Hydrological simulation as a tool for agricultural drought assessment

R.E. SCHULZE
Agricultural Catchments Research Unit, Department of Agricultural Engineering, University of Natal, Pietermaritzburg 3201

Abstract

Following a discussion on the concepts of drought and of hydrological modelling, the ACRU Model is described and then applied at three locations in Natal in order to compare the severity of the 1979-1983 drought with previous droughts in the past 50 years. This is done by using the Model as a simulator of runoff, of supplementary irrigation requirements and of crop yields. Hydrological modelling is shown to be a potentially powerful tool in rational drought assessment. The simulations indicate that the current drought may be classed as the worst experienced in the past 50 years. However, the results also indicate that drought in terms of water resources and water requirements and crop yields do no necessarily coincide.

Introduction

That the intensity of the drought of the early 1980's has reached crisis proportions over many parts of Southern Africa is felt by rural and urban dweller alike. Irrigating time allotments have been curbed, farm dams have dried up, a succession of crop failures has placed severe demands on assistance to farmers by the State and urban water usage has been restricted by up to 50%. It has been maintained by many that this is the worst drought in "living memory" and stated by public officials that we are in the grips of the "200 year" and even the "500 year drought".

As scientists it is important that perceptions of a natural hazard such as drought do not cloud our objectivity and it is up to us to make rational assessments of the situation we are in. Within the scope of hydrology and engineering in an agricultural context our concerns lie with the effects of drought

- on water resources supply and demand, i.e. on runoff generated and crop irrigation requirements, and
- on crop yield losses through moisture stress.

A rational method of assessing the above is the application of hydrological modelling to drought situations. In this paper an agrohydrological model developed in the Department of Agricultural Engineering at the University of Natal in Pietermaritzburg, namely the ACRU Model, is used to illustrate the severity of the drought in terms of runoff, supplementary irrigation requirements and crop yield estimates at three selected locations in Natal. As a preamble to the hydrological model application, the concept of drought is first discussed. Some basic aims and methods of hydrological modelling are then examined, before the ACRU Model is described. Finally simulations are presented from which the severity of the present drought is viewed in a historic perspective.

Droughts: Concepts

A "normal" climate, as described by mean values, very seldom exists and information concerning the "extremes" of climate is often more important than average conditions. One such "extreme" of climate is the phenomenon of drought. A study of drought requires an objective definition but to date no universally acceptable definition has been developed, partly because drought is a "non-event" as opposed to a distinct event such as a flood (Hershfield, Brakensiek and Comer, 1973).

Drought is a geophysical phenomenon referring to subnormal conditions of water occurrence in some physical environment like the atmosphere, the soil, a region or a river. Confusion arises when an attempt is made to apply a single definition to a drought. According to Thomas (1965), meteorological drought differs from agricultural drought and hydrological drought in turn differs from both of these. A meteorological drought can be defined as a prolonged and abnormal moisture deficiency. Agricultural drought is said to exist when soil moisture is depleted so that the yields of plants are reduced considerably. Both meteorological and agricultural droughts can be terminated by rainfall. Hydrological drought, on the other hand, can be thought of as a period during which the actual water supply is less than the minimum water supply necessary for normal operations in a particular region (Thomas, 1965). Drought is therefore a relative rather than an absolute condition.

From the above descriptions drought may be understood as being a supply and demand phenomenon. Hence Gibbs' (1975) qualitative definition of it as a "lack of sufficient water to meet requirements" is probably as satisfactory a general definition as any other. It is essential to distinguish at the outset between drought and aridity, where both are characterized by a lack of water, but, while aridity carries the connotation of a more or less permanent climatic condition, drought is a temporary condition.

Whatever criterion for drought is used, general analysis should always be concerned with the following aspects (Yevjevich, 1967):

- the duration of periods meeting non-exceedence criteria (for example, x consecutive days with less than y mm per day);
- the probability of occurrence (for example, of a drought of selected duration or intensity);
- its severity;
- its time of occurrence within the annual cycle; and
- its areal extent.

While this assessment does not deal with Yevjevich's five criteria *per se*, it does cover all the criteria indirectly from the specific point of view of drought assessment by hydrological modelling.

