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**The impact of climatic variability over the period 1961-
1990 on the soil water balance of upland soils in the North
East Arid Zone of Nigeria**

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Nigeria**

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Abstract

Over the period 1961 – 90 the North East Arid Zone of Nigeria experienced a decline in annual rainfall totals and increased aridity which placed increasing pressure on rain fed, millet-based farming systems. The changes in seasonal rainfall total and distribution have been examined and it has been shown that the rate of decline has been consistent across the region. The decline has been dominated by reduction in the number of rain days during the middle of the rainy season and there is no evidence of a significant change in the length of the growing season. Over the same time period, there has been a small, but significant, increase in mean air temperature which has resulted in a small increase in potential evapotranspiration. Other climatic parameters (vapour pressure, solar radiation and wind speed) appear to have remained stable, although the paucity and dubious quality of much of the historical meteorological data make rigorous statistical analysis difficult.

A water balance model (BALANCE) developed by the author, was calibrated for a millet crop grown on a typical sandy loam soil in Maiduguri (Nigeria). The model was necessarily parsimonious, but was shown to perform well when calibrated against observed soil water content. However, the empirical nature and high sensitivity of key parameters relating to bare soil evaporation and drainage mean that it is difficult to parameterise the model by laboratory, or independent field measurements.

Applying the calibrated model to daily rainfall and average evapotranspiration data from Nguru (Nigeria) for the period 1961 – 93 showed that, with the exception of extreme drought years, the increased aridity would have had little impact on the viability of traditional millet and millet-cowpea intercropping systems prior to the early 1980s. However, after that date, predicted seasonal millet transpiration, and hence predicted yields, have declined, and long duration cowpea intercrops, which were traditionally matured on residual soil moisture after the millet harvest have had insufficient water.

Whilst the BALANCE model has been useful in examining the impact of climatic variability on agro-hydrology, it is not a crop physiological model and the interaction between soil water and crop development is poorly represented. The model cannot,

therefore be applied with confidence to investigate the potential yield benefits of physical or agronomic interventions to alleviate the impacts of aridity. Although more complex models exist to do this, they require detailed parameterisation of the crop physiology, which was not possible within the scope of this study.

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CHAPTER ONE. INTRODUCTION

1. INTRODUCTION

Twenty percent of Nigeria experiences a semi-arid climate (Le Houérou, 1996) which has been characterised by increasing aridity since the 1960s. In these semi-arid areas, annual rainfall totals have been declining and there is a perception that the duration of the growing season has been shortening. Apart from riparian land subject to seasonal inundation and land with shallow groundwater suitable for irrigation, agricultural production is predominantly rain fed. Thus the decline in annual rainfall has put great pressure on traditional agricultural systems and water availability has become a major limitation on agricultural production.

Mortimore (1989) and van Apeldoorn (1981) have provided largely qualitative descriptions of the impact of drought on the region, that show the complexity and interactions between climate, the environment and people in a fragile system. However, there has been little quantification of these impacts. Making the most of the productive capacity of the land requires the maximum utilisation of rainfall which may involve technologies such as runoff harvesting and control, or changing agronomic practices. To predict the potential efficacy of such interventions requires a full understanding of the nature of the climatic changes that have taken place – not just in terms of annual rainfall totals, but also in the distribution of rainfall and changes in potential evapotranspiration. Subsequently, agro-hydrological models can be used to evaluate the potential of various management interventions designed to alleviate the adverse impacts of increasing aridity.

In 1990, the Federal Government of Nigeria, supported by the European Community, established the ‘North East Arid Zone Development Programme’ (NEAZDP) with the objectives of reducing environmental degradation and alleviating the social impacts of aridity. This thesis presents work carried out by the author under a linkage between Silsoe College, Cranfield University (UK) and the Centre for Arid Zone Studies, University of Maiduguri (Nigeria) in support of that programme.

2. AIMS AND OBJECTIVES

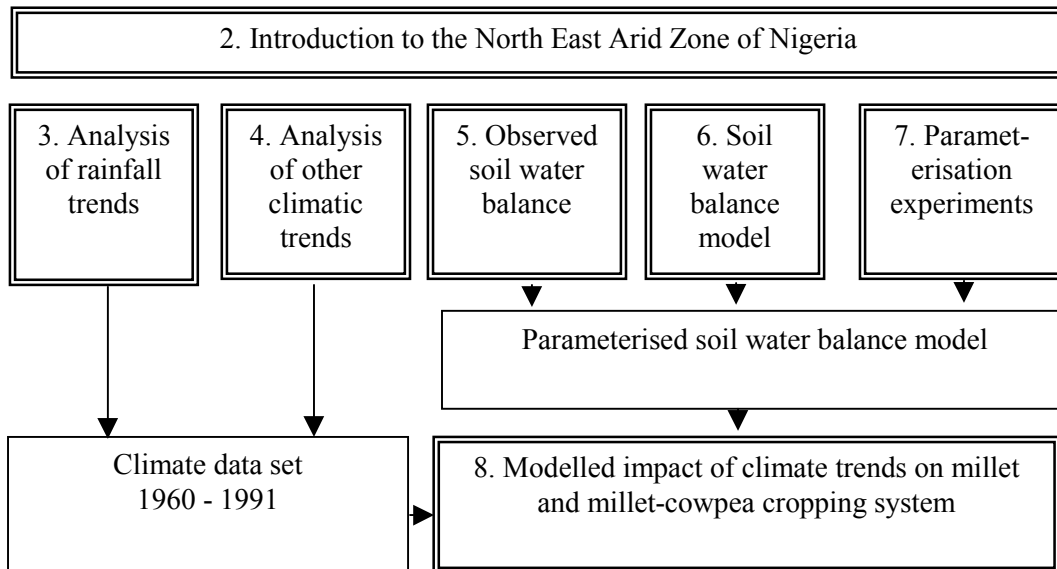
This study aims to evaluate the impact of climatic variability over the period from 1961 to the 1990 on the potential productivity of a rain-fed farming system in North East Nigeria through agro-hydrological modelling. The specific objectives are to;

- quantify the extent and nature of changes in the rainfall regime;
- quantify the nature and extent of changes in potential evapotranspiration;
- to parameterise and calibrate a soil water balance model and compare its predictions with field observations of water balance;
- to apply the model to the time series of climate data to predict the impact of climate variability on the agro-hydrology;
- apply a method to evaluate the potential benefits of water conservation.

3. FORMAT OF PRESENTATION

3.1. Order of discussion

The structure is outlined in Figure 1-1.



NB. numbers refer to chapter numbers.

Figure 1-1 Outline of the thesis structure.

3.1.1. Background to the North East Arid Zone of Nigeria

The environmental and agricultural background to the uplands of the North East Arid Zone of Nigeria is described, and the evidence for climatic change over the period 1961 – 1990 is summarised.

3.1.2. Rainfall trends in the North East Arid Zone of Nigeria 1961 - 1990

Published as Hess, T. M., Stephens, William & Maryah, U. M., 1995. Rainfall trends in the North East Arid Zone of Nigeria 1961-1990. Agricultural and Forest Meteorology 74: 87-97.

The available daily rainfall data from the three synoptic weather stations in the North East Arid Zone of Nigeria (and one just over the border in Niger) are collated and analysed for trends in annual rainfall total, seasonal distribution and length of rainy season. The observed trends in rainfall amounts are further analysed in terms of rain days and rainfall per day.

3.1.3. Trends in reference evapotranspiration in the North East Arid Zone of Nigeria, 1961-91

Published as Hess, T. M., 1998. Trends in reference evapo-transpiration in the North East Arid Zone of Nigeria, 1961-91. Journal of Arid Environments. 38: 99-115.

This chapter collates the available monthly mean climate data for three synoptic weather stations in the North East Arid Zone of Nigeria and analyses temperature, sunshine, humidity, wind and evapotranspiration for trends over the time period. Particular attention is paid to the impact of aridity on humidity measurements and implications for evapotranspiration calculation. The approaches to estimating reference evapotranspiration in situations where full data are not available are discussed and compared.

3.1.4. Water balance and water use of pearl millet-cowpea intercrops in north east Nigeria

Published as Grema, A. K. and Hess, T. M., 1994. Water balance and water use of millet-cowpea intercrops in north east Nigeria. Agricultural Water Management 26:169-185.

The results of a field trial carried out in Maiduguri, Nigeria, to evaluate the water balance components under pearl millet and millet-cowpea intercrops on a sandy soil are presented and discussed. The impact of the intercrop on the water balance is discussed.

3.1.5. The 'BALANCE' Water Balance model

This chapter presents an overview of the BALANCE model that was subsequently used to simulate the soil water balance of upland soils in the North East Arid Zone of Nigeria. Although the model was developed by the author specifically for the present application, the focus of this thesis is on the application of the model rather than its development. A brief description of the modelling approach is given here. The full details of the model are given in an appendix to the thesis.

3.1.6. Determination of soil and plant parameters for use with the BALANCE model on a sandy loam soil in a semi-arid environment.

A series of field experiments were carried out in Maiduguri, Nigeria, to parameterise a soil water balance model (BALANCE) for pearl millet grown on a sandy soil. Special attention is paid to the parameterisation of the drainage and soil evaporation components of the model. The results of the parameterised model are then compared with the observed water balance from Chapter Five above. Sensitivity analysis and further calibration is then carried out to improve the fit of the model. The difficulties of parameterising even simple models is discussed.

3.1.7. The impact of changing rainfall patterns on the efficiency of rainfall utilisation in millet and millet-cowpea farming systems in N E Nigeria

This chapter is a re-working of a paper published as Hess, T. M. and Grema, A. K., 1994. The impact of changing rainfall patterns on the efficiency of rainfall utilisation in pearl millet - cowpea intercropping system in N E Nigeria. Aspects of Applied Biology 38:231-238.

Using the best-fit parameters set identified in Chapter Seven above, the BALANCE model is then run using climate data for the period 1960 – 1991 for millet grown on a sandy soil in Nguru, Nigeria. The predicted trends in the water balance and water balance components are compared with other studies in the region and discussed in the context of millet-cowpea intercropping systems.

3.2. Thesis format

This thesis is presented in the form of a collection of stand-alone papers, which between them, address the aims and objectives above.

Some of the chapters have been published in peer reviewed journals (Table 1.1). One was originally submitted as a peer reviewed conference paper but has been substantially re-worked for this thesis. Chapters 2, 6 & 7 are not considered appropriate for publication due to the site-specific nature of the work.

Although the text has been reproduced in this thesis in a consistent style and format, the structure of presentation and citation style required by the relevant journals has

been retained. For those papers which have been published, copyright rests with the publishers.

3.3. Context of the work

The work for this thesis was undertaken as a part-time candidate whilst I was employed as a member of staff at Cranfield University at Silsoe. The subject area was primarily determined by the linkage¹ with the Centre for Arid Zone Studies (CAZS) at the University of Maiduguri, Nigeria where I was stationed during 1990 to 1992. My role was to support the research activities of the CAZS, including staff members who had registered for PhD degrees with Cranfield University, and to provide liaison with the funding agency and the North-East Arid Zone Development Programme (NEAZDP) for which the linkage was providing research support. I was responsible for managing the linkage, for developing the focus of the water balance research and for providing technical expertise and supervision for a wide range of components of the linkage. This thesis therefore represents the culmination of my research on the impacts of climate change on the water balance, bringing together joint publications in which I played a leading role.

In respect of the joint papers submitted: Chapter 3 was my own work with supervisory contributions from the Dr W Stephens and a contribution towards data collection and coding from Mr U M Maryah (Linkage Study Fellow); Chapter 4 was a joint paper with Dr A Grema (Linkage Study Fellow). I provided the water balance measurement, modelling and interpretation expertise, as well as supervisory inputs to the whole paper; Chapter 6 has been substantially redeveloped for this thesis from a conference paper based on his work with support on agronomic aspects from Dr A Grema.

¹ University Linkage between the Centre for Arid Zone Studies, University of Maiduguri, Nigeria and Silsoe College, Cranfield University, UK funded by the European Union (Project No. 6 ACP. Uni.011).

Table 1.1. Publication of chapters in peer reviewed journals

Chapter no.	Journal	Publication date	Author(s)
2			T M Hess
3	Agricultural and Forest Meteorology	1995	T M Hess W Stephens [†] U M Maryah [‡]
4	Journal of Arid Environments	1998	T M Hess
5	Agricultural Water Management	1994	A K Grema [‡] T M Hess
6			T M Hess
7			T M Hess
8	Earlier version published in Aspects of Applied Biology	1994	T M Hess A K Grema [‡]
9	Journal of Arid Environments	1999	W Stephens [†] T M Hess

[†] Supervisor, [‡] Research Student

4. ACKNOWLEDGEMENTS

This study was based on work carried out by the author under the University Linkage between the Centre for Arid Zone Studies, University of Maiduguri, Nigeria and Silsoe College, Cranfield University, UK funded by the European Union (Project No. 6 ACP. Uni.011). The assistance of the following is gratefully acknowledged: the staff of the University of Maiduguri for field and laboratory assistance; the Department of Meteorological Services, Lagos, Nigeria and Dr. M V K Sivakumar at the International Crops Research Institute for the Semi-Arid Tropics, Niamey, Niger, in the provision of climate data.

5. REFERENCES

- Le Houérou, H. N., 1996. Climate change, drought and desertification. *Journal of Arid Environments* 34:133-185.
- Mortimore, M.J., 1989. *Adapting to drought: farmers, famines, and desertification in West Africa*. Cambridge University Press, Cambridge. 299pp.
- van Apeldoorn, G.J., 1981. *Perspectives on drought and famine in Nigeria*. George Allen & Unwin. London. 184pp.

CHAPTER TWO. BACKGROUND TO THE NORTH EAST ARID ZONE OF NIGERIA

1. LOCATION

This study is focussed on the North East Arid Zone of Nigeria, comprising the Northern parts of Borno and Yobe States. The region lies between 12°N and the Niger border and the 10°E meridian and the Cameroon border (Figure 2-1).



Figure 2-1 Map of Nigeria showing the North East Arid Zone.

2. CLIMATE

The climate of the region has been described as ‘Sudanic’ (van Apeldoorn, 1981) with one rainy season of 2½ - 5 months. Although commonly referred to as the North East *Arid Zone*, the climatic regime is more appropriately referred to as semi-arid as the ratio of average rainfall to average potential evapotranspiration is between 0.20 and 0.45 (Le Houérou, 1996).

Its characteristics are dominated by the movement of the Inter-tropical Convergence Zone (ITCZ). During December and January the ITCZ lies at a latitude of 2-5°N and the region is under the influence of dry, continental, relatively stable air masses (Nieuwolt, 1977). Rainfall during this period is extremely rare, temperatures are high and the relative humidity is low. From February to June the ITCZ moves northwards bringing a zone of heavy rainfall behind it. Air temperatures rise until the rainfall arrives around June. By July / August the ITCZ is at its most northerly position (15 – 20°N) and the North East Arid Zone receives its maximum rainfall. Air temperatures are lower and relative humidity rises. From September to November, the ITCZ moves southwards and the rains cease.

Climate data are available from three synoptic stations in North East Nigeria and several rainfall monitoring stations with records of various durations. The key stations used in this study are shown in (Figure 2-2).



Figure 2-2. Location of main climate stations within, and around the North East Arid Zone of Nigeria.

2.1. Rainfall

It is difficult to quote statistics for mean annual rainfall in a region where rainfall is very variable and reporting periods differ. In general, however, the mean annual rainfall of the region is less than 700mm (Table 2.1) and shows a general reduction in amount from south-west to north-east, suggesting that distance from the source of moisture (i.e. the Atlantic Ocean) is the dominant factor (Kowal and Knabe; 1972).

Table 2.1. Estimates of mean annual rainfall (mm) in the North East Arid Zone of Nigeria (after Kowal & Knabe, 1972).

Station	State	Mean annual rainfall (mm)	Latitude °N	Longitude °E	Altitude (m)
Geidam	Yobe	432	12.88	11.93	305
Gashua	Yobe	509	12.87	11.05	335
Nguru	Yobe	552	12.53	10.28	343
Maiduguri	Borno	704	11.51	13.05	354
Potiskum	Yobe	775	11.42	11.02	415

The rainfall regime is characterised by a single peak; the rainy season starting in April / May as the Inter-Tropical Convergence Zone (ITCZ) passes northwards, with a maximum in August, and finishing quite rapidly in September / October. The rest of the year is virtually dry (Table 2.2). The timing of the onset of rains varies from south (earliest) to north, being set back by about 14 days per degree of latitude. The retreat of the rains is much faster, averaging 6.7 days per degree of latitude from north to south (Kowal and Kassam, 1972). The combined effect results in a shorter and lower magnitude, rainy season in the northern part of the region than in the south.

**Table 2.2. Average monthly rainfall (mm) at five stations
in the North East Arid Zone of Nigeria. (source FAO, 1984)**

Month	Potiskum	Maiduguri	Nguru	Maine Soroa
January	0	0	0	0
February	0	0	0	0
March	0	0	0	0
April	10	7	3	3
May	51	39	28	13
June	91	72	61	33
July	216	174	125	106
August	259	229	236	187
September	137	106	104	60
October	23	17	10	11
November	0	0	3	0
December	0	0	0	0
Total	787	644	570	413

2.2. Temperature

The maximum and minimum air temperatures generally follow the seasonal change, being higher in summer than in winter. However, maximum, and to a lesser extent, minimum air temperatures are depressed during the rainy season (June – September) (Figure 2-3). The peak temperatures are therefore recorded prior to the onset of the rains, when the mean monthly maximum reaches 40°C and individual days can reach as high as 46°C. The coolest month is January.

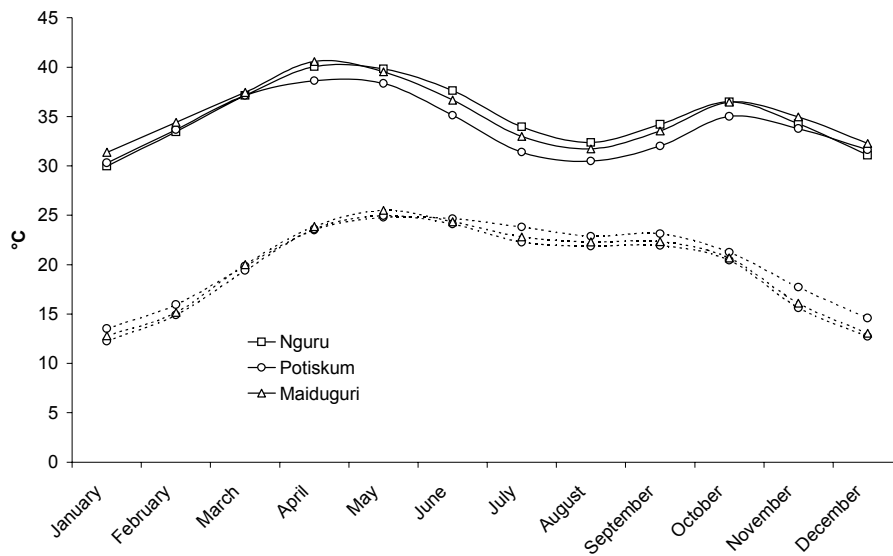


Figure 2-3 Long-term (1961-90) mean monthly maximum (—) and minimum (- -) air temperature, °C, for three stations in the North East Arid Zone of Nigeria

2.3. Humidity

The mean monthly saturation vapour pressure (e_a) follows the seasonal trend in temperature (Figure 2-4), however, the actual vapour pressure (e_d) is a function of the humidity of the air mass and is related to the seasonal variation in rainfall. As a consequence, the average saturation deficit ($e_a - e_d$) is very high (over 4kPa) during the months prior to the onset of the rains and reduces dramatically (less than 1.5 kPa) once the rains start (Figure 2-5).

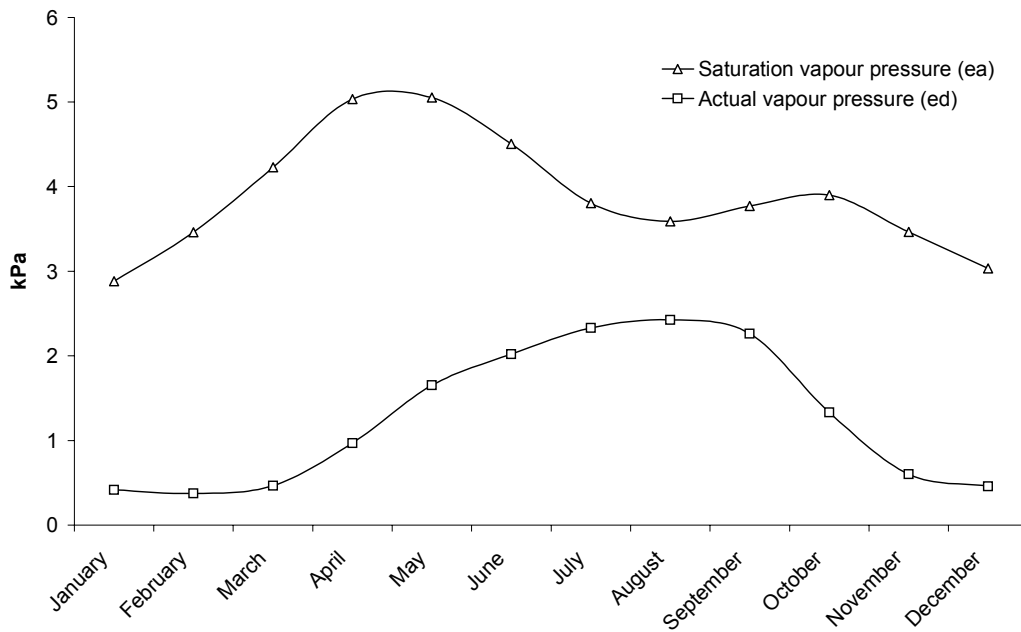


Figure 2-4 Long-term (1961-90) mean saturation (ea) and actual vapour (ed) pressure, kPa, for mean of three stations in the North East Arid Zone of Nigeria.

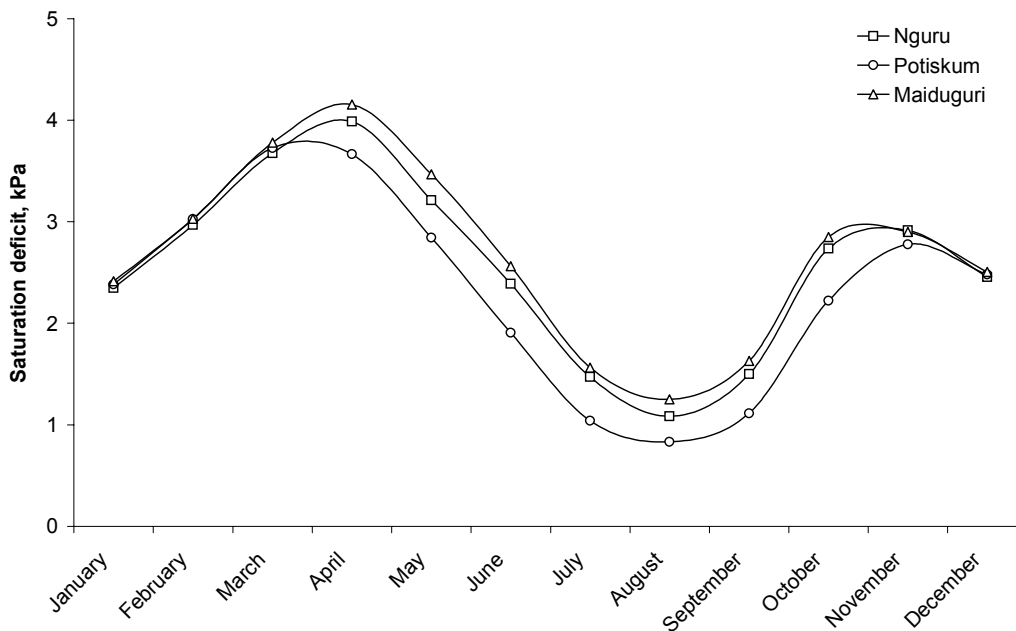


Figure 2-5 Long-term (1961-90) mean monthly saturation deficit, kPa, for three stations in the North East Arid Zone of Nigeria.

2.4. Evapotranspiration

Potential evapotranspiration, ETp, peaks in April and May, when the saturation deficit is high, and falls during July and August as the saturation deficit reduces. There is a brief rise during September and October as the saturation deficit increases once more, falling to a minimum in December and January, when air temperatures are at a minimum. Mean annual ETp increases northwards by about 60 mm per degree of latitude (Kowal and Knabe; 1972). Published figures for mean annual ETp vary for a given station, as does the method used to estimate ETp, however, in general ETp varies over the area from 1,500 - 1,800 mm year⁻¹ and is two to three times the mean annual rainfall (Table 2.3).

Table 2.3 Average daily and annual reference evapotranspiration (Penman-Monteith) for five stations, mm d⁻¹, after FAO (1984).

Month	Potiskum	Maiduguri	Nguru	Maine Soroa
January	4.4	4.8	3.7	6.5
February	5.4	5.8	4.2	7.9
March	6.1	6.6	4.6	9.2
April	6.8	6.7	5.4	10.1
May	7.2	6.4	6.4	9.4
June	6.2	5.9	6.2	8.7
July	4.8	4.6	5.4	7.4
August	4.0	4.0	4.4	5.9
September	4.4	4.4	4.7	6.6
October	4.8	5.1	4.8	7.9
November	4.8	5.2	4.4	8.0
December	4.5	4.6	4.1	7.1
Total	1927.0	1947.5	1774.0	2878.6

2.5. Growing season

The growing season commences in early- to mid-June with the establishment of rains. Benoit (1977) defined the start of the growing season as the time when cumulative rainfall is equivalent to, or greater than one half of potential evapotranspiration, provided that a dry spell of five days does not begin within seven days. Using this criterion, the mean start of the growing season ranges from 2 June in the south west to 29 June in the north east of the North East Arid Zone (Hess et al., 1995). The end of the growing season follows the abrupt end of the rains which

occurs in mid-September in the north and early October in the south (Kowal and Knabe, 1972). Kowal and Knabe estimated the length of the growing season based on an estimate of availability of water to crops. They suggested that the growing season reduces by 19 days for each degree of latitude moving northwards but depends on the amount of residual moisture that may be retained in the soil after the end of the rains.

3. SOILS AND LAND USE

The soils of the semi-arid region of Nigeria have been described by Ojanuga (1987) and for Borno State² by Rayar (1987). The area is dominated by three soil types according to parent material which support quite distinct land use patterns.

3.1. Aeolian deposits

The most extensive parent material is aeolian deposits (dune sands) occurring as longitudinal dunes between Kano and Maiduguri. Where the dunes have been subdued by Aeolian sand drift, hummocky sand plains are found. The soils developed on these deposits are deep and very sandy and show no profile development. Infiltration rates vary according to soil texture, ranging from 65 – 340 mm h⁻¹ on fine sandy and loamy sand soils. These soils are poorly graded with low clay content and are susceptible to erosion (Usman, 1994). Although runoff is generally low, surface sealing of the sandy soils occurs when disturbed by cultivation or raindrop impact resulting in increased runoff. The aeolian sands have a low water holding capacity (Table 2.5) and soil moisture limits crop production.

