1950–1978 for Gao, Tillaberi and Niamey.

Table 1 Mean value for different water balance components for a 100-day millet variety (mm per growing season), as calculated with SWATRER for the period 1950–1978

Water balance component (mm)	Station: Gao	Tillaberi	Niamey	Gaya*
Rainfall	211	415	487	527
	(217)	(445)	(595)	(746)**
Potential evapotranspiration	1370	665	662	610
Potential transpiration	283	132	130	121
Actual transpiration	115	124	129	121
Actual evaporation	94	150	163	180
Deep seepage	2	75	57	33
	(3)	(83)	(157)	(272)**

* Only two years of data.
** From sowing until the end of the calendar year.

With Fig. 5, finally an attempt is made to generalize simulation results for southwest Niger. Shown is a risk-probability map for millet production from the water supply point of view. The map shows three probability lines (90%, 75%, and 60%). They indicate the percentage of years that the annual ratio of actual to potential transpiration for a representative 100-day millet variety is equal to 0.9. Considerable yield depressions however occur, when this ratio is less than 0.9 (Penning de Vries *et al.*, 1989). An exact relationship between this ratio and the yield was not yet been established. The development of such a relationship is anticipated for future work.

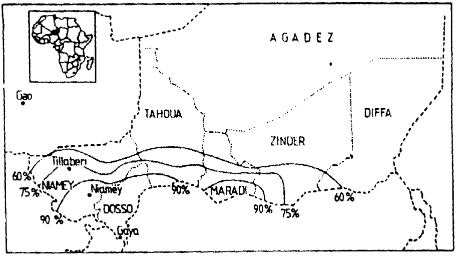

Fig. 5 Risk-probability map for millet production in southwest Niger, as obtained with SWATRER.

CONCLUSIONS

From a comparison of measured and calculated soil moisture and transpiration data it is concluded that the SWATRER model adequately describes the soil water dynamics of millet for the conditions in southwest Niger. It therefore appears to be justified to simulate also the soil water balance for millet over longer time periods. From the regional simulation results a risk-probability map for millet production can be presented. From an analysis of the map it is concluded, that in large parts of southwest Niger the crop water supply, in general, cannot be considered as the most limiting factor in millet production.

Acknowledgements The research reported on was financially supported by the German Research Foundation (DFG). Valuable assistance from Dr J. S. Wallace and Dr J. H. C. Gash (Institute of Hydrology, Wallingford, UK) is thankfully acknowledged. Weather data were generously provided by AGRHYMET (Niamey, Niger).

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