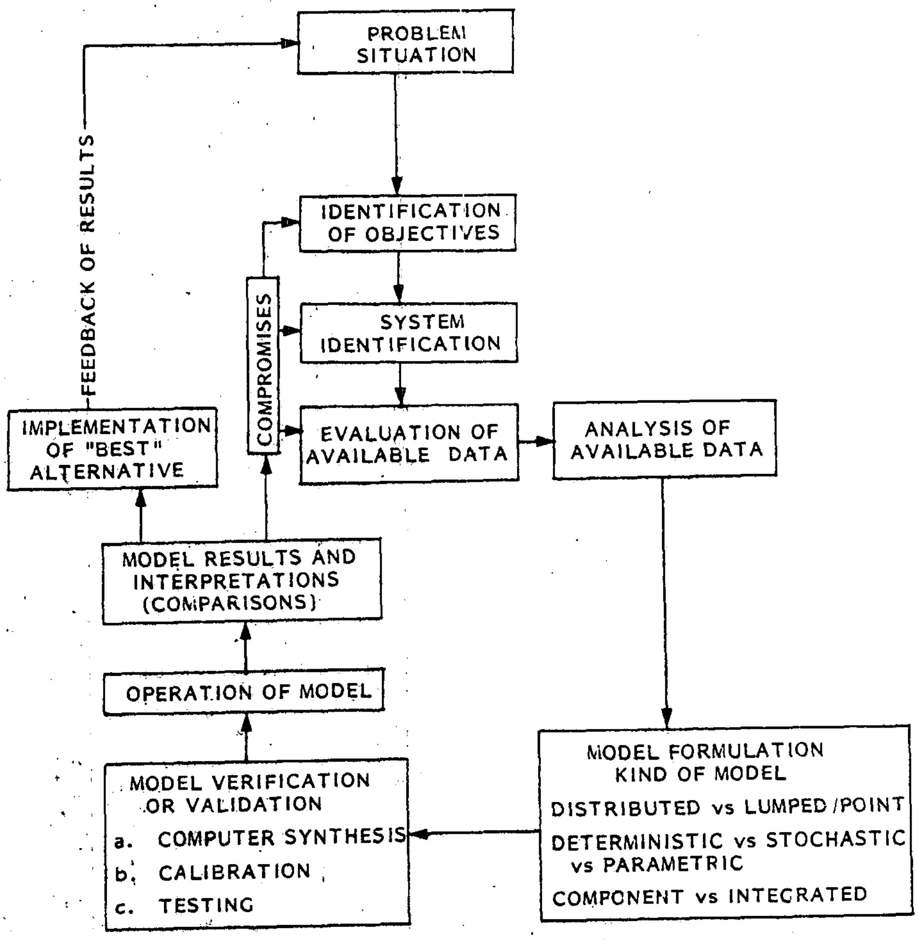

Figure 1
Conceptual framework of a hydrological model (After Riley and Hawkins, 1976)

Hydrological Modelling: Background

A hydrological model provides a way of transferring knowledge from a measured or a study situation to an unmeasured situation where management decisions are needed in regard to water resources systems (Branson *et al.*, 1981). A hydrological model is therefore a quantitative expression of observation, analysis/simulation, and prediction/assessment for planning, design and management.

Literature and practice abound with a multitude of types of models developed for different applications related to water resources, for example, for data management, design, operation, river basin management or research and teaching (Fleming, 1975). All sound conceptual hydrological models, however, have been developed in a series of thought and action steps. An adaptation of these steps as given by Riley and Hawkins (1976) is illustrated in Figure 1. The conceptual framework according to Riley and Hawkins (1976) comprises.

- a problem situation; for which
- objectives have to be identified;
- available data have to be evaluated then analysed;
- a conceptual model has to be created to represent the various systems of the real world; and this in terms of model complexity;
- a working computer model has to be developed to quantify the various processes identified in the conceptual model;
- the model (and/or component parts thereof) has to be verified or validated or calibrated against observed data;
- thereafter the model has to be operated, either as a predictive tool or for detection or identification of certain effects (for example, of drought);
- the results have to be interpreted; and, finally and ideally,
- alternatives to the model should be considered in relation to the original problem situation.

The ACRU* Model

In terms of the framework of hydrological model development outlined in the previous section, the ACRU Model has been (and is being further) developed for general use, but with specific applicability in Southern Africa. It is a conceptual, integrated (i.e. multi-purpose and multi-component) model outputting (at present) either runoff elements (stormflow and baseflow) or supplementary irrigation requirements (dependent on the interplay of crop and soil characteristics with rainfall and evaporative demand) or seasonal crop yields (maize and sugarcane). The Model uses daily input of climatic data (rainfall and evaporation/temperature). The basis of the Model revolves around multi-soil-layer moisture budgeting. Model components and model performance have been tested under diverse conditions using data from hydrological and agricultural research stations in South Africa and in the U.S.A. and results of various component

*The Model name is derived from the Agricultural Catchments Research Unit of the Department of Agricultural Engineering at the University of Natal, Pietermaritzburg.