Most crop production on the aeolian soils is rain-fed. The upland, rain-fed farming system, known locally as *tudu*, extends as far north as a line about 20km north of Nguru - Gashua - Geidam, beyond which it is too dry for cultivation except where shallow groundwater exists in oases. The staple food crop of the area was traditionally a long season (90 days) pearl millet (*Pennisetum typhoides* (S&H)), but short season (75 days) sorghum (*Sorghum bicolor*) has been increasing in popularity due to its drought tolerance. Local farmers choose from a broad range of cultivars

² The boundaries of Borno State at that time included the present Yobe State.

according to the timing of the onset of rains and perceived risk of drought. For example, in a study of four villages in Northern Nigeria, Adams and Mortimore (1997) identified up to 34 named varieties of millet and sorghum used in a single village. By the 1990s millet and sorghum were grown in roughly equal proportions, despite the dietary preference for millet. This has been in response to perceived shortening of the rainy season and increased risk of mid-season drought - sorghum being more drought tolerant than millet.

Cereal crops are at risk from pest attacks from locusts, grasshoppers and 'electric' beetles. This situation appears to have been getting worse in recent years and has been popularly ascribed to increasing aridity and reduced 'bush' vegetation.

The main cash crop is cowpea (*Vigna unguiculata*), but some sesame (*Sesamum indicum*) and groundnut (*Arachis hypogaea*) are also grown. Cowpea is grown for both food (grain) and fodder for livestock. It is quick growing, nitrogen fixing and drought tolerant. Cultivars of cowpea vary in maturity between 60 and 100 days and short season varieties can often be grown on residual soil moisture after the main cereal crop.

Cowpea and millet are traditionally grown in association in W Africa, where the primary objective is to produce an optimum yield of millet. Roughly 70% of the cowpea grown in the region is intercropped with millet (or sorghum). Yields of cowpea are drastically reduced compared to sole crops due to shading by the millet, but it is grown as a bonus crop for grain and fodder and does not significantly reduce the yield of the standing crop. Millet is usually planted in June, or as soon as the rains are established and prostrate, photoperiod sensitive varieties of cowpea are planted in July (Muleba and Ezumah, 1985).

Intercropping provides many benefits to the farmer over sole cropping, however, its benefit in terms of efficiency of utilisation of rainfall are unclear. The traditional, long season varieties perform better in mixtures, but short season varieties, such as *40 days*, often perform better as a sole crop.

3.2. Alluvial deposits

Alluvial deposits occur in the major drainage valleys of the Yobe system (Yobe, Hadejia, Jama'are, Katagum, Gana and Yedseram). The soils are variable in nature, ranging from sands to clays and are generally deep but confined to the floodplains (*fadama*), spillans, delta fans and other bottomlands. In the inter-dunal, fossil floodplains saline or saline-alkali soils are sometimes found. The characteristics and use of the soils of the *fadama* have been described by Kundiri et al. (1997) based on local farmers' interpretation.

Rice (*Oryza sativa*) was originally grown in the area as a cash crop, but recently it has become a staple food crop for the people of the area. Rice seed is broadcast on the *fadama* before the onset of the rains in May / June, for germination with the first rain. The crop emerges as the floods arrive and grows as the flood level rises, to be harvested after the recession of the flood in October. Selection of suitable rice varieties to suit the nature of the flood is crucial to its success, as too great or too little flood will reduce yields. Some farmers make observations of the flood levels upstream and choose quick growing (80 days) or long season (120 days) varieties according to the speed of passage of the flood peak.

After the recession of the flood, the *fadama* are grazed or short season (≈ 60 days) cowpea is often grown on residual soil moisture. Although the crop is shallow rooting (< 30 cm), the sandy clay soils hold sufficient moisture for a good crop and the cowpea is usually successful. This is a useful crop for the farmers, in that it requires little attention and is less prone to pest attacks than rainy season crops.

The majority of the population of the area are concentrated along the watercourses of the Yobe system where irrigation is possible. In this area, irrigated wheat (*Triticum aestivum*) and vegetables are grown. Vegetables grown under irrigation are profitable cash crops. The main crops grown include; onions (*Allium cepa*), sweet and chilli peppers (*Capsicum annum*), tomato (*Lycopersicon esculenta*), okra (*Hibiscus esculentus*), aubergine (*Solanum melongena*), cucumber (*Cucumis sativus*), 'garden egg' and 'egusi' melon (*Citrullus lanatus*). Irrigated farming is much more profitable and less risky than rain-fed farming, although time consuming and labour intensive. Motorised pumps are used to lift water from the river, from channels cut from the

river, or from shallow tubewells on the *fadama*. It is estimated that around Gashua alone, there are over 2,000 irrigation pumps in use (Garba, personal communication). Until the early 1990s, a Government Task Force on wheat production provided seeds and fertiliser at subsidised prices for wheat farmers, but now the full price is payable and farmers are experiencing difficulties in obtaining inputs. There is no local market for wheat, and the majority of the produce is sold outside of the region.

3.3. Lacustrine deposits

South of Lake Chad in the New Marte - Dikwa - Ngala area, dark grey, cracking clay (vertisol) soils are found on lacustrine and lagoonal clays. A typical soil profile has been described by Adderley et al. (1997). Infiltration rates are generally less than 10 mm h^{-1} on the sandy clays and clays. The soil is rock hard when dry and difficult to cultivate when wet, thus the potential for rainy-season farming is limited. A local sorghum landrace called '*Masakwa*' is often grown during the dry season using residual soil moisture.

3.4. Soil water relations

Rayar (1987) observed that maximum water holding capacities were linearly related to clay content and quotes values for soils in Borno State ranging from 30 to 35% on lighter soils, and around 50% on the heavier textured soils. The figures in Table 2.4 below, are for selected sites in the North East Arid Zone of Nigeria. The author does not define the term 'maximum water holding capacity' but it is likely that the figures refer to total porosities as they compare well with figures of 34 - 46% for total porosity of the soils of Sudano-Sahelian Zone of Nigeria given by Kowal and Kassam (1978).

There is little information of available water capacities of soils in the region however it is estimated that due to the fineness of their particles, the soils are 'likely to hold an appreciable amount of moisture' (Maduakor, 1991). Kowal and Knabe (1972) present representative values of available water capacity for soils of the Sudano-Sahelian Zone of Nigeria as shown in Table 2.5.

Table 2.4 Maximum water holding capacities for soils in N Borno (after Rayar; 1987)

Site	Texture Class	Water Holding Capacity %
Nguru	LS	31.1
Geidam	LS	32.7
Madakali	LS	35.7
Gajabure	LS	34.3
Baga	LS	31.4
Ngamma	LS	33.8
Tongoshi	LS	37.9
Gashua	SL	33.4
Kuruawa	SCL	36.7
Gubio	SCL	51.5
Mongono	C	50.4
New Marte	C	47.2

Table 2.5. Available water capacities of soils of the Sudano-Sahelian Zone of Nigeria (after Kowal & Knabe, 1972)

Textural Class	AWC (%)	
	Mean	Range
Coarse sand	6.3	4.3 - 8.3
Fine sand	8.3	7.6 - 10.0
Fine loamy sand	13.3	11.6 - 15.0
Sandy clay	15.0	15.0
Clay loam	19.3	18.3 - 20.0
Sandy clay	15.0	13.3 - 17.7
Vertisol	21.0	16.6 - 25.0

4. NATURAL VEGETATION

Only 15% of the arable land in the region is cultivated (Rayer, 1987), therefore natural vegetation predominates, although in many places this has been modified by the effects of extensive grazing. The vegetation of the region may be typical of ‘Sudan Savanna’ and ‘Sahel Savanna’, typified by a mixture of grasses, shrubs and trees (Kowal and Knabe, 1972) and has been classified as ‘sub-arid wooded savanna’ by Kowal & Kassam (1978). A more detailed classification, produced by Leeuw and Tuley (1972), showed the region to be a mixture of shrub savanna, tree and shrub

savanna and parkland. Abdalla (1994) identified five main vegetation types in the region;

- a. Shrub grassland on deep sandy soils (especially in the north of the region) where scattered woody plants make up less than 10% of the ground cover.
- b. Wooded shrubland on sandy and loamy soils. Woody species constitute 10 – 40% of the ground cover, shrubs ≈30% and the rest is grasses.
- c. Shrubland patches in the Yobe floodplain with 40 – 60% cover of bushes.
- d. Woodland in the transitional zones between the upland and floodplains, with distinct tall trees covering up to 70% of the surface.
- e. Riparian forests along river channels, lake shores and isolated depressions susceptible to periodic water-logging, with 60 – 80% ground cover.

5. CLIMATE CHANGE

The mean annual rainfall figures above conceal great year-to-year variability. For example, over the period 1942-91 the annual rainfall recorded at Nguru varied from 235 mm to 868 mm. Not only are there random variations but also there appear to be medium term trends. Bunting et al. (1976) noted that the period 1931 - 1960 was one of greater than 'average' rainfall in West Africa generally. Nicholson (1989) identified a steady downward trend in annual rainfall totals in the Sahel and Sudan zones of West Africa since the 1950s with a long sequence of dry years commencing around 1968. Tahule and Woo (1998) identified a change in the mean annual rainfall of Northern Nigeria starting between 1964 and 1972. There was a short revival between 1970 and 1978, only to be followed by a further decline in the early eighties (IWACO, 1985). The decline in mean annual rainfall since the change point has been calculated as $1 - 3 \text{ mm year}^{-1}$ (Tahule and Woo, 1998).

The causes of rainfall fluctuations in the Sahel and Sudan zones of Africa are poorly understood, but may be attributable to one or other, or a combination of, two causes; large-scale patterns of atmospheric circulation and local land surface processes.

Simulation experiments by Folland et al. (1986) concluded that sea surface temperature (SST) anomalies in the Atlantic Ocean have a major impact on Sahelian

rainfall. Years of low rainfall in north Africa are associated with higher temperatures south of the equator and lower temperatures to the north. The cause of these temperature differences may be natural or associated with human induced global warming.

Desertification, whether caused by climatic anomalies or human activity leads to a reduction in the vegetation cover, soil moisture and evapotranspiration and increased surface temperatures, surface albedo, and levels of atmospheric dust. These may result in reduced rainfall, exacerbating the desertification. Nicholson (1989) has suggested that such feedback mechanisms may intensify drought and result in dry periods lasting for longer than would otherwise occur. Xue (1997) has demonstrated through the use of global circulation models (GCMs) that the degradation of the land surface in the Sahel could account for the observed changes in rainfall over the past 40 years. The interactions between the atmosphere and the biosphere have been extensively studied in Niger under the HAPEX-Sahel project (Goutorbe et al. 1997). Savenije (1995) has suggested that the observed trends in rainfall in the Sahel not only be due to land use changes in the Sahel, but also on land use practices in the Savanna and forest belts to the south.

It is clear from the above that there has been a general increase in aridity in the North East Arid Zone of Nigeria, and in the Sahel generally, over the period under consideration, but the causes are complex and not fully understood. This makes prediction of future rainfall regimes difficult, however, the agricultural impacts of the historical changes need to be understood in order to suggest alleviation strategies under alternative future climatic scenarios.

6. REFERENCES

- Abdalla J. D., 1994. The evaluation of satellite imagery in a geographic information system (GIS) for monitoring land cover changes in a semi-arid area of North-Eastern Nigeria. PhD thesis. Silsoe College, Cranfield University. Unpublished.
- Adams, W.M. and Mortimore, M.J., 1997. Agricultural intensification and flexibility in the Nigerian Sahel. *The Geographical Journal*, 163:150-160.
- Adderley, W.P., Jenkins, D.A., Sinclair, F.L., Stevens, P.A. and Verinumbe, I., 1997. The influence of soil variability on tree establishment at an experimental agroforestry site in North East Nigeria. *Soil Use and Management*, 13:1-8.
- Benoit P., 1977. The start of the growing season in Northern Nigeria. *Agricultural Meteorology* 18:91-99.
- Bunting, A.H., Dennett M.D., Elston J. and Milford J.R., 1976. Rainfall trends in West African Sahel. *Quarterly Journal of the Royal Meteorological Society* 102:59-64.
- FAO, 1984. Agroclimatological data for Africa. Vol. 1 Countries north of the equator. Food and Agriculture Organisation. Rome.
- Folland, C.K., Palmer, T.N. and Parker, D.E., 1986. Sahel rainfall and worldwide sea temperatures, 1901-85. *Nature*. 320:602-607.
- Goutorbe, J.P., Dolman, A.J., Gash, J.H.C., Kerr, Y.H., Lebel, T., Prince, S.D. and Stricker, J.M.M., 1997. HAPEX-Sahel. Elsevier Science, 1088pp.
- Hulme, M. and Kelly, M., 1993. Exploring the links between desertification and climate change. *Environment*. July/August 1993. pp5-45.
- IWACO B.V., 1985. Study of the water resources in the Komadougou - Yobe basin. Nigeria - Niger Joint Commission for Cooperation, Niamey, Niger Republic.

- Kowal, J. M. and Kassam, A. H., 1978. *Agricultural ecology of savanna*. Oxford University Press, Oxford.
- Kowal, J. M. and Knabe, D. T., 1972. *An agroclimatological atlas of the Northern States of Nigeria*. Ahmadu Bello University Press, Nigeria.
- Kundiri, A.M., Jarvis, M.G. and Bullock, P., 1997. Traditional soil and land appraisal on fadama lands in northeast Nigeria. *Soil Use and Management* 13:205-208.
- Leeuw, P.N. and Tuley, P., 1972. Vegetation. In, *The land resources of North East Nigeria*. Volume 1. The environment. Land Resources Division / Overseas Development Administration / Foreign and Commonwealth Office. Surbiton, England.
- Le Houérou, H. N., 1996. Climate change, drought and desertification. *Journal of Arid Environments* 34:133-185.
- Maduakor, H. O., 1991. Physical and hydraulic properties of soils of Sudano-Sahelian regions of Nigeria. In Sivakumar, M. V. K., Wallace, J. S., Renard, C. and Giroux, C. (eds) 1991. *Soil water balance in the Sudano-Sahelian zone*. Proc. Int. workshop, Niamey, Niger, February 1991. IAHS publication no. 199. IAHS Press, Institute of Hydrology, Wallingford, UK.
- Muleba, N. and Ezumah, H. C., 1985. Optimizing cultural practices for cowpea in Africa. In Singh, S. R. and Rachie, K. O. (eds). *Cowpea research, production and utilisation*. John Wiley & sons, Chichester, UK. pp289-295.
- Nicholson, S.E., 1989. Long-term changes in African rainfall. *Weather* 44:46-56.
- Nieuwolt, S., 1977. *Tropical climatology. An introduction to the climates of the low latitudes*. John Wiley & Sons. Chichester. pp.207.
- Ojanuga, A. G., 1987. Characteristics of soils of the semi-arid region of Nigeria. In Sagua, V. O., Ojanuga, A. U., Enabor, E. E., Mortimore, M., Kio, P. R. O., and Kalu A. E., (eds) 1987. *Ecological disasters in Nigeria: drought and*

- desertification. Proc. Nat. Workshop, Kano, December 1985, 64-77. Federal Ministry of Science and Technology, Lagos, Nigeria.
- Rayar, A. J., 1987. Studies on some physio-chemical parameters of the soils of Borno State. *Annals of Borno (Maiduguri)* 4:283-291.
- Savenije, H. H. G., 1995. New definitions for moisture recycling and the relationship with land-use changes in the Sahel. *Journal of Hydrology*. 167:57-78.
- Singh, S. R. and Rachie, K. O. (eds), 1985. Cowpea research, production and utilisation. John Wiley & sons, Chichester, UK.
- Tarhule, A. and Woo, M-K., 1998. Changes in rainfall characteristics in Northern Nigeria. *International Journal of Climatology*. 18:1261-1271.
- Usman, H. 1994. Soils susceptible to erosion in northeastern Nigeria. *Arid Soil Research and Rehabilitation*. 8:217-225.
- van Apeldoorn, G.J., 1981. Perspectives on drought and famine in Nigeria. George Allen & Unwin. London. pp184.
- Xue Y.K., 1997. Biosphere feedback on regional climate in tropical north Africa. *Quarterly Journal of the Royal Meteorological Society*. 123:1483-1515.

CHAPTER THREE. RAINFALL TRENDS IN THE NORTH EAST ARID ZONE OF NIGERIA 1961 - 1990³

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Abstract

Daily rainfall records for 1961 - 90 for Nguru (12.53 °N, 10.28 °E, alt. 343m), Potiskum (11.42 °N, 11.02 °E, alt. 415m) and Maiduguri (11.51 °N, 13.05 °E, alt. 354m) in Nigeria and Maine Soroa (13.13 °N, 11.58 °E, alt. 339m) in Niger were analysed to describe any changes in season duration, rain-days per season and rainfall amount per rain-day. There was a consistent decrease in annual rainfall of 8 mm year⁻¹ at all four stations. The majority of this reduction occurred in August or September. Although there was a delay in the onset of the rains at the two westernmost stations, the main reason for the reduction in rainfall was a reduction of 6 -25 days in the number of rain-days during the rainy season. This increased the mean duration of dry spells during the rainy season by up to 1.5 days. No change in the average rainfall per rain-day was detected except at Maine Soroa where there was a slight reduction. The results are discussed in terms of their implications for sustainable agriculture in the region.

1. INTRODUCTION

North East Nigeria has a unimodal distribution of rainfall. The rainy season starts in June or July as the Inter-Tropical Convergence Zone passes northwards, peaks in August, and finishes quite rapidly in September or October. The rest of the year is

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virtually dry (Figure 3-1). The mean annual rainfall total declines from south-west to north-east, with increasing distance from the source of moisture, i.e. the Atlantic Ocean, (Kowal and Knabe, 1972). The onset of rains is earliest in the south and is delayed by about 14 days per degree of latitude northwards, however the retreat of the rains is much faster, averaging less than 7 days per degree of latitude southwards (Kowal and Kassam, 1978). The combined effect is that the rainy season becomes progressively shorter and drier as one moves northwards.

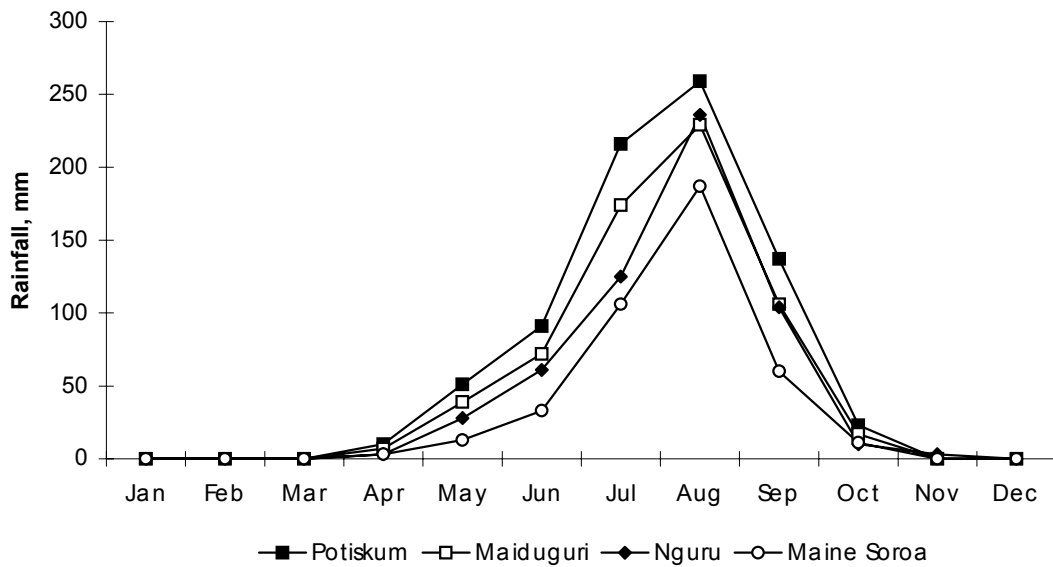


Figure 3-1 Average monthly rainfall for four stations in the North East Arid Zone (after FAO, 1984).

The mean annual rainfall figures, however, conceal considerable year-to-year variability and the published figures can vary markedly depending on which years were included. For example, figures for Nguru (12.53 °N, 10.28 °E, alt. 343m) range from 471 mm for the period 1966 - 78 (Iwaco, 1985), to 570 mm for a 16 year record with an unspecified starting date (FAO, 1984) and up to an obviously erroneous value of 719 mm for 1916 - 83 (Akintola, 1986).

Not only are there random variations in annual rainfall but also there appear to be medium term trends. Bunting *et al.* (1976) noted that the period 1931 - 1960 (previously used as a standard for comparison of met data) was one of greater than 'average' rainfall in West Africa generally, and Hulme (1992) found that considering

the following 30-year period, mean seasonal rainfall in the Sahel had fallen by as much as 30%. Nicholson (1989) identified a steady downward trend in annual rainfall totals in the Sahel and Sudan zones of West Africa since the 1950s with a long sequence of dry years commencing around 1968. The causes of rainfall fluctuations in the Sahel and Sudan zones of Africa are poorly understood, but they are generally attributed to large-scale patterns of atmospheric circulation. However, it may well be that local land surface processes, such as change in albedo, evapotranspiration, surface temperatures and atmospheric dust may intensify drought and result in dry periods lasting for longer than would otherwise occur (Nicholson, 1989).

The North East Arid Zone of Nigeria, corresponding to the northern parts of Yobe and Borno States, has shown signs of increasing desertification over the last 30 years placing stress on the indigenous population. As a result, the Federal Government of Nigeria, supported by the European Community, established the North East Arid Zone Development Programme with the objectives of reducing environmental degradation and alleviating the social impacts of aridity. The downward trend in annual rainfall of this region has been recognised (IWACO, 1985), and a good relationship between the onset of the rains and the season duration has been shown further north in Niger (Sivakumar, 1988). However, the changes in rainfall distribution have not been analysed in detail. A decline in annual rainfall total could arise from a reduced season duration, a reduced number of rain-days within the season, reduced rain per rain-day or a combination of the three. The implications of a changing rainfall regime on the agriculture and hydrology of the region, and possible strategies for alleviating the impacts of reduced annual rainfall, will vary depending the nature of the decline. The objective of this paper is to document the nature of the changes in the rainfall regime in the North East Arid Zone of Nigeria and to determine which rainfall descriptors have shown significant trends over the period 1961-1990. It is not within the scope of this paper to speculate on the mechanisms responsible for the changes, nor to predict what will happen in the future, however an understanding of what has happened over the 30 years will help to explain the changes that have been observed in the environment and will provide a rational basis for considering interventions to ameliorate the impacts of aridity.

1.1. Methods

Daily rainfall data were collated for four synoptic stations that encircle the area, for the period 1961 to 1990, corresponding to most recent standard reporting period. The stations are located at Nguru (12.53 °N, 10.28 °E, alt. 343m), Potiskum (11.42 °N, 11.02 °E, alt. 415m) and Maiduguri (11.51 °N, 13.05 °E, alt. 354m) in Nigeria and Maine Soroa (13.13 °N, 11.58 °E, alt. 339m) in Niger. The data were aggregated to provide monthly and annual totals. The mean annual rainfall for 1961-1990 was compared with the mean of 1931-1960 by a t-test.

In order to consider the social and economic value of the annual rains, the period of agronomically useful rainfall must be defined. Several authors have used differing criteria for the definitions of onset and end of rains in the region (Table 3.1), including definitions of a 'false start'. Each of these methods was tested for the local data. Although the precise dates varied for each method, the trends were similar in all cases. The method of Kowal and Kassam (1978) was devised for decadal (10-day) rainfall totals, and is therefore less appropriate where daily data are available, and the method of Benoit (1977) refers more explicitly to 'growing' season rather than 'rainy' season. The method of Sivakumar (1988) for onset was found to be too strict for Nigeria, resulting in years with no apparent onset of rains. Therefore the method of Stern *et al.* (1982) was adopted for the definition of onset and the method of Sivakumar (1988) for end of rains. The duration of the rainy season was taken as the difference between the end and start of rains and the seasonal rainfall as the total rainfall during the rainy season. The centroid of the seasonal rainfall was defined as the date by which half of the seasonal rainfall had fallen. In addition, the number of rain-days (rain >0.1mm) per year and mean rain per rain-day were calculated.

Table 3.1. Definitions used for onset and end of rains.

<i>Author</i>	<i>Criteria for onset</i>	<i>Criteria for false start</i>
Stern <i>et al.</i> (1982)	Rainfall at least 20mm in 2 days	10 dry days in the following 30.
Sivakumar (1988)	Rainfall at least 20mm in 3 days	7 dry days in the next 30.
Benoit (1977)	Rainfall of at least 0.5 ETp over any period	5 dry days immediately following.
Kowal & Kassam (1978)	Rainfall at least 25mm in 10 days.	Rainfall less than 0.5 ETp in the next 10 days.
	<i>Criteria for end</i>	
Stern <i>et al.</i> (1982)	No rainfall in 15 days.	
Sivakumar (1988)	No rainfall in 20 days.	
Kowal & Kassam (1978)	The last 10-day period with at least 12.5mm of rain provided that rainfall in the preceding 10 days exceeded ETp.	

Note: ETp = potential evapotranspiration.

The annual total rainfall, seasonal distribution and daily distribution were tested for the absence of time trends by the correlation between the value of the parameter and the year of measurement. Where a significant time trend was apparent, the slope of the linear regression line between the value of the parameter and the year of measurement was calculated to give an indication of the influence of the trend. In each case, regression was used to indicate the general nature of the trend, rather than to produce a predictive model.

The data from the four stations were tested for correlation between the date of onset and end of rains. The relationships between date of onset, number of rain days and average rain per day and seasonal rainfall were also tested. If the duration and magnitude of the rains could be predicted once the onset date was known, this would be of great help in tactical agricultural planning.

2. RESULTS AND DISCUSSION

2.1. Annual rainfall total

At all four stations there is a significant difference (at 1% level) in mean annual rainfall between the two World Meteorological Organisation (WMO) normal periods of 1931-60 and 1961-90 (Table 3.2). The changes are equivalent to -23%, -18%, -20% and -14% at Nguru, Potiskum, Maiduguri and Maine Soroa respectively. These

correspond well with the typical change for the Sahel observed by Hulme (1992) and emphasises the need to identify which time period has been included in the calculation of long-term means.

The annual rainfall at each station over the period 1961 - 1990 is shown in Figure 3-2. In each case there is a significant negative correlation between the annual rainfall and the year of measurement. The linear regression could only explain between 16% and 35% of the variation in annual rainfall and the standard deviation of the residuals is high (95mm - 164mm), implying that the linear model cannot be used for prediction of future rainfalls. However, the slopes of the regression lines were all parallel and significantly different from zero, averaging -8 mm year^{-1} . This would suggest an underlying trend that would account for a fall of almost 250mm in the annual rainfall total over the 30 year period. Consequently, the annual rainfall totals from 1961-1990 alone could not be used for prediction of future rainfall probabilities. As the residuals from the regression appeared to be normally distributed, confidence intervals for deviations from the trend could be calculated, however it would be unwise to extrapolate the linear trend outside the period used for analysis, which would lead, for example, to the unlikely conclusion, that by 2035, Maine Soroa would receive no rainfall at all!

Table 3.2. Estimates of mean annual rainfall annual rainfall with 80% and 20% probabilities of exceedance and for four stations in the North East Arid Zone, 1931 - 1960 and 1961 - 1990.

Station	Period	Annual Rainfall (mm)		
		80%	Mean	20%
Potiskum	1931-60	655	805	956
	1961-90	511	662	813
Maiduguri	1931-60	549	690	830
	1961-90	418	553	688
Nguru	1931-60	457	566	676
	1961-90	334	434	534
Maine Soroa	1931-60	316	398	480
	1961-90	243	342	441

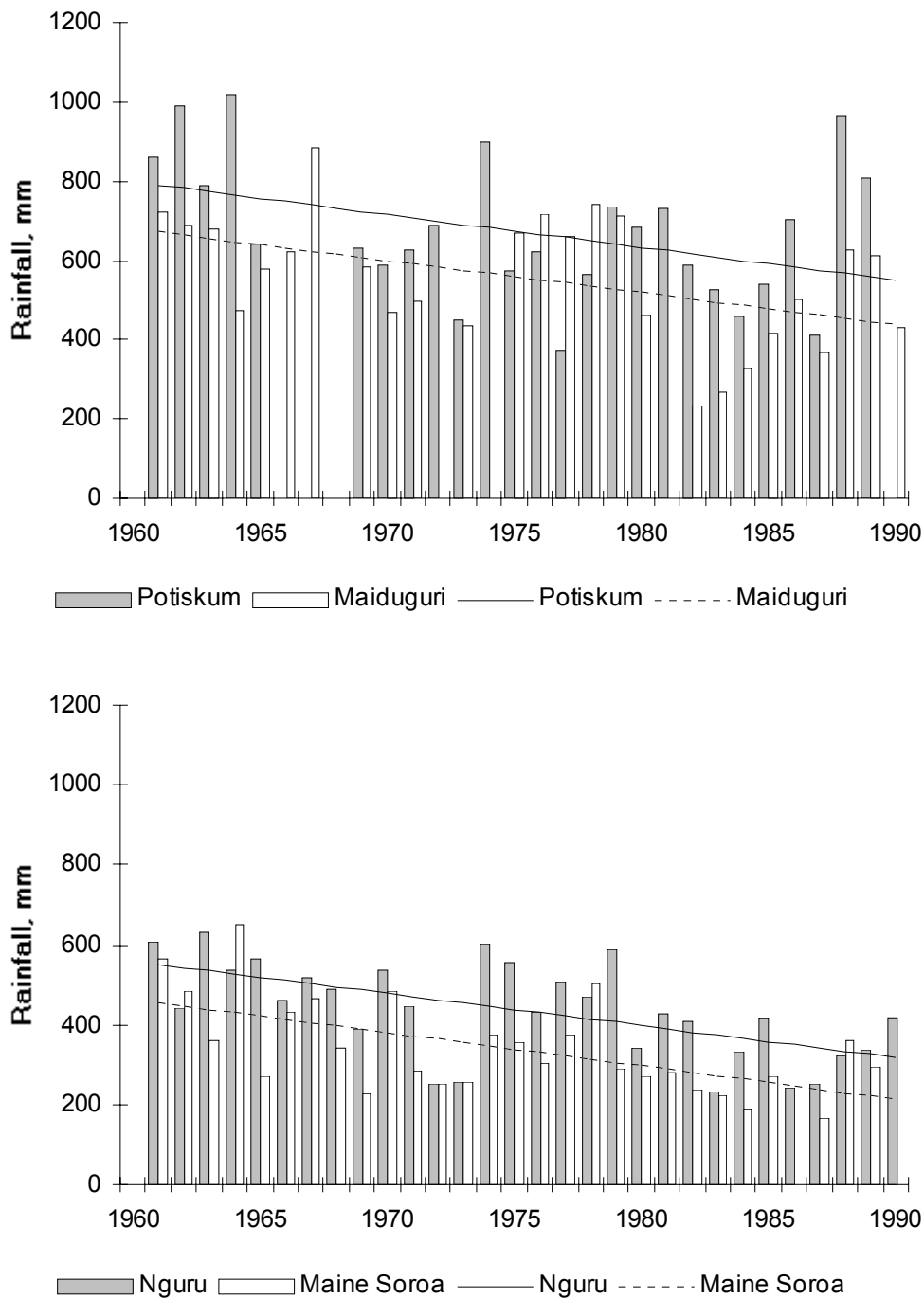


Figure 3-2 Annual rainfall (mm) for 1961 – 1990 showing linear trends for a) Potiskum and Maiduguri and b) Nguru and Maine Soroa.

2.2. Seasonal distribution of rainfall

A comparison of the average decadal (10-day) rainfall for 1961-70 and 1981- 90 shows that, at each station, the declining annual rainfall has been dominated by a

reduction in the mid-season rainfall (Figure 3-3). The August rainfalls at Maiduguri, Nguru and Maine Soroa and the September rainfall at Potiskum had all declined by 2 to 6 mm year⁻¹.

All four stations exhibited year-to-year variation in the rainy season which, on average, began later and was of shorter duration at Nguru (average 1 July - 21 September) and Maine Soroa (11 July - 16 September) than at Potiskum (16 June - 14 September) and Maiduguri (15 June - 20 September). At the two westerly stations of Potiskum and Nguru there appears to have been a progressive delay in the date of onset (Figure 3-4), although this was not the case when the definitions of Benoit (1977) or Kowal and Kassam (1978) were used and may therefore have been an artefact of the criteria used to determine the start date. At the other two stations there was no evidence to suggest that the date of onset of rains has been changing. There was less variation in the timing of the end of rains and none of the stations showed a significant trend. Consequently, a reduction of rainy season duration was only observed at Potiskum and Nguru.

With the exception of Potiskum ($r=-0.45$) there was no correlation between the dates of onset and end of rains and Figure 3-5 shows that the timing of the end of rains is more stable than the onset. Therefore, the season length is primarily a function of the date of onset.

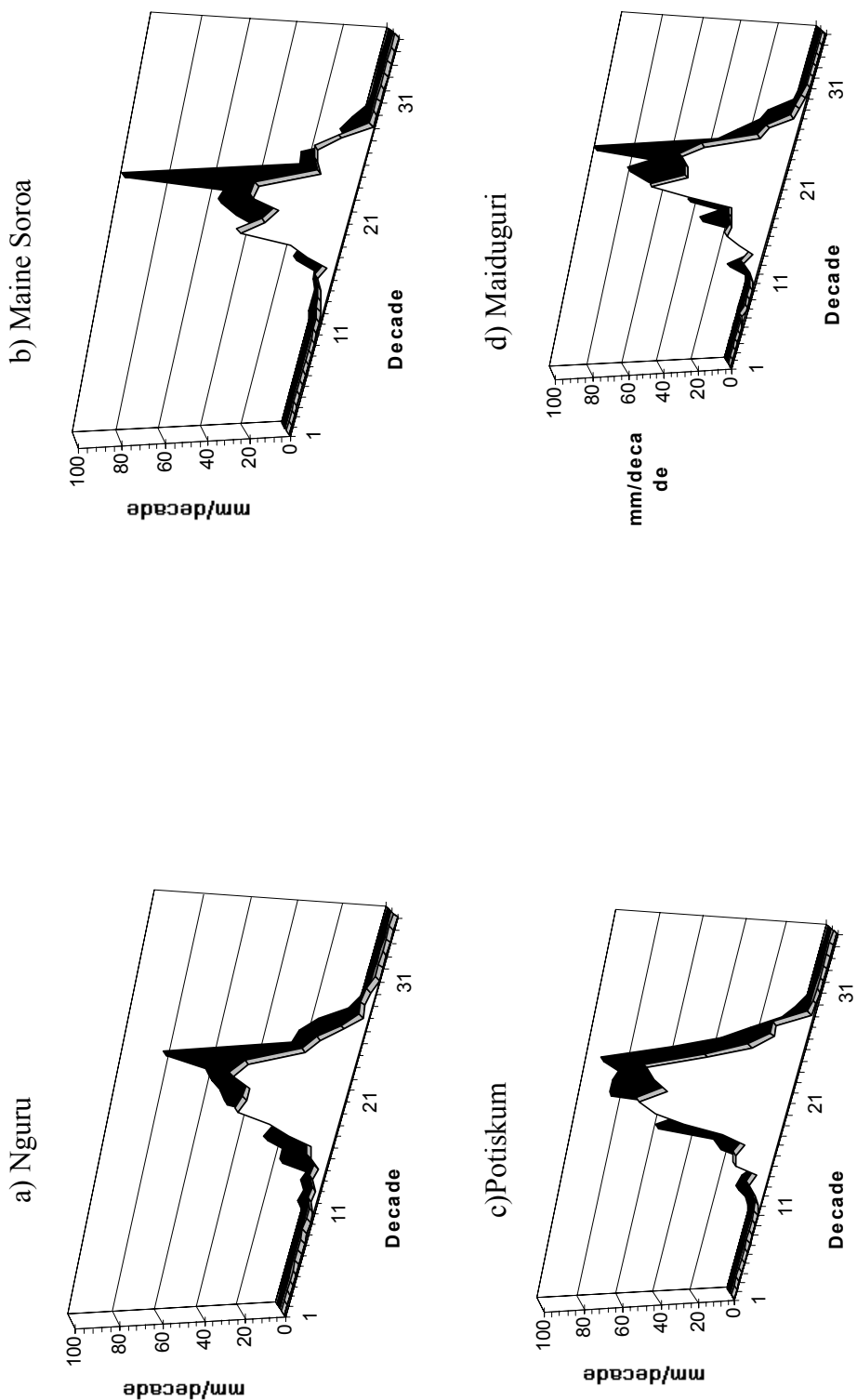


Figure 3-3 Seasonal rainfall distribution by 10-day period (1 = 1 January), 1961 – 1970 (■) and 1981 – 1990 (□) for a) Nguru, b) Maine Soroa, c) Potiskum and d) Maiduguri.

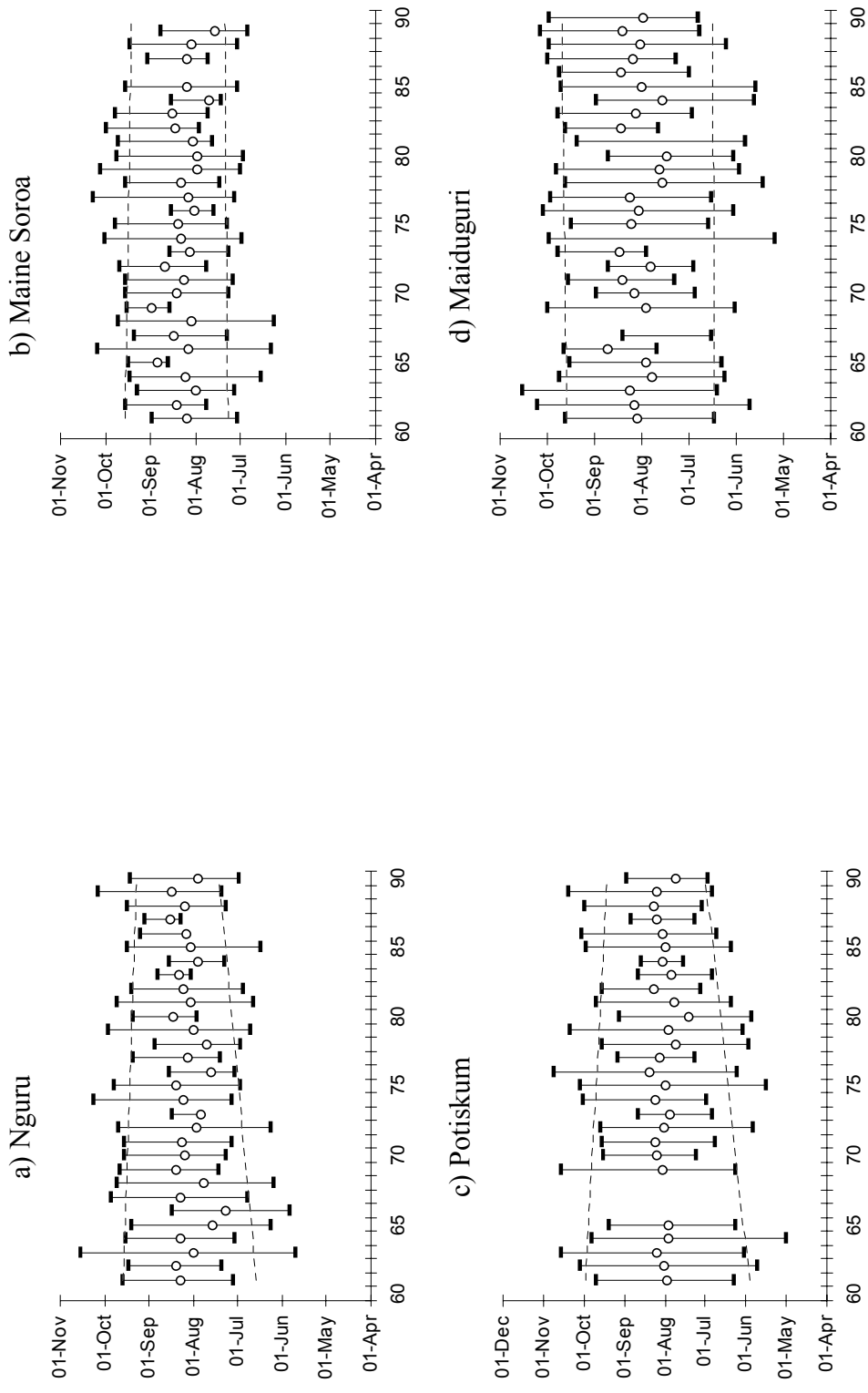


Figure 3-4 Duration of rainy season (I), rainfall centroid (O) and trend lines (---) for a) Nguru, b) Maine Soroa, c) Potiskum and d) Maiduguri.

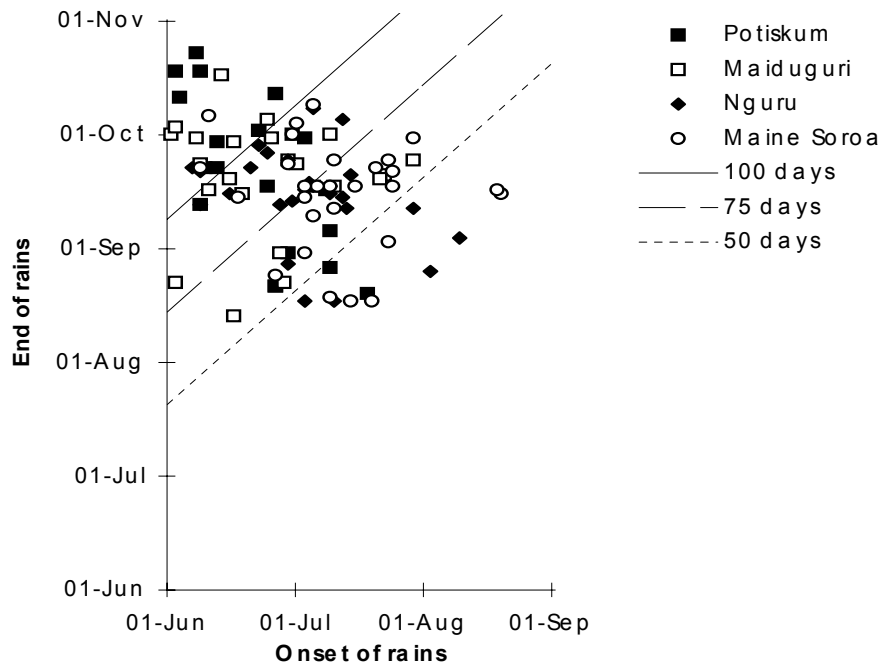


Figure 3-5 Relationship between date of onset and end of rains at four stations in the North East Arid Zone showing isochrones of equal season length.

2.3. Number of rain-days and rainfall per day

The average amount of rain per rain-day has remained stable at Potiskum, Maiduguri and Nguru over the 30 year period (Table 3.3) however at Maine Soroa it has shown a small, but statistically significant decline over time ($0.15 \text{ mm rain-day}^{-1} \text{ year}^{-1}$). More importantly, there has been a dramatic fall in the number of rain-days per year at each station, regardless of whether or not the season duration has remained stable (Figure 3-6). Over the period 1961 to 1990, the mean number of rain days per year has reduced by 25 days at Potiskum and Maiduguri, 21 days at Nguru and 6 days at Maine Soroa. The relationships between seasonal rainfall and date of onset ($R^2 = 0.42$; Figure 3-7) or season length ($R^2 = 0.54$) were poor implying that the date of onset cannot be used for predicting the seasonal rainfall without wide margins of error.

Table 3.3. Number of rain-days per year and average rain per day for 1961-70, 1971-80 and 1981-90

Station	No. rain-days			Mean rain per rain-day (mm)		
	1961-70	1971-80	1981-90	1961-70	1971-80	1981-90
Potiskum	53	42	29	14.2	13.6	16.9
Maiduguri	47	35	30	12.0	14.1	12.5
Nguru	36	27	20	12.7	13.6	13.5
Maine Soroa	26	25	20	13.5	11.3	10.3

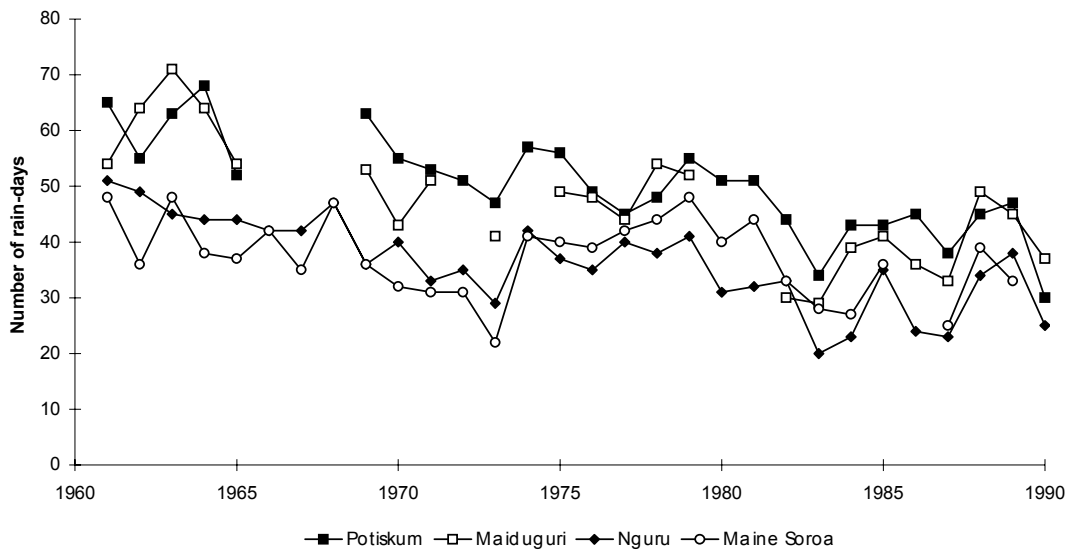


Figure 3-6 Number of rain-days per year at four stations in the North East Arid Zone (1961 – 1990).

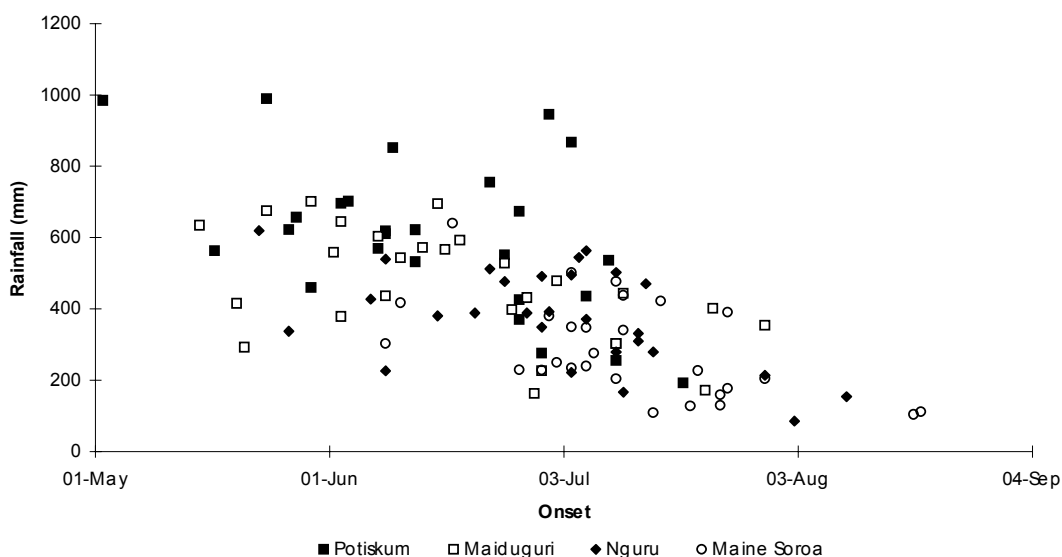


Figure 3-7 Relationship between date of onset and seasonal rainfall at four stations in the North East Arid Zone.

As the season length and average rain per day have not generally changed, the observed reduction in annual rainfall is predominantly due to the reduction in the number of rain days per year ($R^2 = 0.72$). It follows that the average interval between rain-days has increased at most stations. At Maiduguri and Nguru this has resulted in an increase in the mean duration of dry spells during the rainy season of 1.5 days and at Maine Soroa of only 0.6 days. The increased duration of dry spells at Potiskum was not significant, which suggests that the reduction in the number of rain-days per year has largely occurred at the beginning of the season and has resulted in the delayed onset seen at that station. As the distribution of dry spells has not remained stable, attempts to predict the likelihood of dry spells of a given duration, as carried out by Sivakumar (1992) for other stations in West Africa, would be invalid without first removing the underlying trend.

2.4. The implications for agriculture

Research in Sudan has shown that the yield of millet and sorghum are more closely related to the number of rain-days than to the seasonal rainfall total (Olsson, 1993). It should therefore be possible to determine likely future yields. However, the marked downward trend in the number of rain-days in the North East Arid Zone of Nigeria complicates any general discussion on the likely future for agricultural development

since it cannot be assumed that the trend is merely part of a longer term cycle that has currently reached its nadir. To make realistic decisions to encourage the sustainability of agricultural and rangeland production it should either be assumed that the trend will continue downwards or that a new baseline has been established. In both cases the risk of crop failure and rangeland overgrazing are greater now than in the previous decades.

There are also important implications for groundwater recharge, particularly around the oases in the north of the region. Here, any decline in the amount of water percolating beyond the root zone would have a commensurate, but delayed, effect on the viability of agriculture around the oases margins that depends on high water tables for growth.

3. CONCLUSION

In line with the regional trend, the North East Arid Zone of Nigeria has experienced a significant decline in annual rainfall over the period 1961-1990, with an average trend of 8mm year^{-1} . This decline has been dominated by a reduction in the number of rain-days during the rainy season rather than any shortening of the season or reduction in mean rainfall per rain-day. As a consequence the risk of dry spells during the growing season has increased. Although the potential duration of the rainy season could be predicted once the date of onset is known, the amount of rain that is likely to fall during the season cannot be predicted with confidence. This analysis suggests that agronomic research in the region should concentrate approaches to alleviate, or enable crops to withstand, periods of drought within the season.

4. ACKNOWLEDGEMENTS

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5. REFERENCES

- Akintola J.O., 1986. Rainfall distribution in Nigeria 1892 - 1983. Impact Publishers, Ibadan, Nigeria.
- Benoit P., 1977. The start of the growing season in Northern Nigeria. *Agricultural Meteorology* 18:91-99.
- Bunting A.H., Dennett M.D., Elston J. and Milford J.R., 1976. Rainfall trends in West African Sahel. *Quarterly Journal of the Royal Meteorological Society* 102:59-64.
- FAO 1984. Agroclimatological data for Africa. Vol. 1 Countries north of the equator. Food and Agriculture Organisation. Rome.
- Hulme M., 1992. Rainfall changes in Africa 1931-1960 to 1961-1990. *International Journal of Climatology* 12:685-699.
- IWACO, 1985. Study of the water resources in the Komadougou Yobe basin. Technical Report No. 2: Climatic analysis. IWACO B.V. Consultants, Rotterdam, The Netherlands. (Unpublished).
- Kowal J.M. and Kassam A.H., 1978. *Agricultural ecology of Savanna*. Oxford University Press, Oxford.
- Kowal J.M. and Knabe D.T., 1972. *An agroclimatological atlas of the Northern states of Nigeria*. Ahmadu Bello University Press, Zaria, Nigeria.
- Olsson L., 1993. On the causes of famine - drought, desertification and market failure in the Sudan. *Ambio* 6:395-403.
- Nicholson S.E., 1989. Long-term changes in African rainfall. *Weather* 44:46-56.
- Sivakumar M.V.K., 1988. Predicting rainy season potential from the onset of rains in Southern Sahelian and Sudanian climate zones of West Africa. *Agricultural and Forest Meteorology*. 42:295-305.

Sivakumar M.V.K., 1990. Exploiting rainy season potential from the onset of rains in the Sahelian zone of West Africa. *Agricultural and Forest Meteorology*. 51:321-332.

Sivakumar M.V.K., 1992. Empirical analysis of dry spells for agricultural applications in West Africa. *Journal of Climate*. 5:532-539.

Stern R.D., Dennett M.D. and Dale I.C., 1982. Analysing daily rainfall measurements to give agronomically useful results. I. Direct methods. *Experimental Agriculture* 18:223-236.

CHAPTER FOUR. TRENDS IN REFERENCE EVAPOTRANSPIRATION IN THE NORTH EAST ARID ZONE OF NIGERIA, 1961-91⁴

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Abstract

The North East Arid Zone of Nigeria has experienced a decline in mean annual rainfall over the period 1961-90. This paper seeks to establish whether changes have occurred in the mean value of other climate parameters that would affect reference evapotranspiration during the growing season. It was shown that for the three stations tested, monthly mean daily maximum, and particularly minimum, temperatures have increased over the period 1961-91 by up to 1.5°C. Although monthly mean daily relative humidity has been declining, this has been due to the increased temperature, and monthly mean daily vapour pressure has remained stable.

As sufficient climate data to use the Penman-Monteith equation were not always available, other radiation and / or temperature based equations were tested. However, none of the methods used produced results that were comparable to the Penman-Monteith equation. The closest agreement was obtained using the Penman-Monteith equation with long term monthly mean values of the missing parameters (where these themselves were not subject to change over time).

The observed increases in temperature have not be great enough to result in significantly increased reference evapotranspiration. Only at Maiduguri, did the calculated reference evapotranspiration show any significant trend over the period, which was primarily due to increases in recorded wind speed. An inconsistent and broken wind speed record at Maiduguri casts doubt over the validity this increase.

⁴ Published as Hess, T M (1998). Trends in reference evapo-transpiration in the North East Arid Zone of Nigeria, 1961-91. *Journal of Arid Environments*. 38: 99-115.

Keywords

Evapotranspiration, Temperature, Nigeria, Sahel

1. INTRODUCTION

There is clear evidence that the average rainfall of the North East Arid Zone of Nigeria declined over the period 1961 - 1990 (Hess et al., 1995) with consequent changes in the soil water balance and hence the viability of rainfed cropping systems. However, a reduction in rainfall may also be accompanied by reduced cloud (and hence increased solar radiation) and reduced relative humidity. In addition, declining rainfall has been associated with increased temperature in some African dryland regions (Hulme, 1996). The effect of these would be to increase potential evapotranspiration and therefore exacerbate the impacts of reduced rainfall on the soil water balance.

Actual evapotranspiration is the lesser of the demand for water by the atmosphere and the supply of water at the surface. In semi-arid environments such as north east Nigeria, for much of the year actual evapotranspiration is supply limited. However, during the growing season sufficient moisture may be available such that actual evapotranspiration is demand limited for much of the time. In the North East Arid Zone of Nigeria, the growing season commences with the onset of rains in June (Hess et al., 1995) and includes a period after the end of the rains when crops can utilise residual soil moisture. In this region, the end of the growing season occurs at the end of October (Kowal and Kassam, 1978).