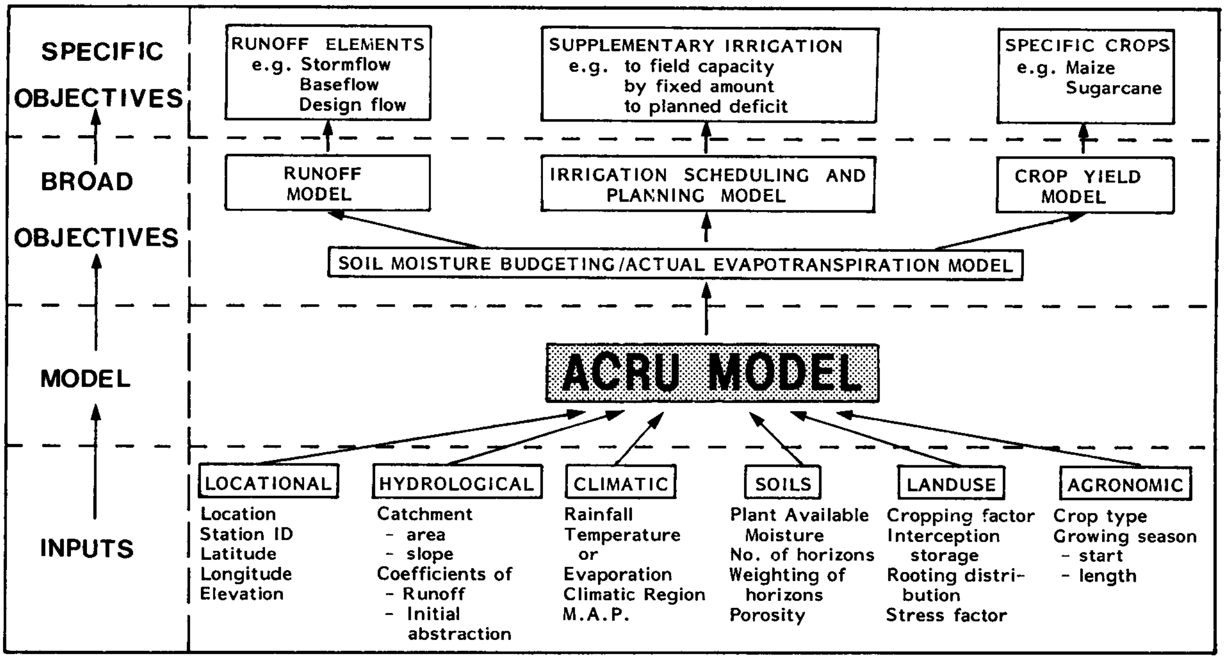

Figure 2
The ACRU Model

tests have been published by Clemence and Schulze (1982) and by Schulze (1982a, 1982b and 1983). A full description of the Model, including verification with goodness of fit statistics is given by Schulze (1984). Crop yield submodels used have been described and tested by Du Pisani (1978) and by Thompson (1976). The concepts of the ACRU Model are summarized in Figure 2. It is not the purpose of this paper to describe in detail the structure of the Model. In view of its application to a drought analysis, however, two important elements of the model that are related to the assessment of plant stress and moisture availability are illustrated below.

The partitioning and redistribution of moisture

From the point of view of moisture budgeting at daily level the partitioning and redistribution of moisture in the ACRU Model is depicted diagrammatically in Figure 3. In a two-layered soil profile that precipitation (P) which is not abstracted as interception

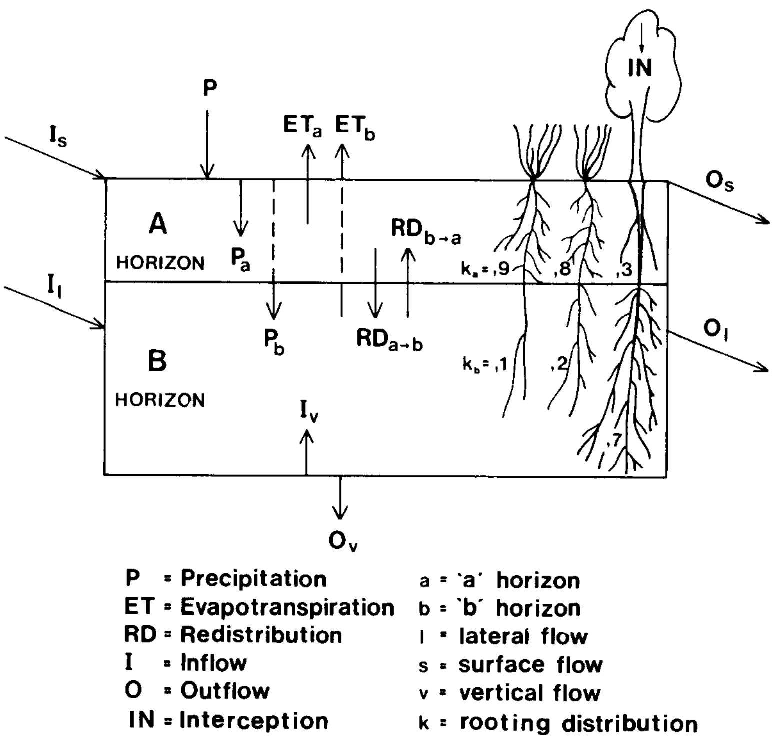

Figure 3
Partitioning and redistribution of moisture

(IN) or as overland flow (O_s), first infiltrates into the A-horizon (P_a). When that is "filled" (in relation to the plant available and porosity values of that horizon) the remaining precipitation (P_b) would percolate into the B-horizon. Should the B-horizon attain a degree of saturation, vertical drainage out of the system takes place (O_v). Evapotranspiration (ET), dependent on potential rate of atmospheric demand and on cropping characteristics, takes place simultaneously from the A-horizon (ET_a) and the B-horizon (ET_B) as functions of the vegetation rooting distributions in the respective horizons (k_a, k_b) and of whether the vegetation is stressed (following section). Downward redistribution of soil moisture may be either saturated or unsaturated ($R_{a \rightarrow b}$) while unsaturated upward moisture redistributions ($R_{b \rightarrow a}$) may also take place, both dependent on relative moisture gradients.