Potential evapotranspiration is the evapotranspiration from a vegetated surface assuming that water is freely available to the plants. Hence potential evapotranspiration will vary between plant species and stages of growth. In order to make comparisons between locations or over time, it is usual to define a reference surface, usually taken to be short green grass (Doorenbos and Pruitt, 1977) or alfalfa (Wright and Jensen, 1972). Recently, the concept of reference evapotranspiration of a hypothetical surface has been introduced to standardise the definition and calculation of a reference figure. The reference evapotranspiration, ET_0 is defined as;

'the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m⁻¹ and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water'. (Allen et al., 1994)

Monthly ET_o can be calculated using evapotranspiration equations, such as the Penman-Monteith equation (Monteith, 1981) provided that a) monthly mean daily maximum and minimum air temperatures, relative humidity, global solar radiation and wind speed data are available and b) that the data were measured over a reference surface.

Although synoptic weather stations in the North East Arid Zone generally record the data required to calculate ET_o, there have often been periods when one or more of the necessary instruments have not been functioning. Therefore there is an incomplete record for the period 1961 -1991 at all stations. There are two possible solutions to this problem:

- Alternative equations could be used. Many other equations have been proposed for estimation of reference evapotranspiration which have less demanding data requirements, although many of these have been calibrated for particular environments. These are based on temperature and solar radiation or only temperature.
- If the individual climate parameters are stationary over time, missing data can be estimated using mean values or inferred from other parameters.

The application of reference evapotranspiration equations assumes that meteorological measurements are taken over a freely transpiring surface with adequate fetch in all directions, thus the air at the evaporating surface should be saturated and there should be no advection of energy to or from the site. The effect of aridity of the surface can lead to increased air temperature, reduced vapour pressure and increased wind speeds and therefore artificially high values of ET_o (Ley et al., 1996) in response to reduced actual evapotranspiration. At none of the weather stations used in this study were reference conditions maintained. Therefore the

possible impact of aridity on the meteorological measurements needs to be considered.

This paper seeks to determine whether the potential evapotranspiration during the growing season has been changing over the period 1961-91, assesses the possible impacts of aridity on the estimates of ET_0 and discusses the implications for applying the concept of reference evapotranspiration in arid environments .

2. METHODS

2.1. Data set

Three synoptic meteorological stations in the North East Arid Zone were selected. . These were Nguru (12.53 °N, 10.28 °E, alt. 343m), Potiskum (11.42 °N, 11.02 °E, alt. 415m) and Maiduguri (11.51 °N, 13.05 °E, alt. 354m). Monthly means of daily records of maximum temperature, minimum temperature, relative humidity, sunshine duration and wind run were collated for the period 1961 - 1991. These data are required to estimate monthly reference crop evapotranspiration by the Penman-Monteith method.

There were many months when one, or more parameters were missing. Table 4.1 shows the number of months of data for each site and the percentage non-missing for each parameter. Only 45% of the site-months of data had a full record. In particular the data from Nguru has long periods when either sunshine duration or daily wind run are missing, such that there were only 13 months with full data.

Table 4.1. Percentage of months with complete data for each parameter (June - October, 1961-1991).

Parameter	Station			Total
	Maiduguri	Nguru	Potiskum	
Maximum temperature	97%	94%	88%	93%
Minimum temperature	98%	81%	88%	89%
Mean relative humidity	95%	96%	79%	90%
Sunshine duration	86%	64%	65%	72%
Daily wind run	80%	31%	61%	57%
All	70%	8%	52%	43%

In order to separate the effects of air temperature and humidity on relative humidity, mean daily vapour pressure, ed (kPa), was calculated from

$$ed = \left(\frac{ea_{T_{\max}} + ea_{T_{\min}}}{2} \right) \frac{RH}{100} \quad (3-1)$$

where $ea_{T_{\max}}$ and $ea_{T_{\min}}$ are the saturation vapour pressures (kPa) at mean daily maximum and minimum temperatures ($^{\circ}\text{C}$) respectively and RH is the mean daily relative humidity (%). Dew point temperature, T_d ($^{\circ}\text{C}$), was estimated from (Jensen et al., 1990).

$$T_d = \frac{116.9 + 273.3 \ln ed}{16.78 - \ln ed} \quad (3-2)$$

As none of the stations used recorded solar radiation directly, a relationship was derived between daily solar radiation, R_s ($\text{MJ m}^{-2} \text{d}^{-1}$), and daily relative sunshine duration of the form:

$$R_s = \left(a + b \frac{n}{N} \right) R_a \quad (3-3)$$

where R_a is extra-terrestrial radiation ($\text{MJ m}^{-2} \text{d}^{-1}$); n is sunshine duration (h d^{-1}); N is maximum possible sunshine duration (h d^{-1}); and a and b are dimensionless empirical constants. Values of R_s were recorded for 101 days between 23 June 1992 and 5 December 1992 at the University of Maiduguri research farm, about 10km from the synoptic weather station at Maiduguri Airport where sunshine duration was recorded over the same period. Extra-terrestrial radiation and maximum possible sunshine duration were calculated from the latitude and time of year (Duffie and Beckman, 1991). A linear regression of R_s/R_a against n/N was used to determine values for a and b in equation 3-3 which was then used to estimate solar radiation for all months with a recorded value of sunshine duration.

2.2. Stationarity of mean monthly weather data and the effects of aridity

For each month, the stationarity of the weather parameters over time was tested using linear regression between the year of observation (independent) and the value of the parameter (dependent). A trend was assumed if the slope of the least squares regression line was significantly different from zero. The difference between mean

daily minimum air temperature and mean daily dew point temperature was taken as an index of the aridity of the station.

Reference crop evapotranspiration was calculated by seven methods for all months where sufficient data were available. The equations used are presented in Appendix I.

Studies in the Sahel (Monteith, 1991) and in other arid regions (Jensen et al., 1990) have shown the Penman-Monteith equation to be the most reliable of the commonly used reference evapotranspiration equations in arid and semi-arid environments. The form of the Penman-Monteith equation for reference evapotranspiration (Allen et al., 1994) requires values of temperature, humidity sunshine and wind speed.

The other methods used require temperature and sunshine data only. The method of Jensen and Haise (Jensen and Haise, 1963) has been used successfully in inland arid and semi-arid areas of the USA. It has been used for Nsukka, Nigeria (6.87 °N, 7.40 °E, alt. ≈400m) with a method for estimating daily solar radiation (Hargreaves and Samani, 1982). The so-called Modified Jensen and Haise Method (Nwadialo, 1991) was found to correlate well with the FAO Modified Penman Method (Doorenbos and Pruitt, 1977) during the dry season.

Although the Priestley-Taylor method (Priestley and Taylor, 1972) has been shown to underestimate evapotranspiration in the dry season in Niger, it agreed more closely with the Penman-Monteith method in the rainy season, especially when rainfall was abundant (Monteith, 1991).

The Makkink equation (Makkink, 1957), which forms the basis of the FAO Radiation method, and Blaney-Criddle (Allen and Pruitt, 1986) method were tested as they have both recommended for use in areas where full data are lacking (Doorenbos and Pruitt, 1977).

It has been suggested (Smith et al., 1996) that where full climate data are not available, the Penman-Monteith equation can be used with long-term monthly average values of wind speed and estimates of mean daily vapour pressure, assuming dew-point temperature equal to mean monthly minimum air temperature. As both wind speed and sunshine duration data are frequently missing for the chosen stations,

the performance of the Penman-Monteith equation, using mean monthly values for both sunshine and wind was tested. In order to maintain independence, the long term monthly average values were taken from a published source (FAO, 1984) rather than the original data set.

2.3. Comparison of methods

The results from each evapotranspiration calculation method were compared to those from the Penman-Monteith equation for the 202 site-months for which the latter could be calculated. As the Penman-Monteith method was the only one to include humidity as an input, the other equations tested would not account for the effect of station aridity on reference evapotranspiration. Therefore, for the purposes of comparison, the Penman-Monteith equation was used assuming equilibrium conditions, i.e. mean vapour pressure is equal to saturation vapour pressure at the minimum air temperature.

The correspondence between the methods was tested by calculating the root mean square error (RMSE), mean bias error (MBE) and the t-statistic (Jacovides and Kontoyiannis, 1995), defined as;

$$RMSE = \left(\frac{1}{n} \sum_{i=1}^n d_i^2 \right)^{0.5} \quad (3-4)$$

$$MBE = \frac{1}{n} \sum_{i=1}^n d_i \quad (3-5)$$

$$t = \left[\frac{(n-1)MBE^2}{RMSE^2 - MBE^2} \right]^{0.5} \quad (3-6)$$

where n is the number of data pairs, and d_i is the difference between the i^{th} values predicted by each technique. The MBE was also calculated on a monthly basis to determine whether the performance of the tested equation was consistent throughout the growing season.

3. RESULTS AND DISCUSSION

3.1. Estimation of solar radiation

The linear regression line fitted through the observed data on sunshine fraction and relative solar radiation, Figure 4-1, gave values for the constants a and b in equation 3-3 of 0.24 and 0.41 respectively. Values for other locations in Northern Nigeria have been quoted for Samaru (11.18 °N, 7.63 °E, alt. 686m) (Abdulmumin and Misari, 1990) and (Kowal and Knabe, 1972) and for Kano (12.03 °N, 8.32 °E, alt. 476m) by Davies (1965, quoted in Doorenbos and Pruitt, 1977). The equations derived for these locations are shown in Figure 4-1 for comparison. The value of the intercept, a, derived for Maiduguri is not significantly different from those found by (Kowal and Knabe, 1972) and Davies (1965). However, the value of the slope, b, differs from these two, but is not significantly different from that found by (Abdulmumin and Misari, 1990). Although the data from Maiduguri only cover part of one year, they do cover parts of the wet and dry seasons. The observations fall within the envelopes formed by other worker's lines, and are therefore assumed to be reasonable for the present purposes.

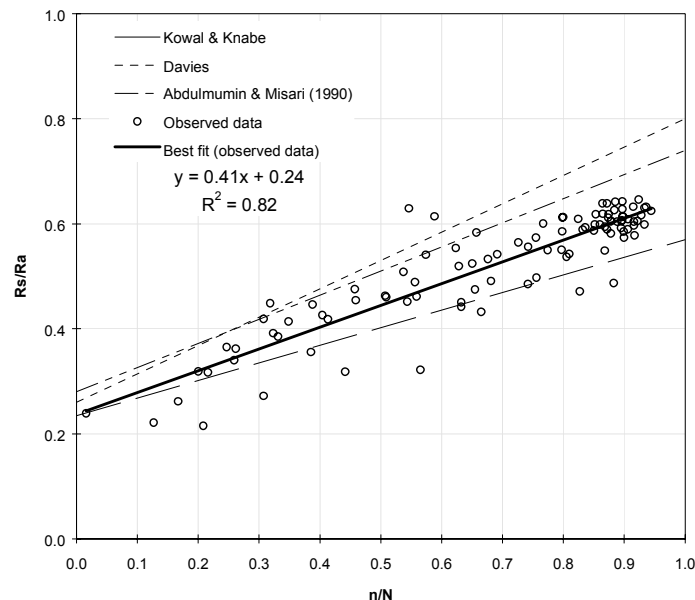


Figure 4-1 Observed sunshine fraction, n/N , and relative solar radiation R_s/R_a , for Maiduguri, 1992 with regression lines from other sources.

3.2. Stationarity of mean monthly weather data

The general trends can be summarised in Table 4.2 and Figure 4-6 which show the average seasonal value of each parameter for each station and year. Minimum air temperature increased at all stations and in most months of the growing season. In addition, maximum temperatures have also risen in August and September.

Table 4.2. Climate parameters showing significant positive (+) or negative (-) trends with time for three stations in the North East Arid Zone in rainy season.

Parameter	Station	Jun	Jul	Aug	Sep	Oct
Maximum Temp.	Nguru	++			+	
	Potiskum			+	+	
	Maiduguri			+	++	
Minimum Temp.	Nguru	++		+	++	
	Potiskum	+	++	++	++	+
	Maiduguri	+		++	++	+
Relative Humidity	Nguru	-		--	--	
	Potiskum	-		-	-	--
	Maiduguri	-	-	--	--	--
Vapour Pressure	Nguru					
	Potiskum					
	Maiduguri	-		--	-	--
Sunshine Duration	Nguru	-			-	--
	Potiskum	-			-	--
	Maiduguri			+		
Wind Run	Nguru	--	--	-	-	
	Potiskum					
	Maiduguri	++	+	++	++	++
+ and -	P <= 0.05					
++ and --	P <= 0.01					

Although relative humidity generally declined, this has largely been due to the increases in air temperature and (with the exception of Maiduguri) mean vapour pressure has remained stationary. At Maiduguri, there was a step change in mean daily vapour pressure in 1970/71. When the data from 1961 - 1970, and 1971 - 1991 are examined separately, neither period shows a significant trend in vapour pressure. This step change was not seen at the other stations suggesting that it is an artefact. Prior to 1970, all three stations had very similar mean vapour pressures during the growing season, however, the sudden drop at Maiduguri represents a significant departure. It is most likely that this drop in mean vapour pressure represents a local

effect resulting from either a change in instrumentation or a change in the condition of the met station. For a station of this type, 90% of the evaporation originates within 280m upwind of the station (Shuttleworth, 1992). As the met station is located close to the runway of the airport, changes to the airport configuration (such as an extension of the runway) could have affected meteorological local measurements.

Sunshine duration has generally remained stable and the slight decreases observed at Nguru and Potiskum may be artefacts of the statistical analysis due to the large number of months with no data.

The observed increase in wind speed at Maiduguri is worthy of special mention. Figure 4-2 shows that the mean growing season wind speed over time falls in two discrete bands. The mean wind speed since 1985 (following a five year break in the data set) was 76% higher than the mean of the 20 years with data before 1985. As the other stations showed no significant increase in wind speed over this time, it is unlikely that such a dramatic change in the values was a real climate phenomenon. One explanation may be that the wind speed records after the five year break relate to an anemometer at 10m rather than 2m. The wind speed data since 1985 have been adjusted by 0.748 to convert a 10m reading to a 2m reading (Allen et al., 1989). However, even after this adjustment, wind speed since 1985 has been 37% higher ($P=0.003$) than before.

⁵ In 1992 it was observed that there were two anemometers at Maiduguri Airport, one at 2m and one at 10m. Although the observer at the time indicated that the 2m instrument was used for the records, it is possible that the 2m data have been re-scaled to 10m by the Nigerian Meteorological Service to conform to the airport standard.

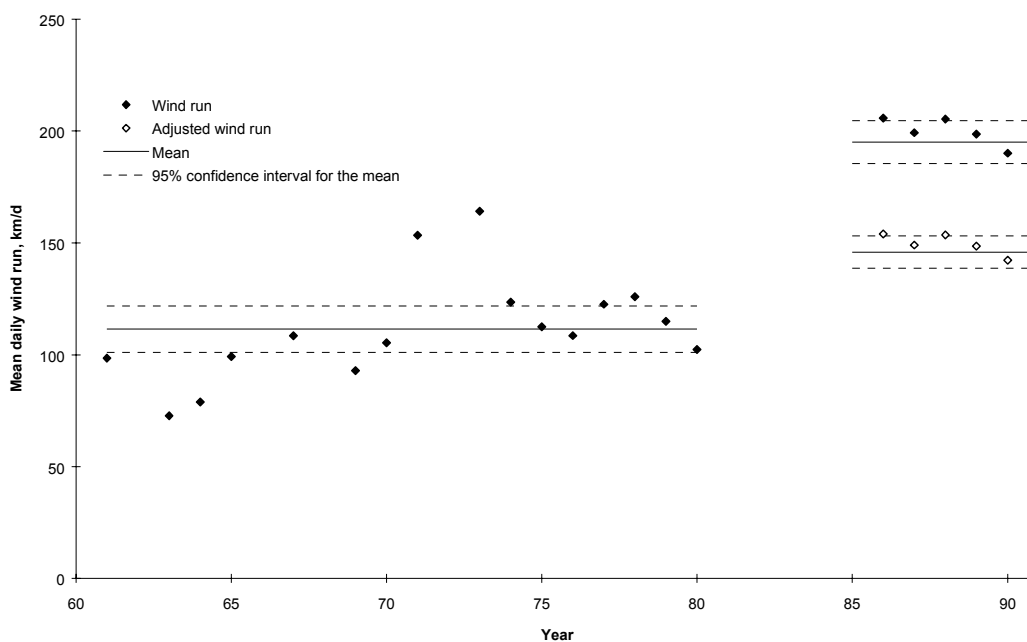


Figure 4-2 Mean growing season wind speed and adjusted wind speed for Maiduguri, 1961-91.

3.3. Effects of aridity on meteorological data

If the area surrounding the weather station is adequately watered, then the minimum air temperature should approach dew point temperature, especially if early morning wind speeds are low. In arid and semi-arid environments a difference of 2-3 °C may be expected (Allen, 1996). Table 4.3 shows the mean difference between monthly mean minimum air temperature (T_{\min}) and dew point temperature (T_d) for the growing season months. In the middle of the growing season $T_d \approx T_{\min}$, however, at the start and the end the difference may be large.

Table 4.3. Mean difference between minimum air temperature and dew point temperature (°C).

Month	Maiduguri	Nguru	Potiskum
June	9.0	6.3	5.1
July	4.4	3.1	1.7
August	2.9	1.4	0.9
September	4.4	2.9	1.7
October	12.3	10.0	7.6

Figure 4-3 shows that the greatest differences occurred in the driest months and can reach 20°C in months with zero rainfall. This is compatible with results from USA and Sudan (Allen, 1996). The greater difference observed at Maiduguri is compatible with the postulated change to non-evaporating surfaces surrounding the met station. These, sometimes large, differences between Td and Tmin mean that the recorded relative humidities may be substantially lower than they would have been had the met stations and surrounding areas been adequately watered.

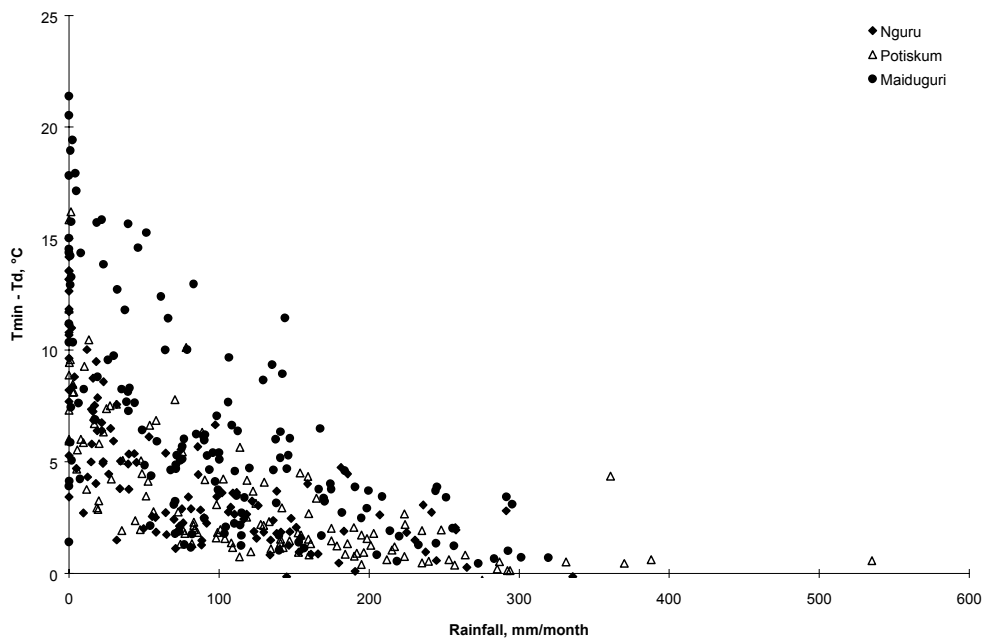


Figure 4-3 Relationship between monthly rainfall and the difference between minimum air temperature and dew point temperature for three stations.

3.4. Performance of evapotranspiration equations

The performance indicators for the relationship between the Penman-Monteith equation and the other equations tested are shown in Table 4.4, and Figure 4-4 shows the mean bias error by month. The results suggest that if full climate data are not available, using the Penman-Monteith method with long term mean monthly values for sunshine duration and wind speed produces an acceptable estimate of the Penman-Monteith ET_0 . This is subject to the caveat that the sunshine and wind should be stationary over the time period considered.

Table 4.4. Root mean square (RMSE), mean bias (MBE) *t*-statistic (*t*) for seven evapotranspiration estimation methods compared to the Penman-Monteith method (assuming mean dew point temperature is equal to mean minimum air temperature).

Method	RMSE mm d ⁻¹	MBE mm d ⁻¹	<i>t</i> [*]
PM (long term mean)	0.24	0.00	0.2
Priestley Taylor	0.33	0.07	3.1
Jensen & Haise	1.01	0.98	50.0
FAO Modified Blaney-Criddle	1.39	1.25	29.6
FAO Radiation	1.45	1.42	62.8
Modified Jensen & Haise	1.55	1.52	74.5
Blaney-Criddle	1.64	1.59	56.8

* t_{crit} at 5% = 1.97, $n = 202$

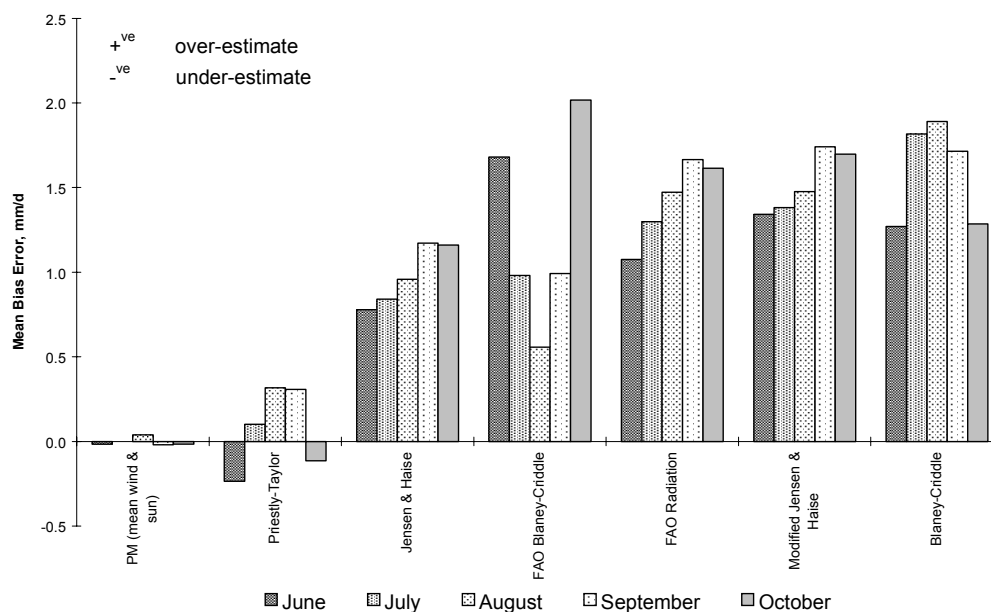


Figure 4-4 Relationship between reference crop evapotranspiration calculated by the Penman-Monteith equation and seven other equations for three stations in the North East Arid Zone by month.

The next closest estimate was obtained using the Priestley-Taylor equation. This slightly underestimated ET_0 in June and October, in agreement with results from Niger (Monteith, 1991), but overestimated in the main part of the rainy season.

Overall, the Priestley-Taylor equation significantly overestimated ET_0 , however the mean bias error was less than 0.1mm d^{-1} . All of the other equations tested significantly overestimated ET_0 throughout the period tested and would not be appropriate for use in the region.

3.5. Stationarity of reference evapotranspiration.

The Penman-Monteith method was used to estimate reference evapotranspiration for all months with non-missing temperature data using calculated vapour pressure as an input. Long-term average values were substituted for missing vapour pressure, sunshine and wind data. In the case of Maiduguri, the post 1985 wind speed was reduced by a factor of 0.748 (see above) and post-1971 the average pre-1971 vapour pressure for each month was used in place of the calculated values.

Table 4.5 and Figure 4-5 show the trends in total seasonal reference evapotranspiration. Over the period 1961-91, there was a significant upward trend in reference evapotranspiration at Maiduguri in most months, and for the growing season overall. At Nguru and Potiskum there were no significant trends.

Table 4.5. Changes in seasonal reference evapotranspiration.

Month	Maiduguri			Nguru		Potiskum	
	Slope mm year^{-1}	Signif.		Slope mm year^{-1}	Signif.	Slope mm year^{-1}	Signif.
June	0.93	0.010	*	0.02	0.951	0.67	0.098
July	0.44	0.180		-0.05	0.858	0.12	0.671
August	0.69	0.000	**	0.26	0.329	0.34	0.081
September	0.67	0.000	**	0.12	0.550	0.10	0.528
October	0.67	0.020		0.09	0.378	-0.11	0.658
All season	0.69	0.000	**	0.14	0.465	0.29	0.075

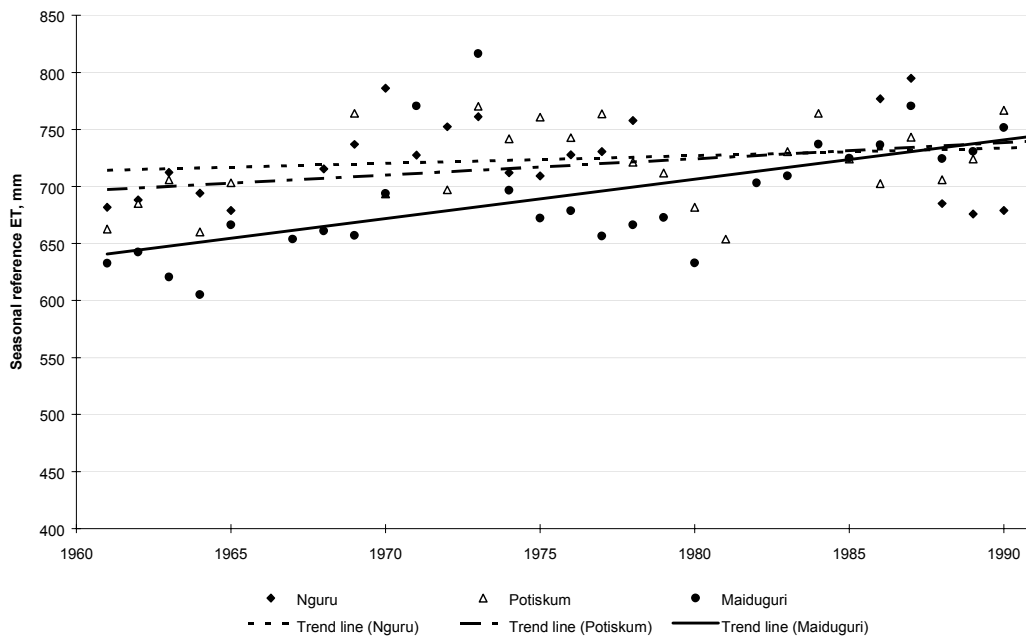


Figure 4-5 Trends in seasonal reference evapotranspiration over the period 1961-91

3.6. Sensitivity analysis

As mean vapour and sunshine have generally remained stable, the trend in reference evapotranspiration at Maiduguri over the period 1961-91 results from the increased wind speed and air temperatures.

The relative impact of temperature and wind speed changes was estimated from a sensitivity analysis. The long-term mean seasonal values for each weather parameter was taken as the base-line. Upper and lower values for temperature and wind were estimated from,

$$P_{upper} = \bar{P} + \frac{n}{2}S \text{ and } P_{lower} = \bar{P} - \frac{n}{2}S$$

where P_{lower} , P_{upper} and \bar{P} are the upper, lower and mean values for the parameter, S is the slope of the regression line of the seasonal mean value of the parameter against year and n is the number. Table 4.6 shows that seasonal ET_0 is more sensitive to the changes in wind speed than air temperature, accounting for 73% of the change in ET_0 . In both cases the sensitivity is linear and there is no complementary effect of the two together.