Soil moisture stress

The water status of a plant i.e. its turgor pressure, is dependent largely on the soil water content of the root zone and on the atmospheric demand. The atmosphere places an evaporative demand upon the plant and the roots absorb the water from the soil water reservoir. When the reservoir becomes depleted, the roots cannot absorb water at a rate to meet demand, plant stress sets in and the plant loses turgor. Subsequently, physiological and metabolic processes are affected and plant growth is reduced, with attendant reductions in plant yield.

A problem faced in hydrological modelling is to determine at what point in the depletion of the plant available moisture reservoir plant stress actually sets in. In modelling terms, the problem may be expressed as the moisture content of which actual evaporation, AE, is reduced to below potential evapotranspiration, PE.

Experimental evidence shows that AE equals PE until a certain fraction, f, of maximum (profile) available soil moisture to the plant, PAM, is exhausted. Beyond this fraction the reduction of AE depends *inter alia* on the remaining water and the PE demand. The classical literature of the past two decades has frequently attributed differences in f to soil textural properties, while others, notably irrigation modellers, maintain that stress sets in at a fixed soil moisture content, for example, 0,5 PAM. However, recent research (Slabbers, 1980) shows that f may vary according to atmospheric demand (PE) and the critical leaf water potential, ψ_l^{cr}, of different crops, the latter being an index of the hardiness of crops to drought situations. Thus Slabbers (1980) derived f as

$$f = 0{,}94 + 0{,}26. \psi_l^{cr}/PE$$

Using the above equation with critical leaf water potentials for different crops, the wide variation of f also for different PEs has been demonstrated previously by Schulze (1980). The implications of stress setting in at such different levels of moisture content are highly significant in terms of drought modelling.

Examples of the Application of the ACRU Model for Drought Assessment

In order to illustrate how the ACRU Model may be applied to a comparative assessment of drought severity the Model was run using daily data from January 1930 to May 1983 (inclusive) at three locations in Natal, namely

Port Shepstone	(30°44'S, 30°27'E, elevation 15 m)
Matatiele	(30°20'S, 28°49'E, elevation 1 462 m) and
Richmond	(29°52'S, 30°16'E, elevation 856 m).

For purposes of drought simulations at Port Shepstone the Model was run for the typical coastal crop of sugarcane using a cropping coefficient of 0,8 throughout the year, as suggested by Thompson (1977), with an interception storage of 1,3 mm per rainday (de Villiers, 1975), on a soil with a PAM of 125 mm of which 33% was in the A-horizon with 60% of the root activity also in the top horizon. At both Matatiele and Richmond a maize crop was selected for hydrological simulations. Both cropping coefficients and interception storages varied according to the crop's growth stage. Values for these variables were taken from Mottram (1982) and De Villiers (1975). A PAM of 125 mm was again used for drought simulations, but with the proportion of active roots in the A-horizon varying from 0,7 at full growth to 0,9 (i.e. effectively soil evaporation) at dormancy, according to Troughton (1962).

Simulation of runoff for small farm dams

The runoff component of the ACRU Model consists of both a stormflow (i.e. surface flow and interflow) and a baseflow routine. The stormflow submodel is based on a multi-soil-layered moisture deficit modification of the SCS Model. This submodel was developed by the author and has been verified on catchments in the U.S.A. (Schulze, 1982b) and with experimental data from the De Hoek/Ntabamhlope and Zululand hydrological research catchments (Schulze, 1984). The baseflow routine contains percolation flow (under saturated and unsaturated conditions) with a lag function to yield an exponential decrease of surplus water into a stream system (Schulze, 1984).