Table 4.6. Effect of 1.2 °C increase in mean air temperature or 56 km/d increase in mean wind speed on seasonal reference evapotranspiration, ET_o, at Maiduguri.

	Tmax °C	Tmin °C	Wind speed km/d	Sun h/d	Vapour pressure kPa	Daily ET _o mm/d	Seasonal ET _o mm
Lower	33.7	21.9	119	7.4	2.2	4.5	688
Upper	34.9	23.1	119	7.4	2.2	4.7	719
Change							31
Lower	34.3	22.5	91	7.4	2.2	4.3	661
Upper	34.3	22.5	147	7.4	2.2	4.9	744
Change							84
Lower	33.7	21.9	91	7.4	2.2	4.2	648
Upper	34.9	23.1	147	7.4	2.2	5.0	763
Change							115

4. CONCLUSIONS

Over the period 1961-91 there has been a significant increase of about 1.5 °C in mean air temperature during the growing season, dominated by an increase in the minimum temperature. At Nguru and Potiskum, sunshine, wind and vapour pressure have generally remained stable, however at Maiduguri there has been a significant increase in wind speed over the period considered.

All of the evapotranspiration equations with fewer data requirements than the Penman-Monteith equation gave significantly higher estimates of ET_o, although the Priestley-Taylor equation, which is based on sunshine and temperature, produced estimates which on average were within 0.1mm d⁻¹ of the Penman-Monteith equation. However, where monthly sunshine or wind speed data are not available, the closest agreement can be obtained by substituting long term monthly average values.

The effect of changes in temperature and other weather parameters on reference evapotranspiration was tested using the Penman-Monteith equation and using long term monthly means to fill-in missing data for parameters that had been shown to be stationary over time. Although all three stations tested show positive trends in ET_o

over time, only at Maiduguri was this statistically significant, given the year to year variability.

The changes in climate observed at Maiduguri have resulted in an increase in the calculated seasonal ET_o of over 100mm during the growing season, primarily due to the increase in observed wind speed. This result must be viewed with caution as the trends in wind speed have not been observed elsewhere in the North East Arid Zone. Comparison with Potiskum, the only other station for which adequate data exist, shows that in the 1960s the mean recorded wind speed at Maiduguri was only 60% of that at Potiskum. In the 1980s however, the two were not significantly different. It is likely, therefore, that changes in instrumentation, siting, maintenance or reading of instruments have resulted in an erroneous wind speed record for Maiduguri.

The effect of the increase in temperature at Maiduguri, ignoring any effect of increase wind speed, would produce an increase in seasonal reference evapotranspiration over the 31 year period of about 30 mm. This corresponds with the calculated (but non-significant) increases at Potiskum and Nguru. Although a 30 mm increase in seasonal reference evapotranspiration may appear small, this is equivalent to 5-10% of the mean annual rainfall. Thus, during periods when water supply is not limiting, actual evapotranspiration may be increased, exacerbating the effects of low rainfall.

An assessment of the relationship between minimum air temperatures and dew-point temperatures indicates that in low rainfall months the ground surface conditions at the met stations used in this study do not conform to a well water surface with an adequate fetch. The reduction in rainfall (Hess et al., 1995) may, in part, account for the observed increase in minimum air temperature at the beginning and end of the rainy season. This also highlights the difficulty of applying the concept of 'reference evapotranspiration' to arid environments where the potential evapotranspiration is itself a function of the actual evapotranspiration.

Acknowledgements

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References

- Abdulmumin, S. and Misari, S. M., 1990. Crop-coefficients for some major crops of the Nigerian semi-arid tropics. *Agricultural Water Management*, 18: 159-171.
- Allen, R. G., 1996. Assessing the integrity of weather data for reference evapotranspiration estimation. *Journal of Irrigation and Drainage Engineering*, ASCE, 22: 97-106.
- Allen, R. G. and Pruitt, W. O., 1986. Rational use of the FAO Blaney-Criddle formula. *Journal of the Irrigation and Drainage Division*, ASCE , 112: 139-155.
- Allen, R. G., Smith, M., Pereira, L. S. and Perrier, A., 1994. An update for the calculation of reference evapotranspiration. *ICID Bulletin*, 43: 35-92.
- Allen, R. G., Smith, M., Perrier, A. and Pereira, L. S., 1994. An update for the definition of reference evapotranspiration. *ICID Bulletin*, 43: 1-34.
- Allen, R. G., Wright, J. L. and Burman, R. D., 1989. Operational estimates of evapotranspiration. *Agronomy Journal*, 81.
- Doorenbos, J. and Pruitt, W. O., 1977. Guidelines for predicting crop water requirements. (FAO Irrigation and Drainage Paper 24). Food and Agriculture Organisation of the United Nations (FAO) Rome .
- Duffie, J. A. and Beckman, W. A., 1991. *Solar engineering of thermal processes*. (2nd. ed.). John Wiley and sons New York .
- FAO. (1984). *Agroclimatological data for Africa*. Vol. 2. FAO plant production and protection series. No. 22. Rome: Food and Agriculture Organisation of the United Nations.

- Frevert, D. K., Hill, R. W. and Braaten, B. C., 1983. Estimation of FAO evapotranspiration coefficients. *Journal of the Irrigation and Drainage Division, ASCE* , 109: 265-270.
- Hansen, E. V., Israelsen, O. W. and Stringham, G. E., 1980. *Irrigation Practices* (4 ed.). Wiley. New York .
- Hargreaves, G. H. and Samani, Z. A., 1982. Estimating potential evapotranspiration. *Journal of the Irrigation and Drainage Division, ASCE* , 108: 225-230.
- Hess, T. M., Stephens, W. and Maryah, U. M., 1995. Rainfall trends in the North East Arid Zone of Nigeria 1961 - 1990. *Agricultural and Forest Meteorology*, 74: 87-97.
- Hulme, M., 1996. Recent climate-change in the worlds drylands. *Geophysical Research Letters*, 23: 61-64.
- Jacovides, C. P. and Kontoyiannis, H., 1995. Statistical procedures for the evaluation of evapotranspiration computing models. *Agricultural Water Management*, 365-371.
- Jensen, M. E., Burman, R. D. and Allen, R. G., 1990. *Evapotranspiration and irrigation water requirements. (ASCE Manuals and Reports on Engineering Practice No. 70)*. American Society of Civil Engineers New York .
- Jensen, M. E. and Haise, H. R., 1963. Estimating evapotranspiration from solar radiation. *Journal of the Irrigation and Drainage Division, ASCE* , 89: 15-41.
- Kowal, J. M. and Kassam, A. H., 1978. *Agricultural ecology of Savanna*. Oxford University Press. Oxford, UK.
- Kowal, J. M. and Knabe, D. T., 1972. *An agroclimatological atlas of the Northern States of Nigeria*. Ahmadu Bello University Press Zaria, Nigeria.
- Ley, T. W., Allen, R. G. and Hill, R. W. 1996. Weather station siting effects on reference evapotranspiration. *Evapotranspiration and irrigation scheduling*.

- Proc. of the International Conference. 3-6 November 1996. San Antonio, Texas. American Society of Agricultural Engineers.
- Makkink, G. F., 1957. Testing the Penman formula by means of lysimeters. *Journal of the Institution of Water Engineers.*, 11: 277-288.
- Monteith, J. L., 1981. Evaporation and surface temperature. *Quart. J. Royal Met. Soc.*, 107: 1-27.
- Monteith, J. L. 1991. Weather and water in the Sudano-Sahelian zone. *Soil Water Balance in the Sudano-Sahelian zone. IAHS Publ. no. 199 February 1991. Niamey, Niger. (pp. 11-29). IAHS Press. Institute of Hydrology, Wallingford, UK.*
- Nwadialo, B. E., 1991. The estimation of reference crop evapotranspiration with minimum data in tropical climate. *Beitr. Trop. Landwirtsch. Vet.Med.*, 175-182.
- Priestley, C. H. B. and Taylor, R. J., 1972. On the assessment of surface heat flux and evaporation. *Monthly Weather Review*, 106: 81-92.
- Shuttleworth, W. J. 1992. Evaporation. In D. R. Maidment (Editor), *Handbook of hydrology. (Chapter 4). New York: McGraw-Hill.*
- Smith, M. 1991. Report on the expert consultation on revision of FAO methodologies for crop water requirements. Food and Agriculture Organisation of the United Nations, Rome, Italy.
- Smith, M., Allen, R. G. and Pereira, L. S. 1996. Revised FAO methodology for crop water requirements. Evapotranspiration and irrigation scheduling. Proc. of the International Conference. 3-6 November 1996. San Antonio, Texas. (pp. 116-123). ASAE / Irrigation Association / ICID.
- Wright, J. L. and Jensen, M. E., 1972. Peak water requirements of crops in southern Idaho. *Journal of the Irrigation and Drainage Division, ASCE* , v96: n IR1 193-201.

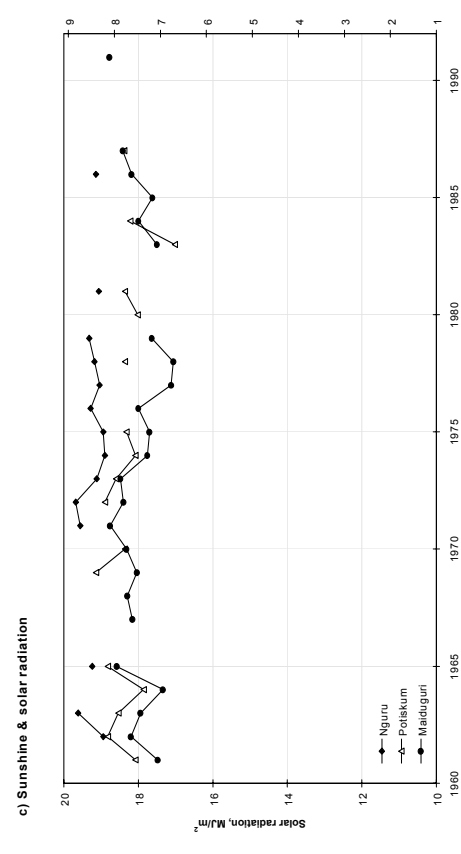
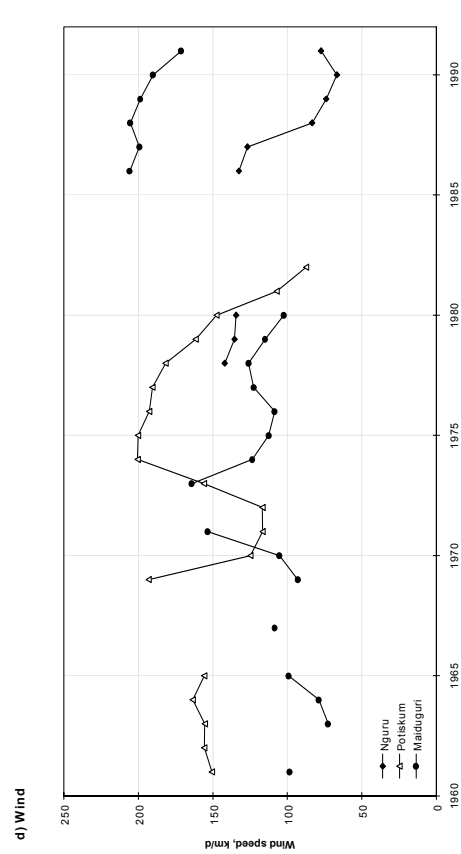
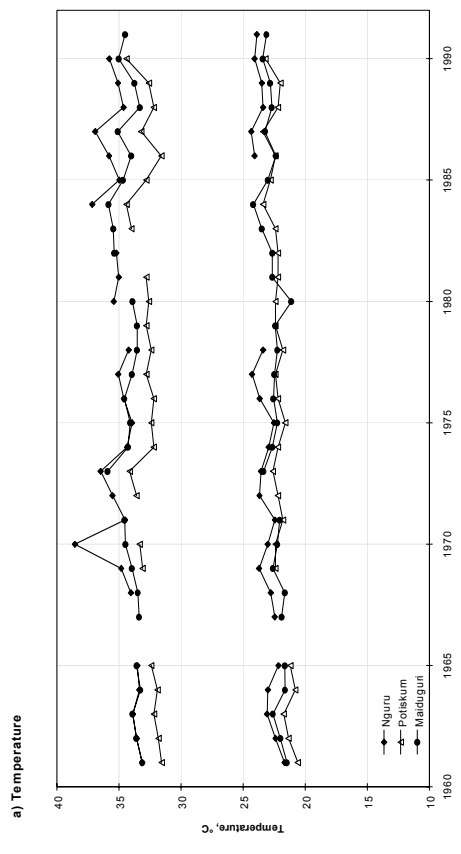
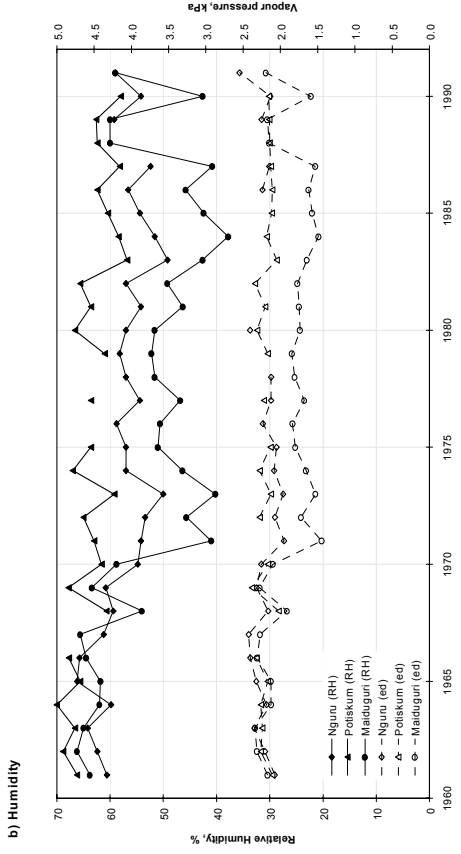


Figure 4-6 Trends in mean growing season weather

CHAPTER FIVE. WATER BALANCE AND WATER USE OF PEARL MILLET-COWPEA INTERCROPS IN NORTH EAST NIGERIA⁶

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Abstract

An experiment was conducted in North East Nigeria to examine the water balance and water use of intercrops of pearl millet and two cowpea varieties as well as sole crops of the same cultivars. The crops were grown on a sandy loam soil in a spatial arrangement typical of husbandry practices of the region. The soil is characterised by rapid drainage and low water holding capacity. Results indicate that intercropping cowpea with millet did not increase the water use rate over sole millet as transpiration by cowpea may be substituting for soil evaporation. Root zone water storage after the millet harvest was sufficient to maintain a long duration cowpea cultivar that was able to make use of water that otherwise would have been lost to drainage during the dry season. As there was no evidence of water stress up to millet harvest, intercropping cowpea with millet increased the efficiency of utilisation of rainfall. It is concluded that water supply may not be the most limiting constraint on agricultural production in such conditions. The implications of these findings for agriculture in the region are discussed.

⁶ Published as Grema, A K and Hess, T M (1994) Water balance and water use of millet-cowpea intercrops in north east Nigeria. *Agricultural Water Management* 26:169-185.

1. INTRODUCTION

The semi-arid region of West Africa is characterised by low and highly variable rainfall, high soil and air temperatures, and high evaporative demand. The soils are poorly structured and inherently infertile. While scarce rainfall is one of the principal limitations to increased productivity, the distribution of water within the soil profile, and therefore the proportion that remains in the root zone for the plants to utilise, appears to be a more crucial limitation than the total rainfall (Payne *et al.*, 1990).

The predominant production system in North East Nigeria is based on pearl millet (*Pennisetum typhoides* (S&H)) which is traditionally sown with the early rains. Intercropping with cowpea (*Vigna unguiculata* L. (Walp)) is the most common association, with cowpea relay planted 2-6 weeks after millet sowing, the exact time being dependent on the establishment of the millet and on the timing of subsequent rainfall. The primary objective of this system is the production of millet grain as the staple food crop, and cowpea seed and fodder production take secondary importance. Any intercropping system should therefore have minimal impact on the millet grain yield. Millet stover is also valued by farmers in the region due to its strong engineering properties, for fencing farmsteads.

The agronomy of this system has been well studied in neighbouring Niger (Ntare, 1989; Nouri and Reddy, 1991). There is, however, a paucity of research on intercropping systems from the millet producing areas of Nigeria. Kassam and Kowal (1975) and Baker and Norman (1975) reported on the water use and energy dynamics of millet and sorghum based systems from the Sudan Savannah zone of Nigeria (rainfall >700mm; growing season >100 days), however the major millet producing areas of the country have lower average rainfall and a shorter growing season. Studies of the water balance of millet have been reported from other parts of Sahelian West Africa (Agnew, 1982; Payne *et al.*, 1990; Klaij and Vachaud, 1992), but these were based on sole crop millet trials.

In such an environment, an understanding of the effects of intercropping on crop water use is particularly important if rational management strategies are to be formulated through the use of crop combinations that make more efficient use of the limited seasonal rainfall.

This paper reports on the components of the water balance of millet, intercropped with two cowpea cultivars as well as those of their corresponding sole crop systems. The implication of the results to effective soil and water management in the region is discussed.

2. MATERIALS AND METHODS

2.1. Site and Climate

The experiment was conducted at the University of Maiduguri research farm (11°54'N, 13°5'E, altitude 352m) in North East Nigeria, during the 1992 rainy season. Average annual rainfall (1961 - 1990) in Maiduguri is 553mm and the distribution is unimodal, starting on average, in mid-June and lasting until the end of September.

The soil has been classified as a Typic Ustipsamment (Rayar, 1984) with aeolian sand formation, loosely aggregated and a sandy loam texture. The dry bulk density of the soil is about 1.50 Mg m⁻³, and varies little with depth except in the top 0.2 m where it is lower (1.40 Mg m⁻³). Steady state infiltration rates vary from 72 to 220 mm h⁻¹ with a mean of 135 mm h⁻¹ (Folorunso, 1986).

2.2. Treatments and Crop Husbandry

Following land preparation and levelling, the experimental micro-plots (6 m x 6 m) were banded at the edges to minimise runoff and runoff. A pre-sowing application of 40 kg ha⁻¹ each of N, P and K was broadcast and raked into the soil.

The experiment was designed as a randomised complete block with four replicates, comprised of the following five treatments: two cultivars of cowpea, each grown as intercrops with millet and sole crops of millet and both cowpea cultivars grown as controls. The millet genotype cv. *Ex-Borno*, native to the area, was sown in hills at 1m x 1m spacing on 25 June and was thinned to three plants per hill, at about two weeks later. Two cowpea cultivars, cv. *Borno-Local* and cv. *IT84S-2246* were sown on 8 July. The intercropped cowpea was planted between millet rows at 0.5m spacing with two plants per hill and at 1m x 0.5m spacing in the sole crop treatments. Both intercropped and sole crops of cv. *IT84S-2246* and cv. *Borno-Local* were harvested

on 24 September and 25 October respectively. Cv. *Borno-Local* is a photoperiod-sensitive, late maturing genotype, native to the area, while the cv. *IT84S-2246* is an exotic, early maturing, photoperiod-insensitive genotype, obtained from the International Institute for Tropical Agriculture (IITA). They represent the two types of cowpea in use in the area: the local farmer material, and the 'new' high-yielding cowpeas that are currently being introduced by extension agents from development projects and research stations. Manual weeding was carried out as required and a broad-spectrum insecticide (Cymbush 10EC) was applied at the flowering and pod-filling stages.

2.3. Crop Measurements

Measurements of crop cover and fractional radiation interception were made with the aid of a Sunfleck Ceptometer (Decagon, USA), and a meter stick, as per Armbrurst (1990). Progressive destructive sampling was employed for the determination of dry matter development in the various treatments. At maturity, an area encompassing six millet and twelve cowpea hills was harvested above ground and the various yield components were determined. The harvest index (HI) was calculated as the ratio of grain yield to above-ground dry matter yield.

2.4. Water Balance Calculations

The water balance equation may be expressed as

$$\Delta S = R + C - ET_a - D - R_o \quad (4-1)$$

where ΔS is the change in soil water storage in the measured profile, R is the rainfall, C is the contribution to the profile by capillary rise from the water table, ET_a is the evapotranspiration, D is the drainage from below the measured profile and R_o is the runoff (-) or runoff (+) over a given time interval. As the water table is deep (>10m), the soil is of light texture and the infiltration capacity is high, runoff, runoff and capillary rise can be ignored, thus the evapotranspiration may be estimated from,

$$ET_a = R - \Delta S - D \quad (4-2)$$

A 25 mm capacity volumetric rain gauge and an automatic rain gauge (Didcot Instruments, UK) were installed on the site before the commencement of the trial. The manual rain gauge readings were used to complete the record during the brief

period when the automatic gauge was not operational. An automatic weather station was installed on the site with sensors for photosynthetically active radiation (PAR) and global solar radiation (Didcot Instruments, UK), relative humidity and temperature (Skye Instruments, UK), connected to a data logger (Campbell Scientific, UK). Data were collected over 101 days between June and December 1992.

Two replicates of each treatment were monitored for soil water storage. Soil moisture content from 0.10-1.80 m depth was measured weekly using a Wallingford neutron probe (Didcot Instruments, UK). The soil moisture content of the surface 0.10 m was determined gravimetrically. At the end of the dry season, the soil water content profile was approximately uniform at a depth of >1.50 m. As drainage from the soil profile had effectively ceased, it can be concluded that as long as the water content at the bottom of the measured profile did not rise, drainage from the measured profile was close to zero. However, especially towards the end of the rainy season significant drainage can occur on such light soils.

The drainage below the measured profile (1.8 m) was estimated using the method of Klaij and Vachaud (1992). Under conditions of unrestricted drainage and hence under unit hydraulic gradient, it can be shown from Darcy's Law, that the drainage flux will be numerically equal to the hydraulic conductivity at the water content observed at the bottom of the measured profile. Three neutron probe access tubes were installed in the project site under bare soil and the relationship between hydraulic conductivity and water content was determined from sequential soil water profiles during the period when there was no drainage taking place below the bottom of the access tubes. Two were wetted artificially by ponding at the surface, the other was wetted naturally by rainfall. In each case, sub-sets of the soil water profile data were chosen where layers could be identified that met the criteria set out by Klaij and Vachaud (1992), i.e. where:

1. a flux plane could be identified >0.3 m below the surface, thus upward movement due to evaporation could be ignored;

2. the difference in water content between the readings above and below the chosen plane was $\leq 0.01 \text{ m}^3 \text{ m}^{-3}$; and therefore conditions of unit hydraulic gradient prevailed,
3. the difference in water content at the chosen plane between two dates was $\leq 0.01 \text{ m}^3 \text{ m}^{-3}$;
4. the water content at the bottom of the profile was less than $0.05 \text{ m}^3 \text{ m}^{-3}$ and did not change over the period of measurement.

2.5. Crop Coefficients

A crop coefficient, K_c , can be defined as;

$$K_c = \frac{ET_c}{ET_o} \quad (4-3)$$

where ET_c is the water use of the particular cropping system and ET_o is reference crop evapotranspiration. The K_c varies through the season in response to crop development and may be defined by the length of each of four development stages and three K_c values; those for stage 1, 3 and the end of stage 4 (Doorenbos & Pruitt, 1977). Using the calculated water use for each system and the Penman-Monteith ET_o values for Maiduguri Airport, the Doorenbos and Pruitt model was set up on a spreadsheet and the crop coefficients and stage lengths were determined simultaneously by iterative techniques.

3. RESULTS

3.1. Weather

The measured global solar radiation from the site was used with records of sunshine duration from Maiduguri Airport ($11^\circ 51'N$, $13^\circ 5'E$) to calibrate the constants in the Angstrom equation,

$$R_s = \left(a_s + b_s \frac{n}{N} \right) R_a \quad (4-4)$$

where R_s is incoming solar radiation, R_a is extra terrestrial radiation, n is the duration of bright sunshine and N the maximum daylight hours. The value of 0.237 derived for a_s agrees with that found by Kowal and Knabe (1972) for Samaru, North

Nigeria, although the value of 0.415 for b_s ($R^2 = 0.82$) was significantly higher, resulting in 23% more solar radiation received on clear days. Both constants were significantly different from those derived for Samaru by Abdulmumin and Misari (1990). The temperatures recorded at the site were within 1°C of those recorded at Maiduguri Airport, therefore daily meteorological data from the airport were used with the Angstrom coefficients above, for calculation of reference crop evapotranspiration (ET_o) using the Penman-Monteith equation by the method of Smith (1991).

The weather for the 1992 season in relation to the 30-year (1961-1990) mean is summarised in Table 5.1.

Table 5.1. 1992 weather data for Maiduguri Airport.

Month	Maximum temperature °C	Minimum temperature °C	0800 GMT relative humidity %	Sunshine duration h d ⁻¹	Wind run (2m) km d ⁻¹	ET_o mm d ⁻¹	Rainfall mm month ⁻¹
April	40.2 (-0.4)	26.0 (+2.2)	21.0 (-0.1)	5.5 (-2.4)	205.7 (+38.6)	6.6 (0.0)	0.6 (-8.5)
May	39.5 (-0.2)	26.4 (+0.9)	41.0 (+8.4)	8.5 (-0.1)	212.0 (+42.5)	6.0 (-0.6)	15.4 (-10.7)
June	37.2 (+0.5)	25.7 (+1.3)	49.0 (+5.5)	6.3 (-1.8)	243.8 (+68.4)	6.7 (+0.1)	27.2 (-43.9)
July	32.6 (-0.5)	23.1 (+0.3)	66.0 (+6.9)	7.0 (+0.2)	205.4 (+48.0)	5.0 (-0.6)	143.5 (-5.0)
August	30.7 (-1.1)	22.2 (-0.1)	65.0 (-0.3)	5.8 (-0.4)	172.5 (+57.0)	4.4 (-0.2)	256.3 (+56.1)
September	33.2 (-0.3)	22.9 (+0.6)	67.0 (+8.8)	7.9 (+0.6)	119.9 (+23.6)	4.7 (+0.2)	88.1 (+6.2)
October	36.5 (0.0)	20.3 (-0.5)	40.0 (+7.2)	9.5 (+0.9)	112.9 (+8.5)	5.0 (+0.5)	10.2 (+0.4)

Note: Figures in brackets refer to deviation from the long term (1961 - 1990) mean. 1992 ET_o values were calculated from daily weather variables, except for relative humidity, for which only monthly average values were available. Long term mean ET_o values were calculated from mean monthly values.

The annual rainfall at Maiduguri Airport in 1992 of 585 mm was a little above the average of 553 mm and has a probability of exceedance of 42%. However, this was dominated by August, which was the only month during the growing season with

above average rainfall (probability of exceedance 27%). At the site, the annual rainfall of 542 mm was 43 mm lower than that recorded at Maiduguri Airport and in particular the total for August was only 256 mm. Seasonal (April to October) ET_o was 1,174 mm, which is lower than 30 year mean of 1,207 mm and has a probability of exceedance of 57%.

The daily rainfall recorded at the site and daily ET_o calculated for Maiduguri Airport for the period April to October is shown in Figure 5-1.