For the purpose of a water resources assessment daily runoff values were summed to annual totals. Because of the longer term cumulative effects of the lack of water supply into dams in drought periods, the worst four consecutive years of simulated runoffs in a 53 year period (1930-1982) of record were extracted for comparison (Table 1). Using the parameter values specified

TABLE 1
THE WORST FOUR YEAR PERIODS OF SIMULATED RUNOFF AT SELECTED STATIONS

Ranking	Mean Annual Runoff (mm) for Four Year Period					
	Matatiele		Richmond		Port Shepstone	
	Period	Runoff	Period	Runoff	Period	Runoff
Worst	1968-71	2,20	1979-82	81,31	1965-68	124,80
2nd worst	1979-82	3,65	1970-73	137,98	1978-81	148,25
3rd worst	1938-41	15,40	1930-33	145,34	1972-75	178,55
4th worst	1930-33	23,28	1944-47	159,10	1938-42	200,75
					(1979-82	177,00)

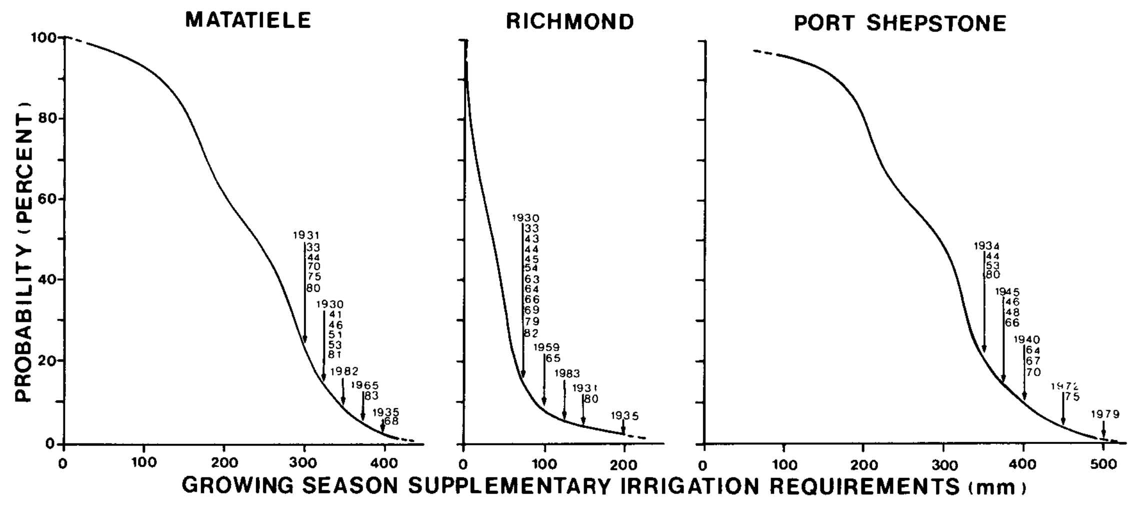

Figure 4
Probabilities of occurrence of simulated growing season supplementary irrigation requirements at three locations

above for this drought simulation, Table 1 shows the current drought to feature prominently either as the worst or certainly the second worst extended dry period in the past two generations.

Simulation of supplementary irrigation requirements

In times of drought not only is rainfall lower than normal, but evaporative demand (through associated higher than average temperatures and lower humidity) is simultaneously higher. The dilemma of the irrigation farmer in times of extended drought is that the additional irrigation requirements strain the already meagre water supplies in such times.

In the ACRU Model a supplementary irrigation routine runs in parallel with the dryland moisture budget. Irrigation water is applied to the crop root zone at the onset of moisture stress by any one of three options depending *inter alia* on practical considerations, namely irrigating to field capacity; or irrigating to a planned deficit e.g. to 80% of field capacity on the assumption that there is a probability of natural rains falling; or irrigating by a fixed amount.

For this exercise on hydrological simulation under conditions of drought the third option was selected, with a 25 mm supplementary irrigation per cycle. Figure 4 shows curves of simulated supplementary irrigation amounts expressed as probabilities of occurrence for the growing seasons applicable to the three locations (October to March at Matatiele and Richmond and all year for sugarcane at Port Shepstone). Years/seasons of particularly high simulated irrigation requirements are indicated in the figure. It will be noticed that groups of years frequently cluster in their high irrigation demands, indicating extended droughts.

For the period 1930 to the end of the 1983 growing season the extended four year droughts have been ranked by irrigation requirement (Table 2). At all three locations the present drought, of which we do at this stage not even know when it will be broken, features as the worst simulated crop water demand drought since 1930. What is of interest to note in a comparison of Tables 1 and 2 is that at the respective locations the most severe simulated water resources droughts in terms of runoff production (Table 1) do not necessarily correspond with the worst simulated irrigation requirements droughts, neither in ranking nor in the periods of droughts being in phase. Perusal of daily simulated values illustrates that this may be explained by the possibility of virtually an entire year's runoff being produced by one or two large storms, while the stored soil moisture from those storms may stave off the need for irrigation only by a matter of a few weeks.