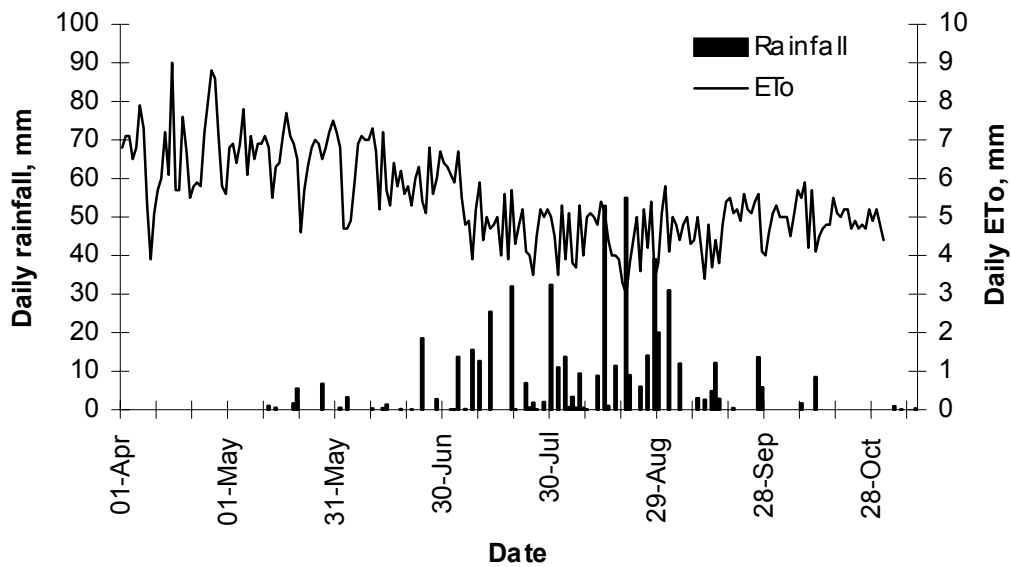


Figure 5-1 Daily rainfall and ET_o for Maiduguri 1992.

3.2. Soil Physical Properties

The drainage fluxes, and hence hydraulic conductivities calculated for each of 12 periods were regressed against mean volume water fraction (Figure 5-2), using the equation:

$$K(\theta) = a\theta^b \tag{4-5}$$

where a and b are constants

The resultant equation was

$$K(\theta) = 1309\theta^{2.967} \tag{4-6}$$

where $K(\theta)$ is the unsaturated hydraulic conductivity in mm d^{-1} at water content θ ($R^2 = 0.93$). Very little drainage occurs at low water contents under unit hydraulic gradient. The drainage rate exceeds 1 mm d^{-1} when the soil water content exceeds $0.09 \text{ m}^3 \text{ m}^{-3}$ and it rises rapidly to 11 mm d^{-1} at $0.20 \text{ m}^3 \text{ m}^{-3}$. Although the data in Figure 5-2 are very clustered, they cover the range of field water contents at which drainage was occurring after the passage of the wetting front ($0.08 - 0.15 \text{ m}^3 \text{ m}^{-3}$). The single point at low water content represents the only observation when any measurable increase in water content was observed below the flux plane prior to the arrival of the wetting front. However, this point is important for determining the slope of the regression line. The water retention at 1.5 MPa tension was determined on a pressure plate in the laboratory to be $0.05 \text{ m}^3 \text{ m}^{-3}$.

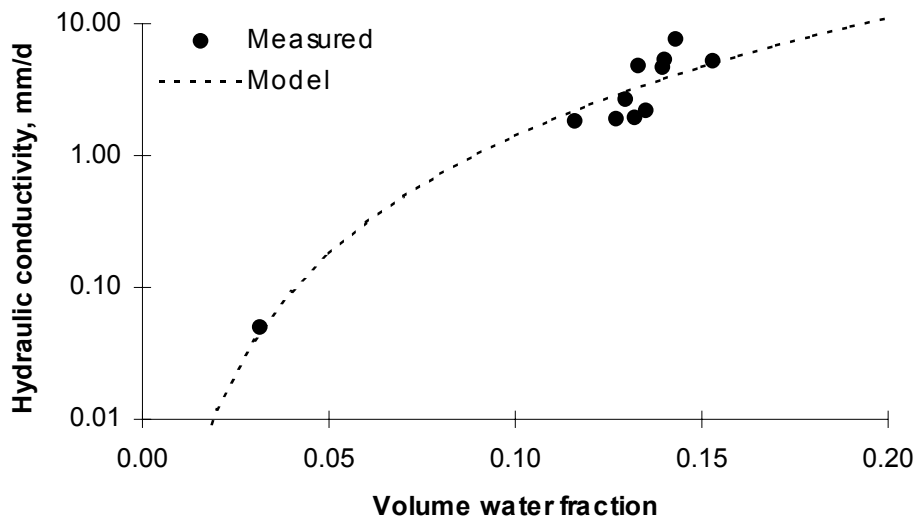


Figure 5-2. Calculated hydraulic conductivity - water content function

3.3. Soil Water Profiles

A typical pattern of wetting and drying of the soil profile is shown Figure 5-3 for one access tube under millet and cowpea cv. *Borno Local*. At the end of the dry season the water content of the profile at 1.80 m averaged $0.04 \text{ m}^3 \text{ m}^{-3}$. Measurements down to 5 m below the surface did not exceed this value, thus it may be inferred that, under natural drainage through the dry season, the soil can dry to a level at which no water is available to plants. Evaporation from the bare soil had reduced the water content of

the upper layers to as low as $0.01 \text{ m}^3 \text{ m}^{-3}$. With the onset of rains, the upper layers wetted rapidly. Once the water content of the soil reached $0.10 \text{ m}^3 \text{ m}^{-3}$ or more, the hydraulic conductivity became sufficiently high to permit the rapid transmission of drainage water to deeper layers. Consequently, the water content rarely rose above $0.15 \text{ m}^3 \text{ m}^{-3}$ anywhere in the measured profile. As the rains declined the profile dried due to both plant water uptake and drainage. By mid-October, the upper soil layers were close to the 1.5 MPa tension water content.

a) wetting phase

b) drying phase

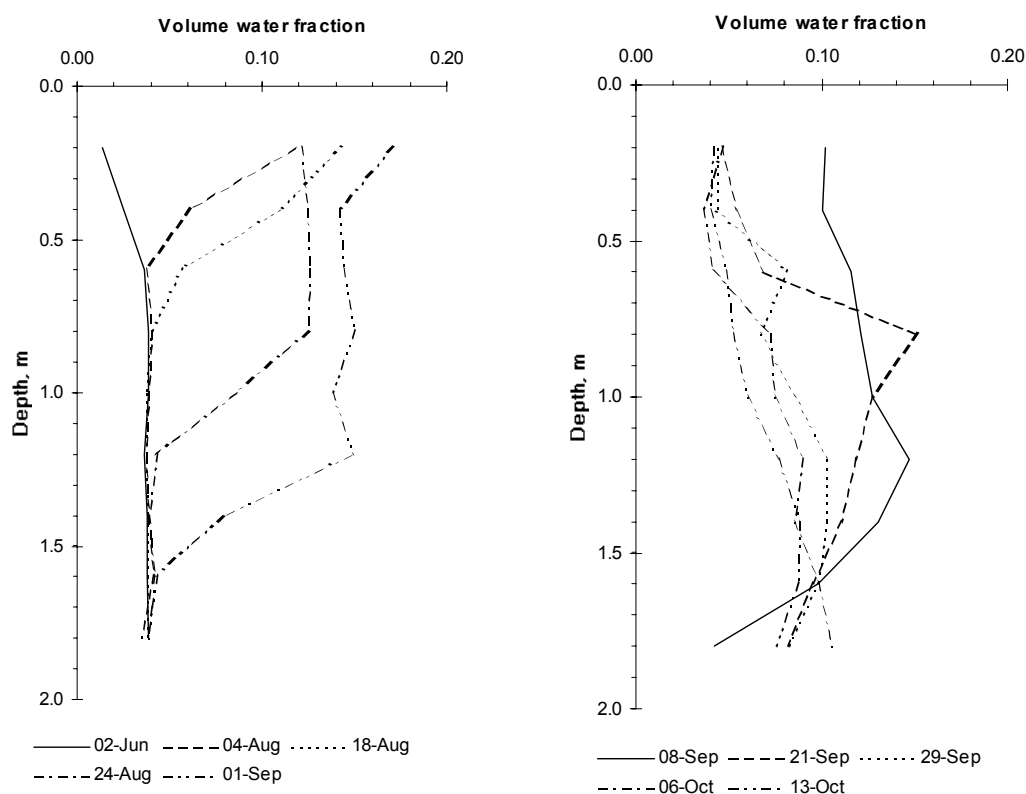


Figure 5-3 Soil water profiles a) wetting phase and b) drying phase

3.4. Water Use

Actual water use (ETa) was calculated for each replicate using the methods described above, however the results from several access tubes had to be rejected due to negative calculated water use during certain weeks.

Figure 5-4 shows the cumulative water use of the various treatments and the values from the fitted model (see below). In the millet based systems the total water use

(359 mm) and average water use rate (3.9 mm d^{-1}) did not vary between treatments up to the time of the millet harvest. Similarly, although the total water use of sole treatments of cowpea cv. *Borno-Local* (385 mm) was substantially higher than that of cv. *IT84S-2246* (303mm), this was due to the longer growing period of that cowpea cultivar and the average water use rate was higher (3.7 mm d^{-1}) for the short season cultivar than for the longer (3.4 mm d^{-1}). The water use rate of cv. *IT84S-2246* exceeded that of cv. *Borno Local* only in the last the two weeks before harvest. The water use of cowpea cv. *Borno-Local* in the intercropping system was not measured after the millet harvest.

The cumulative water use was fitted to the Doorenbos and Pruitt (1977) model to determine crop coefficients (Kc) for each growth stage. The resultant stage lengths and Kc values are shown in Table 5.2 and the cumulative water use predicted by the model is shown with the observed values in Figure 5-4.

3.5. Crop Cover

In the millet based systems, crop cover of sole millet was less than that of the intercropped systems (Figure 5-5), however, the difference was not significant for most of the season. The difference between the two intercropping systems was also not significant. In the sole cowpea treatments, the rates of development are similar at the beginning of the season, but by the end of August, differences in developmental phenology and leaf senescence conditioned a significant divergence of the crop cover profiles ($P < 0.05$). Cowpea cv. *IT84S-2246*, due to its morphologically compact architecture and determinate growth habit, had lower crop cover (maximum $< 70\%$) than cv. *Borno-Local*.

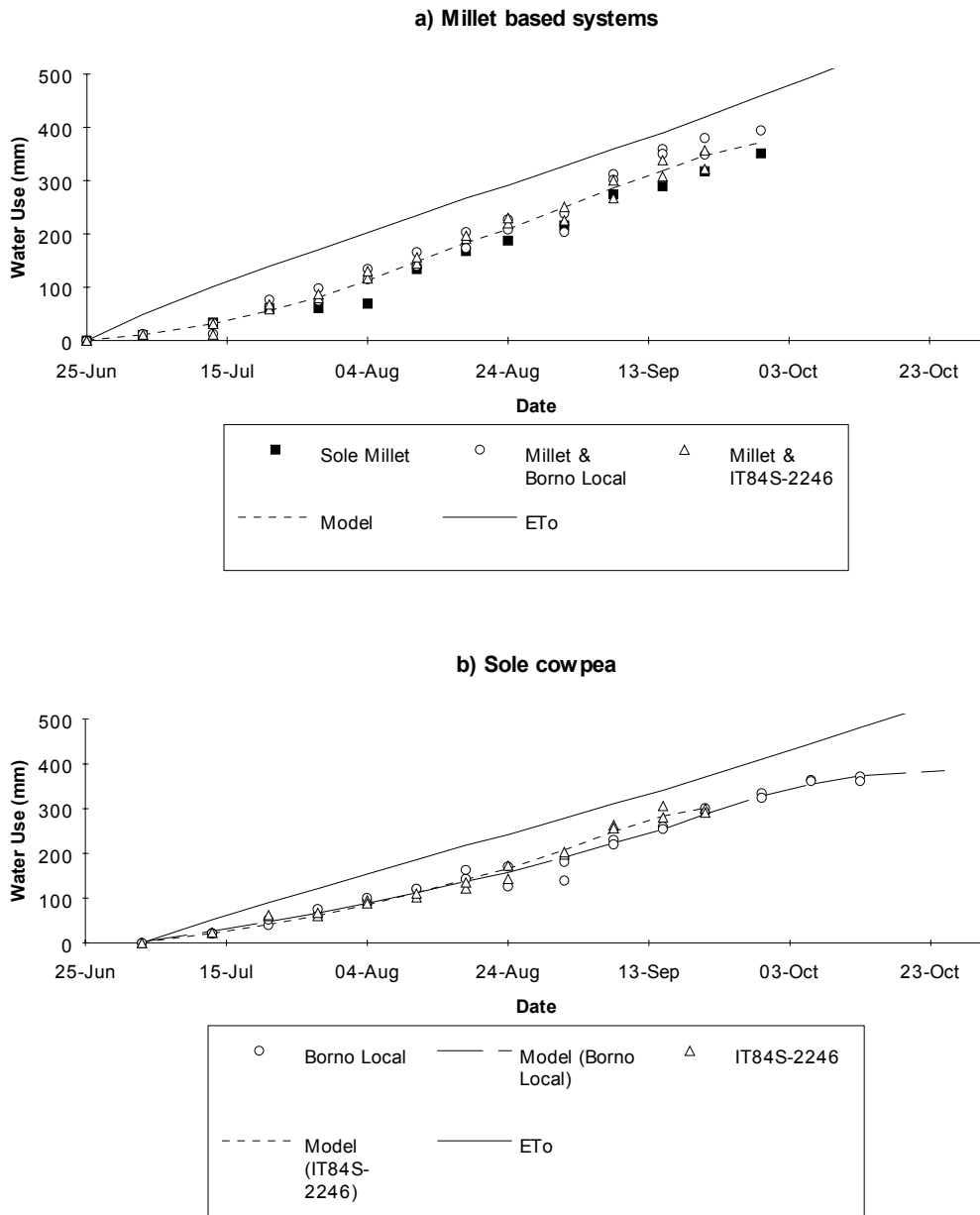
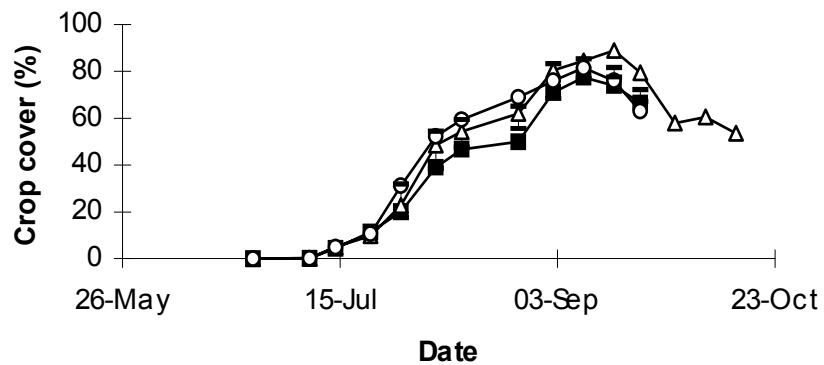


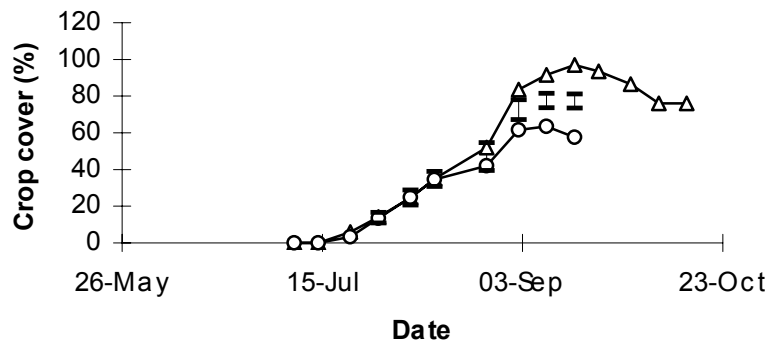
Figure 5-4 Cumulative water use in a) millet based systems and b) cowpea systems

a) Millet based systems



Sole Millet
 Millet & Borno Local
 Millet & IT84S-2246

b) Sole cowpea systems



Borno Local
 IT84S-2246

Note: Vertical bars represent least significant difference at 5% level for each date.

Figure 5-5. Crop cover development in a) millet based systems and b) cowpea systems

Table 5.2. The length of crop growth stages and crop coefficients for sole and intercropped situations derived from fitting to calculated water use values.

Stage	Millet based systems		Cowpea <i>Borno Local</i>		Cowpea <i>IT84S-2246</i>	
	Duration (days)	Kc	Duration (days)	Kc	Duration (days)	Kc
Initial	1	0.10	0	0.41	0	0.29
Crop development	44		82		71	
Mid-season	38	1.11	0	1.13	0	1.34
Late	17	0.38	33	0.00	13	0.00
P*		0.98		0.98		0.76

* P = probability that there is no difference between the observed and predicted cumulative ETc from a paired t-test.

3.6. Storage and Drainage

The drainage term used in the calculation of water use was that occurring below the measured profile of 1.9m. However, the root zone is unlikely to extend to this depth and some of the water stored above 1.9m will find its way to drainage later in the season. Assuming a maximum root depth of 1.3m (Payne *et al.*, 1990), the drainage below the root zone can be estimated as the sum of the change in water content between 1.3m and 1.9m and the calculated drainage below 1.9m. In both cropping systems, root zone storage reaches a maximum of approximately 200mm at the end of August, equivalent to an average water content of $0.17\text{m}^3 \text{m}^{-3}$ (Figure 5-6). At this water content, water is held at such low suction that drainage occurs rapidly, ceasing by the end of September (Figure 5-7). Under the millet based systems there was no significant difference in drainage between treatments up to the time of the millet harvest. However, under the sole cowpea treatments there was greater total drainage under the cv. *Borno Local* than cv. *IT84S-2246* up to early September reflecting the lower water use rate of that cultivar during the latter part of the season. However, by the end of the season, cumulative drainage was similar.

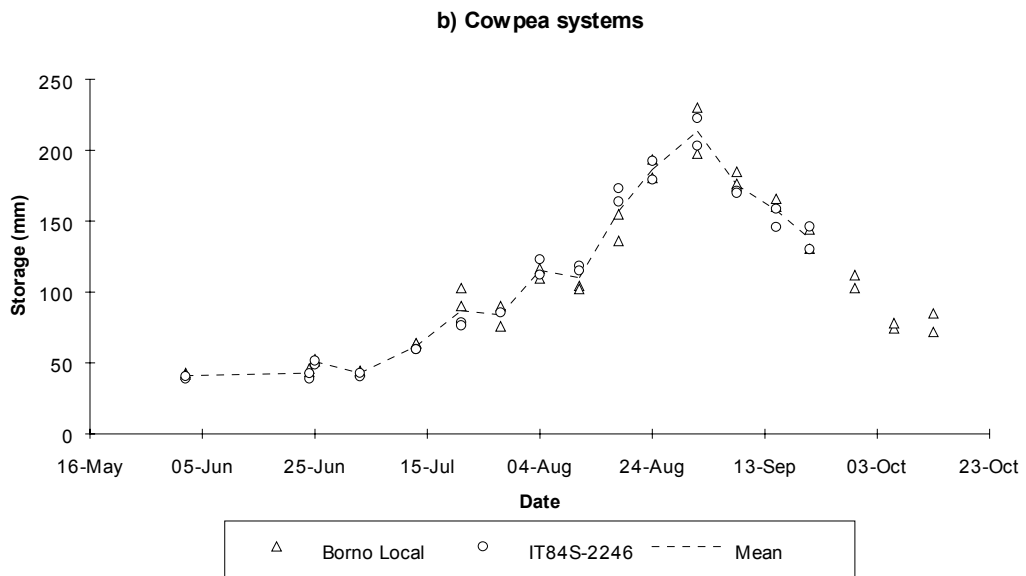
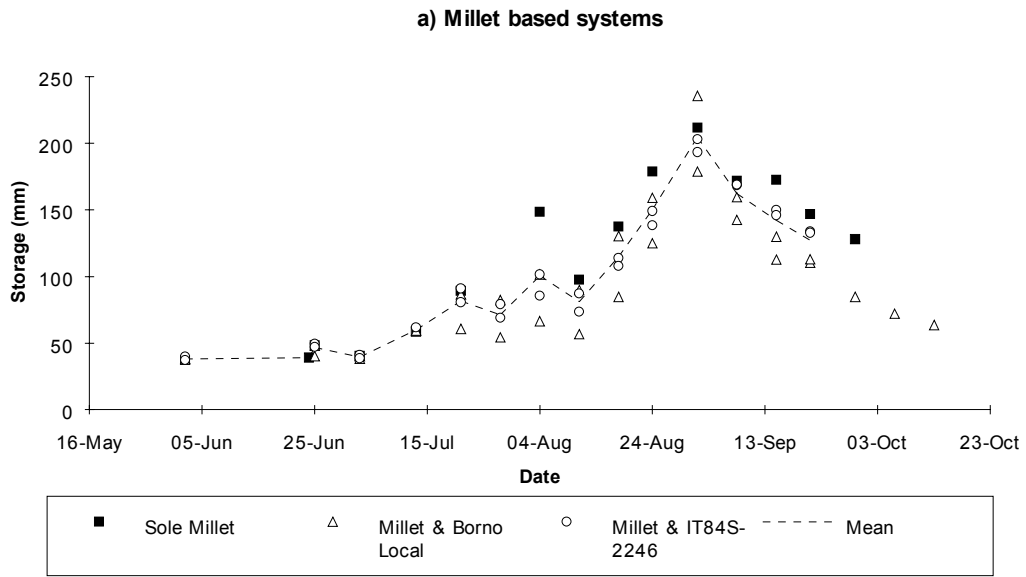
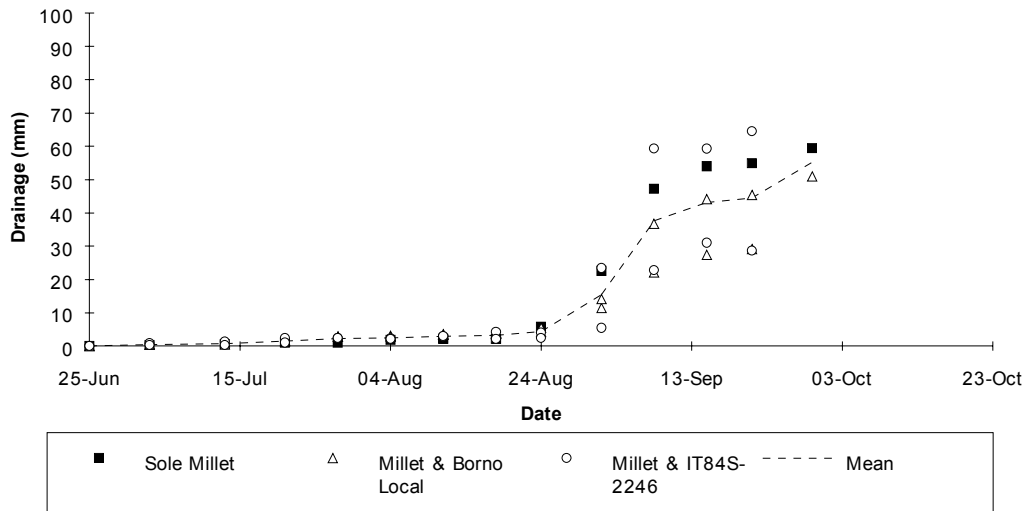


Figure 5-6. Root zone (<1.3m) storage in a) millet based systems and b) cowpea systems

a) Millet based systems



b) Cowpea systems

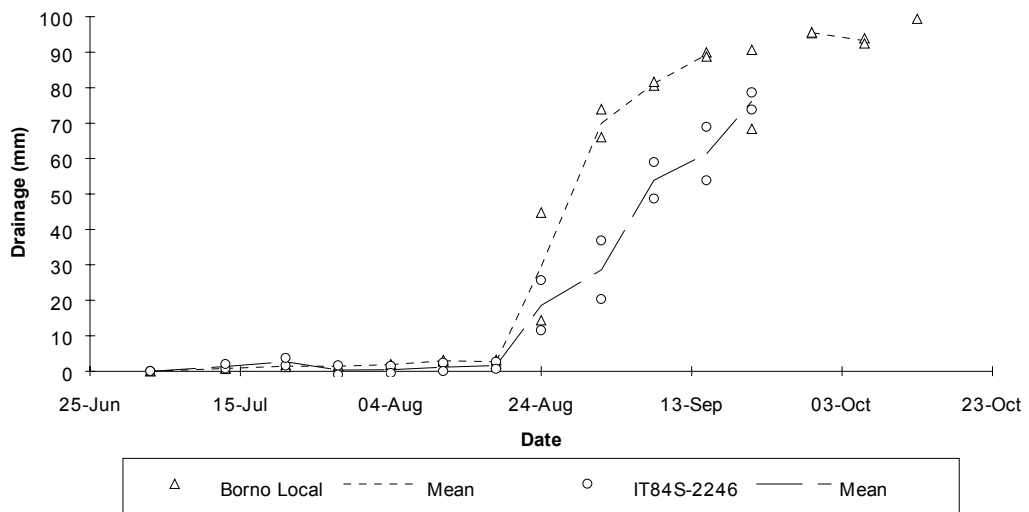


Figure 5-7. Cumulative drainage below 1.30m in a) millet based systems and b) cowpea systems

The root zone storage in the millet based systems at the time of millet harvest averaged 127 mm and did not vary significantly between treatments. This represents 88 mm storage above the pre-season storage that may be considered available to intercrops extending beyond the date of millet harvest. Assuming that the pre-season moisture profile at depth represents the water content to which the soil will drain

over the eight month dry season, all of this additional stored soil water would be lost to drainage and soil evaporation if the soil was left bare. Thus there would be no benefit to the following season's crops.

3.7. Seasonal Water Balance

Table 5.3 shows how the rainfall, up to the time of harvest, was partitioned between water use, drainage below the root zone and increased root zone storage under the various systems. As the storage term represents the increase over the pre-season storage, all of this can be considered to be available water.

Table 5.3. Seasonal water balance components in mm and as percentage of seasonal rainfall

	Sole Millet	Millet & Borno Local	Millet & IT84S-2246	Cowpea cv. Borno Local	Cowpea cv. IT84S-2246
Water use (mm)	318 67%	364 77%	340 72%	366 74%	296 63%
Storage (mm)	99 21%	70 15%	85 18%	34 7%	96 21%
Drainage (mm)	55 12%	37 8%	47 10%	98 20%	76 16%
Rainfall (mm)	471	471	471	498	468

Notes:

Millet based systems 25 June - 21 September

Cowpea cv. *Borno Local* 3 July - 13 October

Cowpea cv. *IT84S-2246* 3 July - 21 September

3.8. Yield Components

Millet suffered a significant ($P < 0.05$) reduction in grain yield over the sole crop when intercropped with both cv. *Borno-Local* (33%) and cv. *IT84S-2246* (23%) (Table 5.4) although the stover yields were similar in both sole and intercropped situations. The intercropped cowpea yields were similar for both cultivars, although cv. *IT84S-2246* yielded significantly ($P < 0.01$) more seed than cv. *Borno-Local* in sole systems. The fodder yields from cv. *Borno-Local* were significantly ($P < 0.01$) higher than those of cv. *IT84S-2246* in both situations. This supports the higher harvest index of cv. *IT84S-2246* compared to that of cv. *Borno-Local*.

Table 5.4. Yield components of millet and cowpea in sole and intercropped situations.