TABLE 2
THE WORST FOUR YEAR PERIODS OF SIMULATED SUPPLEMENTARY IRRIGATION REQUIREMENTS AT SELECTED STATIONS

Ranking	Mean Growing Season Supplementary Irrigation Requirements (mm) for Four Year Period					
	Matatiele		Richmond		Port Shepstone	
	Period	Irrigation	Period	Irrigation	Period	Irrigation
Worst	1980-83	337,50	1980-83	87,50	1979-82	381,25
2nd worst	1965-68	325,00	1930-33	81,25	1972-75	381,25
3rd worst	1951-54	293,75	1963-66	81,25	1964-67	362,50
4th worst	1930-33	281,25	1943-46	62,50	1945-48	350,00

Crop yield estimations

Principles of crop yield modelling

Many very simple crop models use rainfall (plus irrigation) as a direct indicator of yield, resulting in broad generalizations such as "for deep soils each inch of annual precipitation accounts for a bag of maize per morgen" (cited in Crafford and Nott, 1981). Such simplistic models seldom yield satisfactory results. In the case of maize, for example, results from one location cannot be transferred to other locations and different planting dates are not accounted for. Water used by a crop in the growth process comes from the soil moisture store, from which rainwater may be lost through stormflow or deep percolation, and in which rainwater may be distributed unequally. Crop production is usually limited by insufficient water at some stage during the growing season. A sound crop yield model should account for plant water stress and ideally even for the sensitivity on yield of critical development stages at which moisture deficits occur. The structure of the multi-layer moisture budgeting ACRU Model, which accounts also for rooting development and stage of crop growth, facilitates the "attachment" of crop yield models of various complexities to run in tandem with the model.

Crop yield simulation models in the ACRU Model

At the present stage four maize yield simulation models and a sugarcane/sucrose production model are attached to the ACRU Model. Two maize yield simulation models were used in this drought assessemnt. The first, suggested by De Jager (1982) as a robust generally applicable model, is expressed as

$$Y_m = \frac{30\,(AET_{gs} - 100)\,0{,}45}{1000}$$

in which

Y_m = maize yield in t/ha and
AET_{gs} = total actual evapotranspiration in mm (A- and B-horizons) for the duration of the active growing season.

In the De Jager Model it may be seen that a threshold of 100 mm AET is required for maize yield.

The second model was developed by Du Pisani (1978) using data from several locations in South Africa and estimates maize yield (t/ha) by

$$Y_m = PY_m . 0{,}88^{MSD}$$

where

$$PY_m = \text{potential maize yield in t/ha} = \frac{PET_{gs} . 4575}{424{,}4}$$

in which

PET_{gs} = total potential evapotranspiration in mm (A- and B-horizons) for the total duration of the active growing season, and
MSD = number of moisture stress days for the critical growth period 70-100 days after planting.

In simulations with the ACRU Model a stress day was defined when the AET of both the A- and B-horizons were less than 0,5 PET.

The ACRU Model has two options for setting a maize season's planting date: it can either be specified by month and day, or alternatively it can vary from season to season by the computer's selecting the planting date conditional upon at least 25 mm of rain having fallen within a five day period after October 1 and before December 15. This latter option was selected for the present research.

The sugarcane model incorporated in the ACRU Model is that of Thompson's (1976) who collated overseas results with those from various locations of Natal to equate annual sugarcane yield, Y_s in t/ha, as

$$Y_s = 9{,}53 . AET/100 - 2{,}36 \qquad (r = 0{,}95;\ n = 91)$$

For the annual yield estimate a July to June growing season was taken.

Results

Figures 5 and 6 illustrate the seasonal fluctuations of simulated maize yields by the De Jager (1982) and Du Pisani (1978) models (using evapotranspiration and stress day estimations by the ACRU Model) for Matatiele and Richmond respectively. While the long term means of predicted maize yields are similar for the two models (Matatiele: 4,43 and 4,18 t/ha and Richmond: 5,38 and 5,16 t/ha) a higher variability of estimated yield is evident for the Du Pisani model, particularly at Matatiele (Matatiele's coefficients of variation are 21,6% and 53,0% and Richmond's 9,0% and 9,1%.

The persistence of simulated below average crops for the present drought (1979/80 to 1982/83) is rivalled only by those of the late 1960s/early 1970s at Matatiele and the mid 1940s at Richmond (Figures 5 and 6). According to the simulation model no drought in the past 50 years has equalled the present one when considering sugarcane production at Port Shepstone (Figure 7). The 1982/83 season was modelled as the worst ever, followed by the 1979/80 season as the second worst ever. The only reprieve was that the 1980/81 and 1981/82 seasons were estimated as average and above (Figure 7).

Discussion and Conclusions

The results given in this paper warrant discussion on three fronts:

In the first instance the paper shows that hydrological modelling is a potentially powerful tool with a variety of useful applications. The example in question has utilized a locally developed and tested model, the ACRU Model, to illustrate the present drought crisis in a historical perspective by examining simulated runoff, simulated supplementary irrigation requirements and crop yield estimates at three locations in Natal. At this stage of its development the Model has several output options, for example, a daily or monthly hydrological summary and additionally options with statistical analyses of crop yield estimates, irrigation requirements or simulated runoff. The statistical summaries include long term means and variabilities for each month of the year and annual totals as well as probability analyses (Schulze, 1984). Refinements to the Model are an ongoing process.