Cropping System	Millet			Cowpea			
	Grain t ha ⁻¹	Stover t ha ⁻¹	Harvest Index	Seed t ha ⁻¹	Fodder t ha ⁻¹	1,000 seed weight g	Harvest Index
Sole millet	1.39	5.51	0.19				
Millet & Borno Local	0.92	4.73	0.15	0.29	0.46	138.3	0.36
Millet & IT84S- 2246	1.07	5.08	0.18	0.20	0.13	124.7	0.58
cv. Borno Local				0.61	1.29	142.6	0.32
cv. IT84S-2246				1.15	0.27	124.7	0.73
Standard Error	0.13*	NS	NS	0.17**	0.10**	NS	0.05*

* p < 0.05

** p < 0.01

4. DISCUSSION

4.1. Water Balance

The 1992 season was wetter than average, due in particular to the high rainfall in August. The soil water profiles recorded showed water to be moving downwards through the profile throughout the millet season, suggesting that no drought stress occurred. This supports the conclusion of workers from Niger (Payne *et al.*, 1990) that water availability may not be the most limiting constraint to productivity in millet based systems, except in drier conditions. The observed range of drainage of 20-50 mm at 1.80 m depth compares well with the figure of 42 mm recorded by Cisse and Vachaud (1988) at the same depth and accounts for up to 10% of the seasonal rainfall. Therefore, studies which have ignored drainage (such as Nouri and Reddy (1991)) may have overestimated evapotranspiration.

The introduction of cowpea, sown as a relayed intercrop within millet fields, does not appear to increase the water use of the system up to the time of the millet harvest. Similar results were found by Shackel and Hall (1984) under sorghum based intercropping systems. As neither root zone storage nor drainage are significantly reduced in the intercropping systems, it appears therefore that cowpea transpiration is largely substituting for otherwise unproductive soil evaporation. This is supported by

the greater ground cover achieved in the intercropping treatments. The high frequency of rainfall (on average one in three days had rainfall in excess of 1mm between July and September) resulted in wet surface conditions throughout most of the growing season, leading to high soil evaporation losses from the sole millet treatment. Other workers in semi-arid areas (such as Wallace *et al.*, 1993) have shown that soil evaporation can account for a substantial proportion of the evapotranspiration of sole millet crops, especially when the crop cover is low. Similarly water use rate of sole cowpea cv. *Borno Local* was no greater than that of cv. IT84S-2246, despite having greater crop cover during the latter part of the season.

None of the cropping systems displayed an initial stage of constant and low Kc and the ratio of ETc to ET_o increased linearly from the time of planting. This may be due to the rapid emergence and cover development of all the crops studied. In all three systems, the Kc increased to a maximum value, corresponding to the start of the mid-season stage, when ETc was 10-34% greater than ET_o. The maximum Kc value for millet of 1.11 compares well with the results of Abdulmumin and Misari (1990). In the case of the millet based systems, the Kc remained constant at this high value for 44 days during the mid-season stage, however, in both cowpea cultivars, the peak Kc coincided with reaching maximum crop cover, but it declined immediately, reaching zero by the time of harvest.

The need to reject data from several of the plots was a source of concern. The errors are likely to have been caused by an under-estimation of the addition of water to the soil in the week as negative water use rates were calculated during periods when drainage was negligible. This implies that the assumption of zero runoff and runoff was inappropriate. 15% of the rainfall fell at intensities greater than 60 mm h⁻¹ with the maximum recorded intensity over one minute reaching 140 mm h⁻¹. Although the soil infiltration capacity is high, the slope is less than 1% and bunds around the plots restricted large-scale overland flow, it is possible that localised concentration of water occurred on a small (1-2 m) scale, especially where the surface became capped. Indeed, it was obvious to the eye that a few hours after rain there were distinct wetter and dryer patches in the field. Thus the soil surrounding some access tubes received more water than could be accounted for by rainfall alone. However,

no net runoff occurred from the plots and therefore runoff could not be measured or included in the water balance calculation. The high spatial variability of soil characteristics has been reported on this type of soils by many workers in the West African Sahel (e.g. Geiger and Manu, 1993). The soil micro-variability has major implications for soil and water management research in the region, as results of agronomic trials are often specific to weather conditions and hydrological features of experimental sites. Water balance investigations should therefore strive to enhance a high access tube replication and to minimise the occurrence of surface runoff.

4.2. Yield Response

Since the farmers' primary production goal is to have a stable millet grain yield for family subsistence, the selection of cowpea cultivars for intercropping should be based on the relative depression of millet grain yield, whilst still guaranteeing some cowpea seed and fodder. The effect of the introduction of cowpea as an intercrop on the grain yield of the staple millet crop varies with cowpea genotype, with the long duration cv. *Borno-Local* causing more reduction in millet yield than the short duration cv. *IT84S-2246*. It appears unlikely that the observed reduction in millet grain yield in this case was due to competition for water or light, but may be due to soil fertility constraints.

5. CONCLUSIONS

Intercropping cowpea with millet provides an opportunity for the subsistence farmer to more fully utilise land and available rainfall, without jeopardising production of the staple crop. From the results of this study it is apparent that the introduction of cowpea as an intercrop did not cause a significant increase in the water use rate over a sole millet crop. Neither was there evidence of water stress during the millet growing season. The small but significant observed depression of millet yield may therefore have been due to other factors, such as limited phosphorus availability. The seed and fodder output from the cowpea grown as intercrops therefore represent an increase in the efficiency of utilisation of the seasonal rainfall. Additionally, the long duration, local cowpea cultivar made effective use of soil water stored in the root zone after the millet harvest that would otherwise have been lost to drainage before the next rainy season. The conclusions of this study must be viewed with caution as

1992 was notably wetter than average during the middle of the season, and the performance of the system may be different in dryer years when competition for water may exist between the intercropped millet and cowpea. However, the results may allow the calibration of water balance models that can be used to predict the system performance under differing rainfall patterns.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

- Abdulummin, S. and Misari, S. M. 1990. Crop coefficients of some major crops of the Nigerian semi-arid tropics. *Agricultural Water Management* 18:159-171.
- Agnew, C.T. 1982. Water availability and development of rainfed agriculture in south west Niger, West Africa. *Transactions of the Institute of British Geographers* 7:419-457.
- Armbrust, D.V. 1990. Rapid measurement of crop canopy cover. *Agronomy Journal* 82:1170-1171.
- Baker, E.F.I. and Norman, D.W. 1975. Cropping patterns in northern Nigeria. Proc. South and East Asia Cropping Systems Network Workshop, IRRI, 13-20 March 1975. Los Baños, Philippines.
- Cisse, L. and Vachaud, G. 1988. Influence d'apports de matiere organique sur la culture de mil et d'arachide sur un sol sableux du Nord-Senegal. 1. Bilans de consommation, production et developpement racinaire. *Agronomie* 8:315-326.
- Doorenbos, J. and Pruitt, W.O. 1977. Crop water requirements. FAO irrigation and drainage paper 24. FAO. Rome.

- Folorunso, O. A. 1986. Distribution of steady state infiltration rate for Borno Soil. *Annals of Borno* 3:193-204.
- Geiger, S.C. and Manu, A. 1993 Soil surface characteristics and variability in the growth of millet in the plateau and valley region of Western Niger. *Agriculture, Ecosystems and Environment* 45:203-211.
- Kassam, A.H. and Kowal, J.M. 1975. Water use, energy balance and growth of gero millet at Samaru, northern Nigeria. *Agricultural Meteorology* 15:333-342.
- Klaij, M.C. and Vachaud, G. 1992. Seasonal water balance of a sandy soil in Niger, cropped with pearl millet, based on profile moisture measurements. *Agricultural Water Management* 21:313-330.
- Kowal, J.M. and Knabe, D.T. 1972. *Agroclimatological atlas of Northern Nigeria. Samaru, Zaria, Nigeria.*
- Nouri, M. and Reddy, K.C. 1991. Utilisation de l'eau par le millet et le niébé en association et de culture pure. In: M.V.K. Sivakumar, J.S. Wallace, C. Renard and G. Girous (editors), *Soil water balance in the Sudano-Sahelian zone. Proc. Niamey Workshop Feb. 1991. IAHS Publ. no. 199 IAHS Press, Institute of Hydrology, Wallingford, UK. pp. 421-429*
- Ntare, B.R. 1989. Evaluation of cowpea cultivars for intercropping with pearl millet in the Sahelian zone of West Africa. *Field Crops Research* 20:31-40.
- Ntare, B.R. and Williams, J.H. 1992. Response of cowpea cultivars to planting pattern and date of sowing in intercrops with pearl millet in Niger. *Experimental Agriculture* 28:41-48.
- Payne, W.A., Wendt, C.W. and Lascano, R.J. 1990. Root zone water balances of three low-input millet fields in Niger, West Africa. *Agronomy Journal* 82:813-819.
- Payne, W.A., Lascano, R.J. and Wendt, C.W. 1991. Annual soil water balance of cropped and fallowed millet fields in Nigeria. In: M.V.K. Sivakumar, J.S.

- Wallace, C. Renard and G. Girous (editors), Soil water balance in the Sudano-Sahelian zone. Proc. Niamey Workshop Feb. 1991. IAHS Publ. no. 199 IAHS Press, Institute of Hydrology, Wallingford, UK. pp401-411.
- Rayar, A.J. 1984. Soil survey report. University of Maiduguri Teaching and Research Farm, Maiduguri, Nigeria (unpubl.).
- Shackel, K.A. Hall, A.E. 1984. Effect of intercropping on the water relations of sorghum and cowpea. *Field Crops Research* 8:341-387
- Smith, M. 1991. Report on the expert consultation on revision of FAO methodologies for crop water requirements. Land and water development division. FAO. Rome. (unpubl.)
- Wallace, J.S., Lloyd, C.R. and Sivakumar, M.V.K. 1993. Measurements of soil, plant and total evaporation from millet in Niger. *Agricultural and Forest Meteorology* 63:149-169.

CHAPTER SIX. THE 'BALANCE' WATER BALANCE MODEL

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1. OVERVIEW

The model is a one-dimensional, daily, soil water balance. It aims to simulate the soil water storage, input (infiltration) and output (evaporation, transpiration, and drainage) of water in response to climate (Figure 6-1). The model was developed with the objective of being simple to parameterise with limited soil physical data and with input of daily rainfall and reference evapotranspiration only.

A brief description of the model is given here. The details of the model and equations used are given in an Appendix to this thesis.

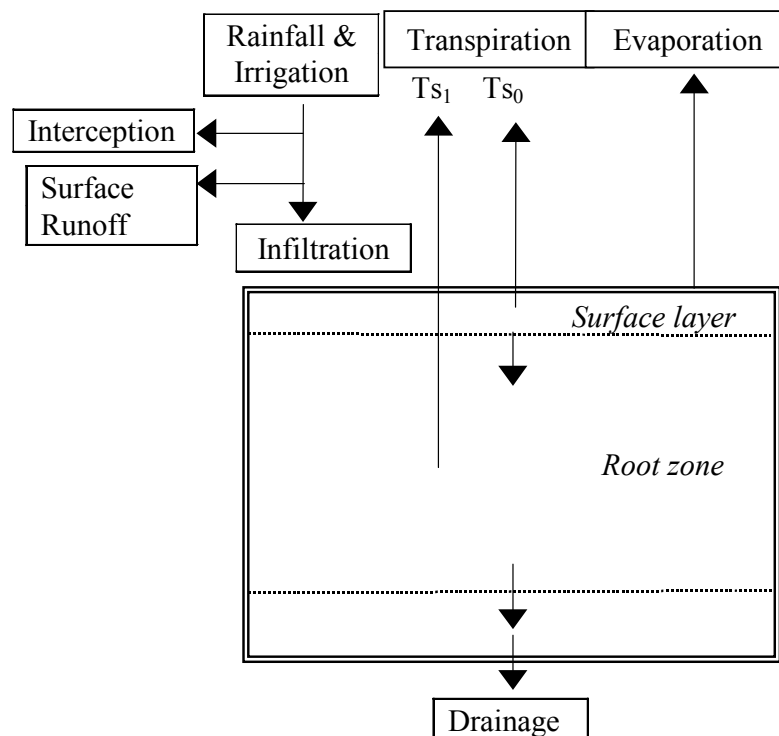


Figure 6-1. Overview of the soil water balance

The upper boundary is the soil surface and the lower boundary is at a fixed soil depth (usually the maximum root depth). Water is stored between these two boundaries in three stores (layers):

1. the surface (0 – 0.15m) layer,
2. the active root zone (0.15m – root depth),
3. the unsaturated layer below the root zone (root depth – profile lower boundary),

The boundary between layers 2 and 3 will change as the roots grow. Before plant roots reach 0.15m, layer 2 will have zero thickness.

1.1. Inputs of water

Inputs of water are from rainfall and irrigation. Net input of water into the soil (infiltration) is taken as the sum of rainfall and irrigation, less interception losses and surface runoff. Interception is estimated as a fraction of rainfall⁷ from a simple linear model, adjusted for plant canopy area. Daily runoff is estimated from daily rainfall using the US NRCS ‘Curve Number’ method (USDA, 1986).

1.2. Outputs of water

There are three outputs of water from the profile;

1.2.1. Soil evaporation

Soil evaporation occurs from the surface layer only. The rate of soil evaporation is estimated from the reference evapotranspiration and the time since wetting (rainfall or irrigation) using the empirical model of Richie (1972). The soil evaporation is weighted according to the canopy cover.

1.2.2. Plant transpiration

Potential plant transpiration is estimated from the reference evapotranspiration and an empirical crop factor. It is weighted according to the canopy cover and extracts water from the surface layer and the root zone. Actual plant transpiration is estimated from the potential and the root zone soil water storage. Adjustments are made to allow for increased transpiration when rain falls on a soil that would otherwise limit transpiration.

⁷ Irrigation may, or may not be subject to interception, depending on the application method.

1.2.3. Drainage

Drainage occurs from the lowest soil water store to the groundwater. The rate of drainage is estimated in the same way for re-distribution of water between layers (see 1.3 below). As the model was intended for use in environments with a deep water table, capillary rise from groundwater is not considered.

1.3. Redistribution of soil water

The BALANCE model is of the ‘tipping bucket’ type as water moves from upper layers to layers below only when the soil water content of the layer exceeds the field capacity value. However, the rate of drainage is estimated from an empirical model based on the amount of excess water, thus layers do not drain instantly, but it may take several days for a fully wetted soil to return to field capacity.

2. REFERENCES

Ritchie J. T., 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Res.*, 8:1204-1213.

United States Department of Agriculture, Natural Resources Conservation Service. 1986. *National Engineering Handbook*. Second edition. June, 1986. U.S. Government Printing Office.

CHAPTER SEVEN. DETERMINATION OF SOIL AND PLANT PARAMETERS FOR USE WITH THE BALANCE MODEL ON A SANDY LOAM SOIL IN A SEMI-ARID ENVIRONMENT.

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1. INTRODUCTION

The BALANCE model (see Chapter Six) has been developed as a simple one-dimensional soil water balance model for use with a minimum data set of soil and crop physical parameters. It is driven by daily rainfall and reference evapotranspiration only and can predict the partitioning of the soil water balance in situations with deep groundwater. As such, it is well suited to the North East Arid Zone of Nigeria and could be used to evaluate the impact of climatic variability on the potential of upland farming systems. Although the model contains many empirical components, most of the parameters have some physical meaning and can be determined from field or laboratory experiments.

The objectives of this study are to parameterise the BALANCE model for a typical upland soil and a millet crop in the North East Arid Zone of Nigeria. This was done by;

- a series of field and laboratory experiments designed to calibrate individual components of the model,
- determination of parameters from literature,
- the validation of the model predictions against observations from an independent field trial,
- testing the sensitivity of the model output to key empirical parameters, and
- evaluating the improvement in model fit by simultaneously optimising the key parameters.

1.1. Experimental site

The University of Maiduguri Research Farm (11°5'N, 13°0' E, altitude 354m) is located on the University Campus near Maiduguri, Nigeria. The soil has been classified as a Typic Ustipsamment (Rayar, 1984). The texture is predominantly sandy loam and it is weakly aggregated. From the surface to 0.80 m, it contains 81% sand, 14% clay and 5% silt (Grema, 1994) however the silt fraction increases and the coarse sand fraction decreases slightly at 1.50 m.

The dry bulk density of the soil was determined to be 1.50 g cm⁻³ (Grema, 1994). There is no variation with depth. Steady state infiltration rate varies from 72 to 220 mm h⁻¹ with a mean of 135 mm h⁻¹ over an area of 0.23 ha (Folorunso, 1986). The site is on a slight north facing slope that forms the 'Bama Ridge' - a 12 m aeolian sand ridge, thought to mark the limit of the former Lake Mega-Chad.

2. METHODS

2.1. Parameterisation

The soil profile may be divided into two textural layers. For each layer, the parameters required to describe the soil are the layer thickness and the volume water fraction at saturation, θ_{SAT} , field capacity, θ_{FC} , and permanent wilting point, θ_{PWP} .

These are all parameters that can be measured in the field or in the laboratory.

Additional soil parameters are required to describe the rate of drainage of wet soil, τ , and the evaporation from bare soil surfaces, U and α . These parameters are empirical and can only be derived by 'fitting' to observed data. The crop parameters required by BALANCE, apart from the cover development dates, are the maximum rooting depth, the crop coefficient at full cover, k_c , and the fraction of total available water ($\theta_{FC} - \theta_{PWP}$) that is available to the plant at the potential rate, or allowable depletion, p . Initial estimates of these can be derived from literature.

2.1.1. *Saturation water content*

The volume water fraction at saturation is difficult to measure by wetting a soil due to air entrapment and rapid drainage, but can be assumed to be equal to the porosity of the soil (Landon, 1991).

Dry bulk density was determined in the field using core sampling. Five samples were taken at 0.25 m depth with 54 mm diameter, 30 mm depth brass rings. These were taken to the laboratory and were dried at 105°C for 48 h, before being weighed. Dry bulk density was calculated from

$$\rho_b = \frac{M_s}{V} \quad (5-1)$$

where

ρ_b is the dry bulk density, g cm^{-3}

M_s is the mass of oven dry soil, g

V is the volume of the soil sample, cm^3 .

For a mineral soil, the porosity can be calculated from;

$$n = 1 - \frac{\rho_b}{\rho_p} \quad (5-2)$$

where

n is the porosity, $\text{cm}^3 \text{cm}^{-3}$

ρ_b is the dry bulk density, g cm^{-3}

ρ_p is the particle density, g cm^{-3}

A particle density of 2.65 g cm^{-3} was assumed (Landon, 1991).

2.1.2. Field capacity and drainage constant, τ

Field capacity water content has been defined in many different ways: as the water content after a fixed period of drying; the water content at a specific soil water potential; the water content at which the unsaturated hydraulic conductivity reaches a specific rate (Nachabe, 1998) or the maximum water content that the soil will hold following free drainage (Landon, 1991). The latter definition is appropriate in this context as BALANCE assumes that no drainage occurs at water contents below field capacity. At water contents above field capacity, BALANCE assumes that the drainage rate is a function of the excess water ($\theta - \theta_{FC}$) and the drainable porosity ($\theta_{SAT} - \theta_{FC}$). The drainage rate is given by,

$$dr_i = \tau (\theta_i - \theta_{FC}) \left(e^{(\theta_i - \theta_{FC})} - 1 \right) / \left(e^{(\theta_{SAT} - \theta_{FC})} - 1 \right) \times 1000 \text{mm.m}^{-1} \quad (5-3)$$

where

- dr_i drainage rate on day i , $\text{mm m}^{-1} \text{ day}^{-1}$
 τ drainage constant
 θ_i volume water fraction on day i
 θ_{FC} volume water fraction at field capacity
 θ_{SAT} volume water fraction at saturation

Field capacity water content, θ_{FC} and the drainage constant, τ , can be found by fitting the above equation to observed water contents measured in a freely draining soil profile with no evaporation or addition of water at the surface.

An experiment was carried out on the University of Maiduguri Research Farm in May 1992. The soil surface was raked and levelled out and bunds were built up to 0.10 – 0.15 m to define an area approximately 2 m x 2 m. Two neutron probe access tubes were installed in the plot.

On the evening of 30 April 1992, water was applied to the surface by a hose from a water bowser and allowed to infiltrate (plate 1). The rate of water application was determined volumetrically and the hose was allowed to run long enough to apply approximately 150mm depth of water (0.6 m^3 over 4 m^2).

There had been no significant rain for the preceding eight months, therefore it was assumed that the soil was at permanent wilting point (estimated at 0.050 volume water fraction) before the test. Taking an estimated saturation volume water fraction of 0.434 (estimated from the dry bulk density above), this should have saturated the profile to 0.40 m. Infiltration of the applied water took about half an hour, after which the plot was covered with black PVC sheeting wide enough to cover the wetted area and at least 0.30 m of the surrounding dry soil to prevent evaporation. Soil was placed on the edges to hold the PVC sheet in place.

Soil water content at 0.10m intervals from 0.20 m – 1.90 m was measured with the neutron probe during the following 28 days. No samples were taken above 0.20 m for safety reasons and gravimetric samples could not be taken due to the need to keep the soil surface covered.



Plate 1 Plots for field capacity determination, University of Maiduguri Farm, April 1992.

Values of τ , and θ_{FC} were found by minimisation of the root mean square (RMS) of the difference between the average of the two observed values and the values simulated by equation 5–3.

2.1.3. Permanent wilting point

Permanent wilting point is arbitrarily defined as the soil moisture content at which the leaves of sunflower plants wilt permanently (Landon, 1991). Volume water fraction at permanent wilting point can be observed in the field, but is more commonly estimated as the moisture content at 1.5 MPa water potential. Undisturbed soil cores were taken from the field and placed in a pressure membrane apparatus at Silsoe College and subjected to a pressure of 1.5 MPa. The moisture content of the soil at equilibrium was determined gravimetrically.

2.1.4. Easily available soil water

When soil water storage is close to field capacity, actual evapotranspiration will be equal to the potential rate. However, beyond a certain depletion, actual evapotranspiration will be less than potential. Rockström, et al. (1998) estimated that for millet in Niger 60% of the available water was easily available.

2.1.5. Soil evaporation

The BALANCE model follows the method of Ritchie (1972) by assuming a two stage approach.

During the first (wet) stage, actual soil evaporation is energy-limited and is assumed to be equal to potential soil evaporation. Arkin *et al.* (1974) and Adams *et al.* (1976) used evaporation plates to measure the potential evaporation rate from a wet soil.

These consisted of shallow (3 mm) metal plates filled with soil and with water supplied to a membrane at the base at a constant potential of -2 kPa. The rate of loss of water from the constant head reservoir represents the evaporation over the surface area of the plate. Measurements of evaporation by such methods represent the potential rate of evaporation, or the rate of evaporation from a wet soil where the rate is limited only by the available energy ('first-stage' evaporation).

Ritchie (1972) assumed that potential evaporation can be estimated from estimates of net radiation at the soil surface;

$$E_p = \left[\frac{\Delta}{\Delta + \gamma} \right] R_n \quad (5-4)$$

where,

E_p potential soil evaporation, mm d⁻¹

Δ slope of the saturation vapour pressure versus temperature curve, kPa °C⁻¹

γ psychrometric constant, kPa °C⁻¹

R_n net radiation at the soil surface, mm d⁻¹

As the soil surface dries, evaporation becomes increasingly limited by the ability of water to diffuse through the dry soil surface. Stage two begins when the rate of evaporation falls below the potential rate and evaporation is supply limited. The precise timing of the start of stage two depends on the soil depth, the hydraulic properties of the soil and the evaporative conditions. Ritchie (1972) set a soil dependant threshold, U , for the cumulative evaporation to determine the onset of stage two. Boesten and Stroosnijder (1986) quote laboratory studies that calculated values of U ranging from 20 - 60 mm, equivalent to 2 - 4 days evaporation, whereas field studies have given considerably lower values in the range of 4 - 12 mm.

Ritchie (1972) assumed that during stage two, cumulative evaporation from bare soil, increases with the square root of time (Black *et al.*, 1969),

$$\Sigma Ea = \alpha t^{0.5} \quad (5-5)$$

where

ΣEa , Cumulative evaporation, mm

t Time after onset of stage two, days

α Soil dependent empirical constant

The daily evaporation rate can be estimated from;

$$Ea = \alpha (t+1)^{0.5} - \alpha (t)^{0.5} \quad (5-6)$$

The value of α for a particular soil can be determined by regression, but many workers have found it to be fairly constant, at around 3.5 mm d^{-0.5} (see Table 7.1 below).

Table 7.1. Estimates of α

Source	α mm d ⁻¹	Location
Dancette and Hall (1978)	3.34	(N Senegal)
Villalobos and Fereres (1990)	3.45	(S Spain)
Ritchie and Johnson (1990)	3.50	(?)

Using a value of 3.5 mm d^{-0.5} for α imposes a practical upper limit to the cumulative stage-two evaporation from bare soil around 20 mm after one month without rain, however, Dancette and Hall (1978) imposed an upper limit equivalent to the air dry water content of the top soil.

BALANCE uses;

Stage	Condition	Equation	
1	$\Sigma Ea \leq U$	$\Sigma Ea = \Sigma Ep$	(5-7)
2	$\Sigma Ea > U$	$\Sigma Ea = U + \alpha t^{0.5}$ (subject to $Ea \leq Ep$)	

Where

ΣE_a cumulative actual soil evaporation, mm

ΣE_p cumulative potential soil evaporation, mm

U upper limit of stage 1 evaporation, mm

α an empirical constant, $\text{mm t}^{-0.5}$

t time since the onset of stage 2, days.

a) Measurement of soil evaporation

Measurements of bare soil evaporation have generally been made by water balances on natural, undisturbed soil, or micro-lysimeters.

Water balance

Where evaporation is measured from plots of fallow land, water balance techniques can be employed. As there is no transpiration by plants, and if no deep percolation is taking place, then changes in the profile water content during rain-free periods give a measure of the bare soil evaporation. This method has the advantage that the soil remains relatively undisturbed and changes in water content can be monitored to a greater depth. Care must be taken to identify the direction of water movement and a zero-flux plane should be identified somewhere in the profile to eliminate inaccuracies due to percolation losses.

Stroosnijder (1987) and Allen (1990) used a neutron probe to measure the soil water profile under bare soil. In each case, the water content of the upper layers was determined gravimetrically due to the inaccuracy of neutron moderation methods near the surface.

Micro-lysimeters

Micro-lysimeters for measuring the actual evaporation from a bare soil, have been described by Boast and Robertson (1982) and Walker (1983). They have been used in many studies, especially where evaporation has been measured from bare soil between row crops (e.g. Shawcroft and Gardner, 1983; Walker, 1984; Boesten and Stroosnijder, 1986; Lascano & van Bavel, 1986; Allen, 1990; Villalobos and Fereres, 1990). The design and construction varies, but usually consists of a brass or PVC tube, 70 - 200 mm diameter and 70 - 300 mm long. They are usually closed at the

bottom, so that the only changes in weight result from evaporation of water from the surface.

Table 7.2. Design of micro-lysimeters

Author	Diameter (mm)	Length (mm)	Material
Boast and Robertson (1982)	76	76	brass
Walker (1983)	76	120	PVC
Shawcroft and Gardner (1983)	203	50-200	PVC
Boesten and Stroosnijder (1986)	70	120	PVC
Martin, Klocke and DeHaan (1985)	150	200	PVC
Villalobos and Fereres (1990)	200	300	steel
Allen (1990)	100	150	plastic

The tubes are driven into the ground and an undisturbed core is removed in the tube. The tube is then sealed at the bottom and weighed. The soil-filled tube is returned to the same location in the field and inserted in the hole that was left. The hole may first be lined to prevent soil adhering to the outside of the tube. Some time later the tube is removed and re-weighed to determine the evaporation loss over the time period.