Secondly, in regard to the drought simulation, the paper has illustrated the severity of the present drought in relation to droughts experienced in the past five decades. The inferences which can be drawn bear out what we have come to accept as being a "normal" feature of our climatic patterns, namely, that there is some persistence of wet and dry years to cluster together, but that these persistencies may be interrupted (for example, a

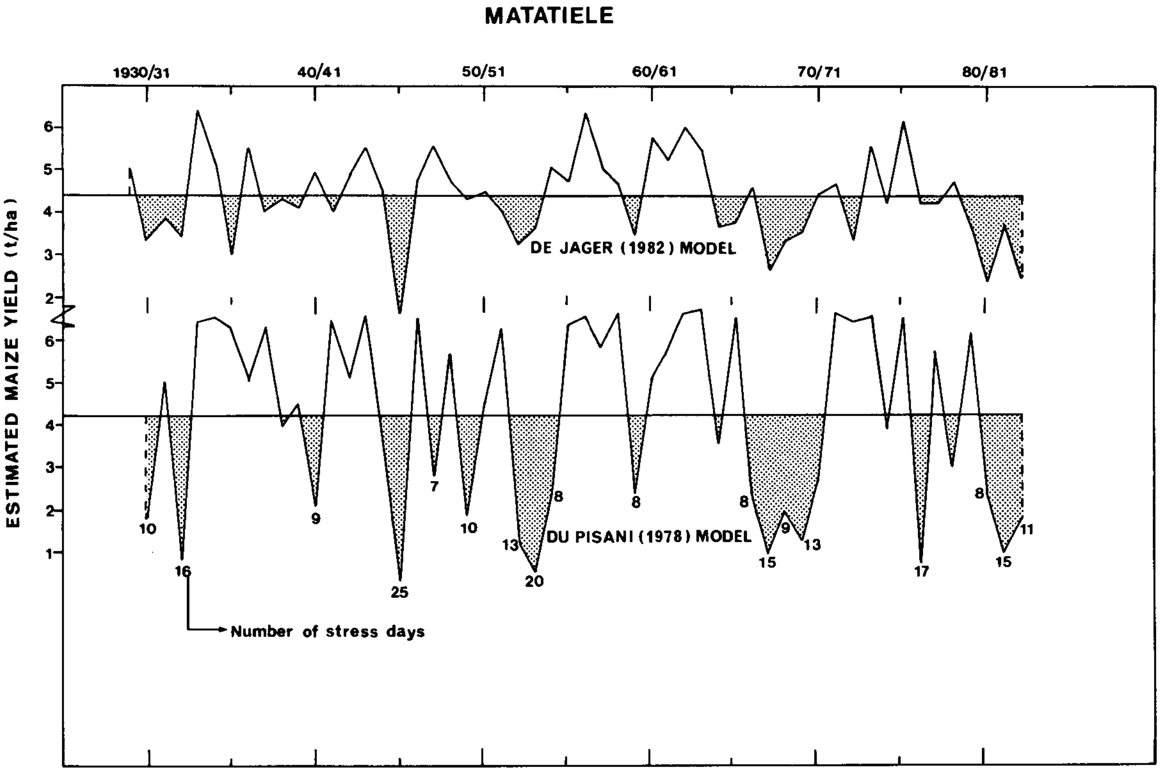

Figure 5
Simulated maize yields at Matatiele

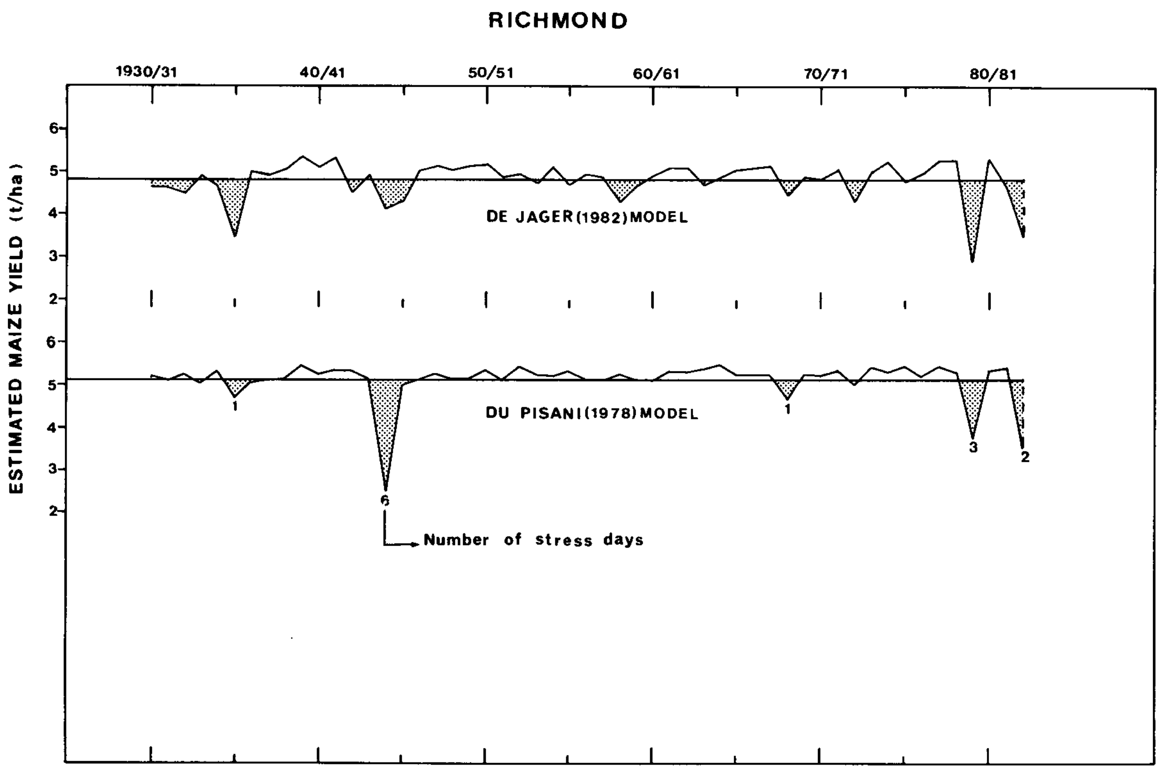

Figure 6
Simulated maize yields at Richmond

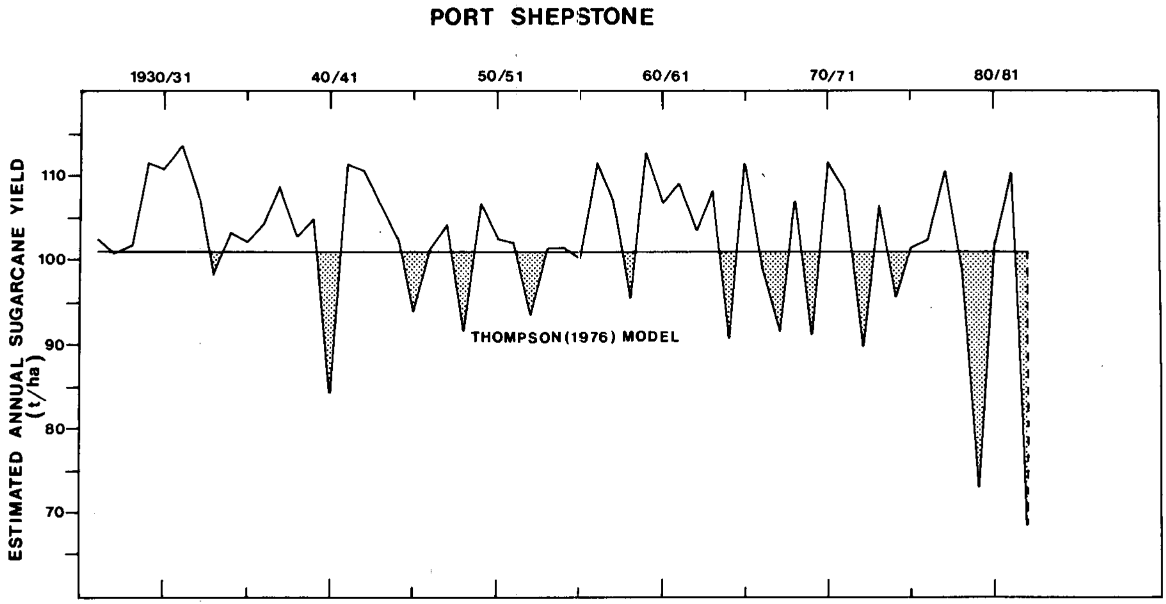

Figure 7
Simulated sugarcane yield at Port Shepstone

wet year occurring within a dry sequence) and that the onset of a sustained drought period may not always be predictable.

Finally, the results have shown that it is necessary to distinguish between different types of drought which may be of relevance to the water resources planners, as the worst simulated droughts in terms of supplementary irrigation requirements were not always in phase with or did not even necessarily coincide with the worst simulated droughts when viewed from the standpoint of runoff production or crop production.

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3.2 Tables are numbered in arabic numbers (Table 1) and should bear a short yet adequate descriptive caption. Their appropriate position in the text should be indicated.

3.3 The SI system (International System of units) should be used.

3.4 References to published literature should be quoted in the text as follows: Smith (1978) the date of publication, in parentheses, following the author's name. All references should also be listed together at the end of each paper and not given as footnotes. They should be arranged in alphabetical order (first author's surname) with the name of the periodical abbreviated in the style of the *World List of Scientific Periodicals* (4th edn, Butterworths, London, 1963-1965, with supplements) and appear as follows:

MATSON J.V. and CHARACKLIS W.G. (1976) Diffusion into microbial aggregates. *Water Research* **10**(10) 877-885.

THRING M.W. (1975) *Air Pollution* p 132 Butterworths, London.