To be reliable, the soil in the micro-lysimeters should resemble that of the surrounding site as closely as possible in all respects, however the insertion and removal of the tube is bound to disturb the field condition. If micro-lysimeters are used over a long period, the soil water profile within the lysimeter will increasingly differ from the surrounding soil, especially where plant roots may be extracting water from beneath bare soil. Also, by sealing the bottom of the micro-lysimeter, an artificial zero-flux plane is introduced. To be reliable therefore, a corresponding zero-flux plane should be present in the surrounding soil. This may be true for longer micro-lysimeters (300 mm or longer), but results from shorter tubes should be viewed with caution.

b) Field experiments

Two field experiments were carried out on the University of Maiduguri Research Farm to determine the bare soil drying characteristics of the soil.

Water balance

The rate of evaporation from a bare soil surface was monitored over 20 days on a 2 m x 2 m plot. Two neutron probe access tube were installed in the plot.

The plot was wetted in the same way as the field capacity experiment above, and covered with black PVC overnight to allow redistribution of the soil water without evaporation. The plot was uncovered the following morning and the first soil moisture readings were taken. The cover was replaced for a further 24 hours and removed on the morning of 2 May 1992.

Soil water content was measured gravimetrically (BSI, 1990)⁸ at 0.05 m and 0.15 m and by neutron probe between 0.20 m – 2.00 m, to provide measurements of a 2.0 m profile. As no change in water content was observed below 1.2m, it is safe to assume that drainage from the bottom of the observed layer was zero. As rainfall over the trial period was zero, soil evaporation can be calculated from the water balance;

$$E = \Delta S \quad (5-8)$$

Where

E is cumulative soil evaporation, mm

ΔS is the change in soil water storage, mm

Daily soil evaporation rate can be calculated from;

$$E_{S_i} = S_{i+1} - S_i \quad (5-9)$$

Where

E_{S_i} is the soil evaporation on day i, mm d⁻¹

S_i is the soil water storage on day i, mm

A two stage soil evaporation model was fitted to the observed data by minimising the root mean square of the difference between the observed and predicted cumulative evaporation.

⁸ Samples for gravimetric moisture content determination were \approx 150 g rather than 300 g as recommended by BSI (1990) however, the balance used had a resolution of 0.001 g rather than 0.1 g.

Daily net radiation was calculated from daily sunshine, temperature and wind data and monthly average relative humidity from Maiduguri Airport (see Hess, 1998 for details).

Micro-lysimeters

Preliminary tests were made during early July to evaluate tubes of different diameter and length. Ideally, the tubes used should be of as large a diameter as possible, to maximise the surface area, and long enough to ensure that there is no restriction to evaporation. In practice, the dimensions of the tube were limited by the ability to insert the tube into the soil and remove an undisturbed core without the soil falling from the tube. This was a major constraint, especially when the soil was dry.

a) Installation



b) Removal



Plate 2 Installation and removal of micro-lysimeters

The final specification for the micro-lysimeters was 75 mm diameter PVC pipe, cut to 0.20 m lengths conforming to the recommendations of Daamen *et al.*, (1993). Three to five tubes were installed on each day by pushing them into the soil by hand until the top of the tube was flush with the soil surface. Further pressure was applied using a wooden block when necessary. Hammering the tubes was avoided due to the excessive disturbance caused. The tubes were then removed from the soil by first excavating about 0.10 m of soil from around the tubes and then pulling by hand and twisting gently (plate 2). This method proved successful after mid-July when the soil was wet enough at 0.20 m depth to hold together. The tubes were then inverted on a plate, and the bottom sealed with strips of self-adhesive 'packing tape'.

The soil-filled tubes were then taken to the laboratory and weighed on a digital balance⁹ before being returned to the site and replaced in the soil. The excavated soil was replaced around the tubes such that the top of the tubes were flush with the soil surface. The tubes were then left for 24 hours.

Before the tubes were replaced, samples were taken of surface soil (0 - 50 mm) from adjacent to the tubes. These were taken using a length of aluminium tube pushed 50 mm into the soil and then removed to extract a plug of soil. These were then taken to the laboratory for gravimetric water content determination¹⁰.

The micro-lysimeter tubes were removed after approximately 24 hours and re-weighed to calculate the net change in weight. Core samples of the surface (0-50 mm) were taken from the tubes for gravimetric water content determination to allow comparison with the surface water content of the surrounding soil.

Rainfall was monitored daily from 11 May, 1992 using a volumetric rain gauge with a 25 mm capacity. From 9 June, 1992 this was supplemented by an automatic rain gauge¹¹. From 30 June, 1992 solar radiation¹², temperature and humidity¹³ were measured hourly and logged on a data logger¹⁴.

Daily evaporation was calculated from the water balance,

$$Ea = R - 0.001 \frac{\Delta M}{A} \quad (5-10)$$

⁹ Sartorius 1264 MP digital balance, weighing up to 3,000g to 0.01g precision, courtesy of the Department of Animal Science, UNIMAID.

¹⁰ Weighing using a Mettler P163 electronic balance, weighing to 160g at 0.001g precision. Drying for at least 24 hours. Oven and balance courtesy of Department of Soil Science, UNIMAID

¹¹ Didcot Rain gauge type DRG 5.1 (ser. no. 038 RL) 0.1mm tip with Rainlog event time data logger (Serial number. 2006).

¹² Didcot Instruments, DRS-2 solar sensor. Serial No. 083. Calibration: 14.52 mV KW⁻¹ m⁻²

¹³ Skye Instruments, SKH 2032 temperature and humidity sensor. Serial No. 4058

¹⁴ Campbell CR10. Campbell Scientific, CR10 measurement and control module. Serial No. E4530 CR10W wiring panel. SC32A optically isolated RS232 interface Serial No. E1914.

were

E_a actual soil evaporation, mm

R rainfall, mm

ΔM change in mass of the lysimeters, g

A Surface area of lysimeters, m²

The model of soil evaporation (equation 5–7) was fitted to the observed daily soil evaporation rates by optimising U and α in order to minimise the weighted sum of squares, where,

$$\chi^2 = \sum \frac{(E - \hat{E})^2}{SE^2} \quad (5-11)$$

χ^2 = the weighted sum of squares

E = mean measured soil evaporation, mm d⁻¹

\hat{E} = modelled soil evaporation, mm d⁻¹

SE = standard error of measured soil evaporation, mm d⁻¹

2.1.6. Crop coefficient

The crop coefficient, kc, is the ratio of crop evapotranspiration to a reference evapotranspiration. A crop coefficient for *ex-Borno* millet was determined from lysimeter measurements of actual evapotranspiration made at Samaru, N. Nigeria using open water evaporation as the reference value (Kassam and Kowal, 1975). The same experiment was re-analysed by Abdulmumin and Misari (1990) using the FAO modified Penman (Doorenbos & Pruitt, 1977) reference crop evapotranspiration, gave a peak kc of 1.0.

The FAO modified Penman reference crop evapotranspiration (Doorenbos & Pruitt, 1977) has been found to overestimate grass (reference) evapotranspiration under a wide range of conditions (Allen et al., 1994). In this study, reference evapotranspiration has been calculated using the FAO Penman-Monteith method (Allen et al., 1998) as described in Hess (1998). In order to correct Abdulmumin and Misari's (1990) estimate of crop coefficient, reference evapotranspiration was calculated by both methods for the growing season months (June – September) between 1961 and 1991 using monthly average data from Maiduguri Airport.

$$kc' = kc \frac{ET_{oFAO}}{ET_{oPM}} \quad (5-12)$$

where

kc' adjusted crop coefficient

kc crop coefficient calculated by Abdulmumin and Misari (1990) = 1.0

ET_{oFAO} ET_o calculated by the method of Doorenbos & Pruitt (1977) (mm)

ET_{oPM} ET_o calculated by the Penman-Monteith method (mm).

2.2. Sensitivity and calibration of the model

The parameterised model was compared with data from one season's trial at the University of Maiduguri Research Farm (see Grema & Hess, 1994, for experimental details). Air temperature, humidity, solar radiation and rainfall were measured at the site using an automatic weather station, whilst daily wind run and sunshine duration were measured at the nearby Maiduguri Airport meteorological station. Daily reference evapotranspiration was calculated using the Penman-Monteith method as described by Hess (1998). The soil water content of sole millet plots, was monitored weekly using a neutron probe and gravimetric sampling and the evapotranspiration and drainage were estimated from the change in profile water content.

The performance of the model was evaluated using the root mean square error (RMSE), mean bias error (MBE) and the t- statistic (Jacovides and Kontoyiannis, 1995), defined as;

$$RMSE = \left(\frac{1}{n} \sum_{i=1}^n d_i^2 \right)^{0.5} \quad (3-7)$$

$$MBE = \frac{1}{n} \sum_{i=1}^n d_i \quad (3-8)$$

$$t = \left[\frac{(n-1)MBE^2}{RMSE^2 - MBE^2} \right]^{0.5} \quad (3-9)$$

where n is the number of data pairs, and d_i is the difference between the ith values predicted and observed.

The parameters used to describe bare soil evaporation and the drainage in the model are empirical and inter-related – a reduction in the value of one during calibration

can, to some extent, be compensated by an increase in the other. For both bare soil evaporation and drainage, the sensitivity of the model predicted water contents to changes in the values of the parameters was tested and new values of each parameter were chosen in order to minimise the RMSE. The calibrated values were compared with the initial estimates from the field experiments.

3. RESULTS

3.1. Parameterisation

3.1.1. *Saturation water content*

The dry bulk density was determined to be 1.51 g cm^{-3} (S.E. $\pm 0.036 \text{ g cm}^{-3}$). Assuming a particle density of 2.65 g cm^{-3} gives an estimated porosity of 0.429 (S.E. ± 0.014). Assuming that the saturation water content is equal to the porosity, gives a volume water fraction at saturation (θ_{SAT}) of $0.429 \text{ m}^3 \text{ m}^{-3}$ (S.E. $\pm 0.014 \text{ m}^3 \text{ m}^{-3}$).

3.1.2. *Field capacity and drainage constant, τ*

Prior to the wetting experiment, the volume water fraction at 0.30 m depth was 0.023 (Figure 7-1). This was slightly below the estimated permanent wilting point water content (see 3.1.3 below) and may reflect the depth of bare soil evaporation, or the variability of soil texture with depth.

Table 7.3 shows the measured volume water fraction at 0.30 m depth from the two access tubes over 28 days after wetting. Both show that wetting had reached 0.30 m by the time of the first reading and a gradual decline in volume water fraction continued over the 28 day period. As evaporation had been prevented, it must be concluded that the profile was still draining after 28 days.

The fitted parameters for field capacity water content and the drainage constant, τ , were $0.094 \text{ m}^3 \text{ m}^{-3}$ and 0.72 respectively. Figure 7-2 shows the measured and fitted volume water fractions at 0.30 m depth for 30 days after wetting. Visually the calibrated fit appears to be good. The RMS was 0.002 and the mean bias error (MBE) between the average of the two observed values and the simulated value was less than the resolution of the observed values (i.e. $<0.001 \text{ m}^3 \text{ m}^{-3}$). From the soil

water characteristic curve (Figure 7-3) the field capacity value is equivalent to the water content at 18.9 kPa suction.

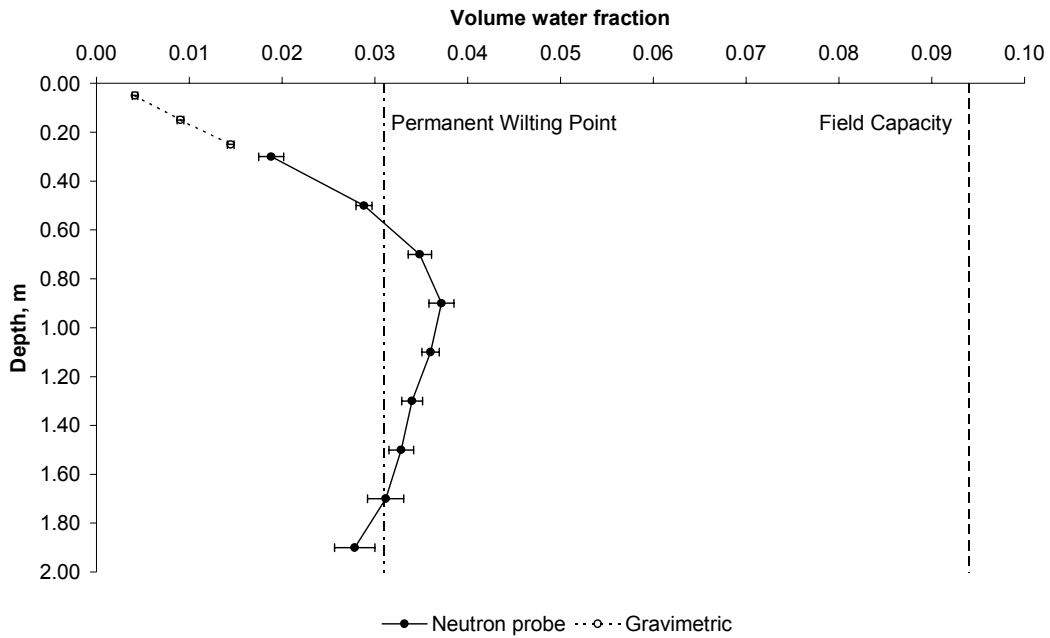


Figure 7-1 Average soil water profile on 27 April 1992 (before wetting) showing standard errors (n=6).

Table 7.3. Measured volume water fraction at 0.30m depth from two access tubes after wetting.

Days after wetting	Volume water fraction	
	Tube 5	Tube 6
1	0.178	0.195
2	0.162	0.177
3	0.155	0.165
6	0.137	0.143
8	0.134	0.138
11	0.129	0.129
15	0.119	0.121
19	0.110	0.111
26	0.104	¹⁵
28	0.105	0.116

¹⁵ No measurement possible due to low battery in the neutron probe.

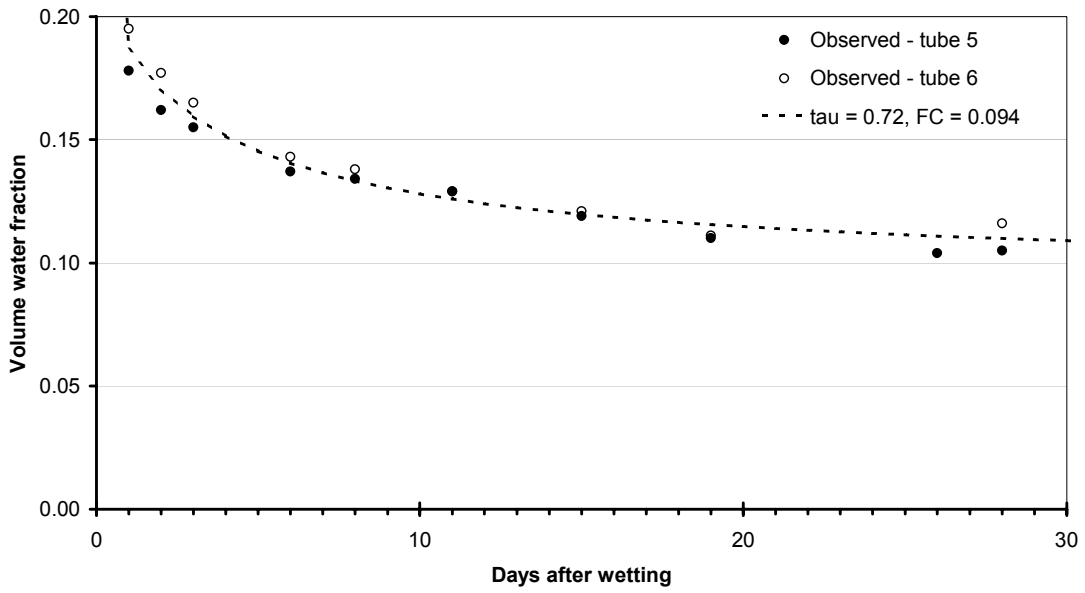


Figure 7-2 Observed and fitted volume water fraction at 0.3 m depth in for a sandy loam soil at the University of Maiduguri Research Farm.

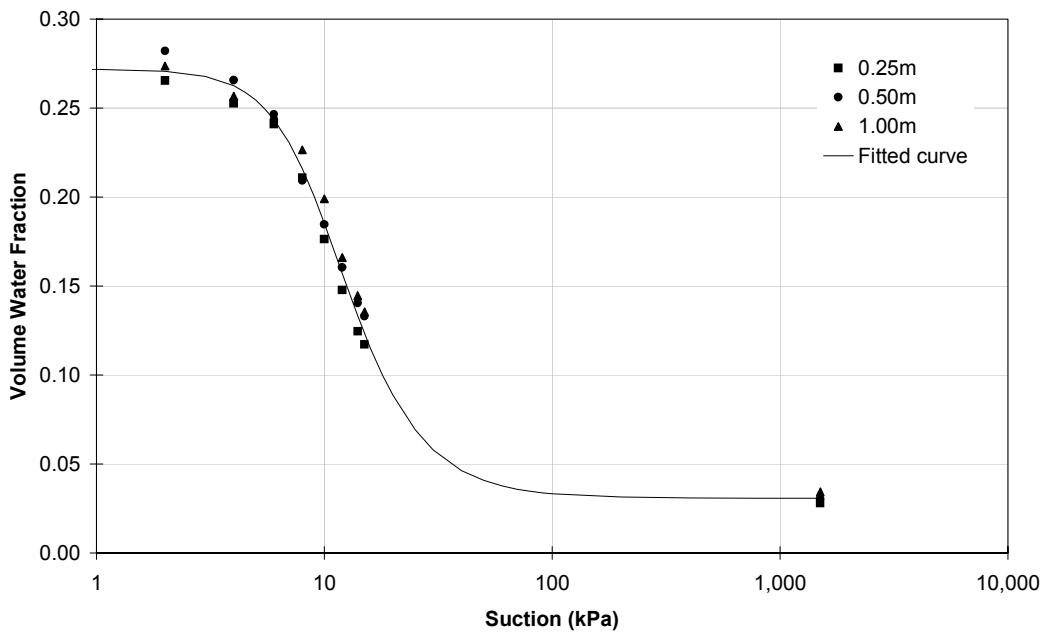


Figure 7-3 Soil water characteristic curve fitted through observed points from three depths.

3.1.3. Permanent wilting point

From the soil water characteristic curve (Figure 7-3) the volume water fraction at 1.5 MPa was estimated to be $0.031 \text{ m}^3 \text{ m}^{-3}$.

3.1.4. Fraction of easily available water

Taking the field capacity and permanent wilting point water contents from above, the water content at 60% available water capacity is $0.07 \text{ m}^3 \text{ m}^{-3}$. From the soil water characteristic curve (Figure 7-3) this is equivalent to a water potential of 25 kPa.

3.1.5. Soil evaporation

a) Water balance

Figure 7-4 shows the observed soil water profiles for the average of the two access tubes between 1/5/92 and 19/5/92. It shows that in addition to the evaporation loss from the soil surface there was redistribution of water taking place within the top 1.00 m. However, below 1.20 m the soil water content did not change over the measurement period, confirming that none of the added water was lost due to drainage.

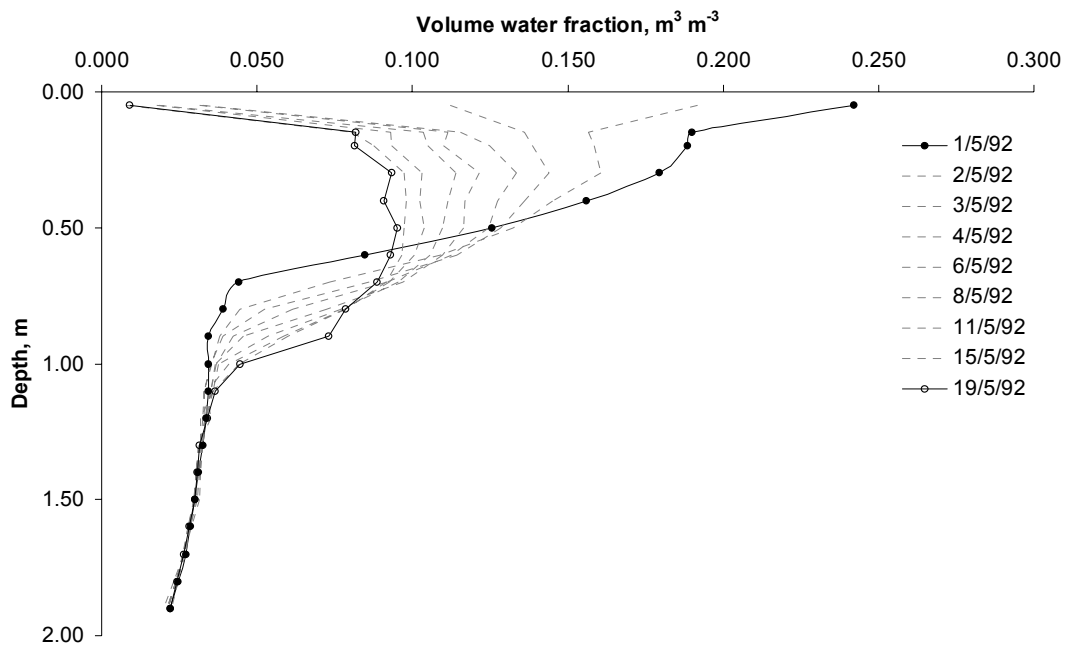


Figure 7-4 Observed soil water profiles in a sandy loam soil on the University of Maiduguri Research Farm allowed to dry by soil evaporation after wetting.

Figure 7-5 shows the change in soil water storage in the 2 m profile over the drying period. Although the plot was covered for the first 36 h, there has still been some apparent evaporation loss over that period. The figure clearly shows two stages of drying, an initial stage of rapid, near-constant evaporation followed by a second period of lower, reducing evaporation.

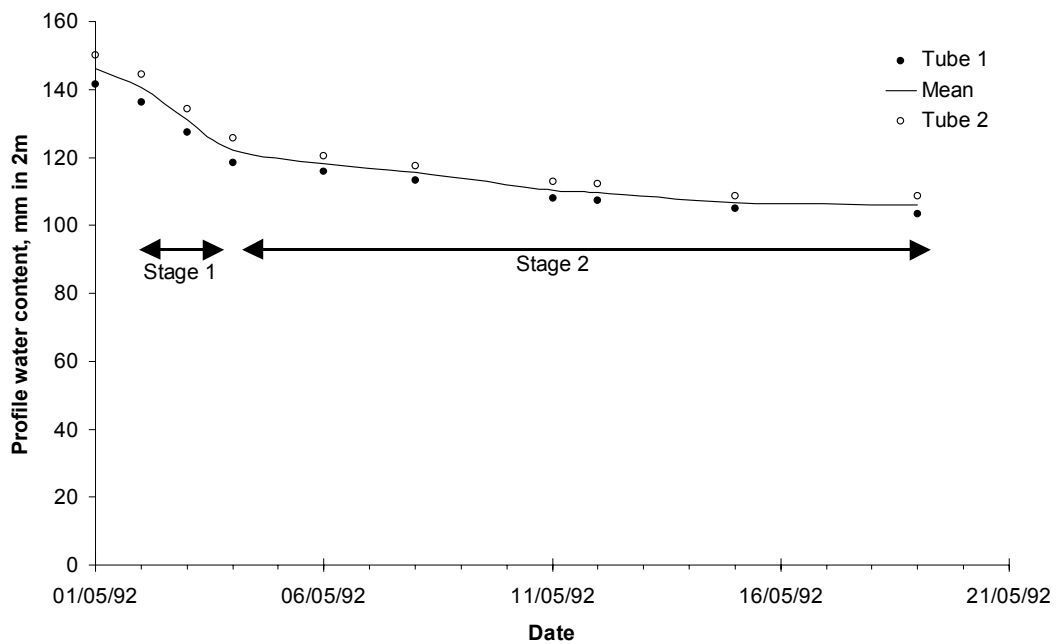


Figure 7-5 Change in water storage in 2m profile in a sandy loam soil on the University of Maiduguri Research Farm allowed to dry by soil evaporation after wetting.

Average net radiation over the measurement period was 4.2 mm d^{-1} , (standard deviation 0.47 mm d^{-1}). The end of stage 1, U , was found to be 22 mm. Taking equation 5-4 for the potential soil evaporation, underestimated the soil evaporation during stage 1 and a good fit in the model (Figure 7-6) could only be achieved by taking,

$$E_p = 1.6 R_n \quad (13)$$

Where

E_p potential soil evaporation, mm d^{-1}

R_n net radiation, mm d^{-1}

The constant in the equation for stage 2 evaporation, α , was found to be $3.3 \text{ mm d}^{-0.5}$.

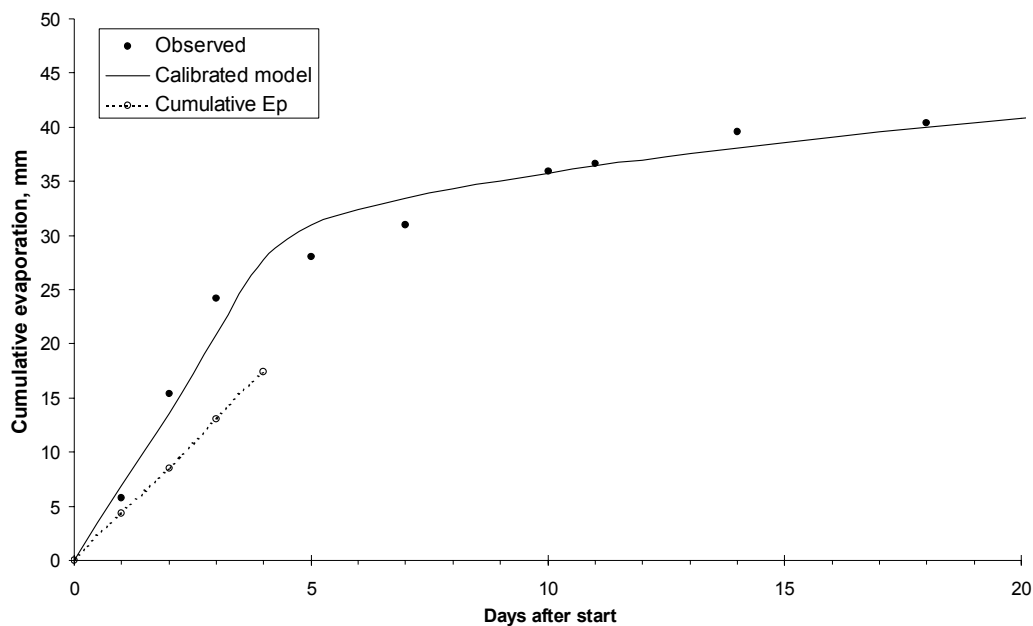


Figure 7-6 Observed and predicted cumulative bare soil evaporation from the water balance experiment on University of Maiduguri Research Farm.

b) Micro-lysimeters

Ten observations were made between 13 July and 30 July 1992. On three of these occasions rain had fallen during the 24 hour observation period, and adjustments were made to the water balance to allow for this.

On eight occasions, the water content of the top 50 mm of soil inside the lysimeter tube was measured and compared with the water content of the surrounding surface soil. Analysis of variance showed a significant difference ($p = 0.05$) between the water content inside and outside the lysimeters after evaporation. Closer inspection of the data showed the difference to be greatest on one day (23 July), when there had been a delay of four days between samples being taken from the lysimeters and being weighed wet. Drying during this period could have accounted for the reduced water content of soil from inside the tubes. When data from this day were excluded from the analysis of variance, the effect of the lysimeters became less significant ($p = 0.17$), however, Figure 7-7 shows that the surface soil inside the lysimeters tends to dry more than the surrounding soil, especially after several days of drying. This may be due to increased disturbance caused during insertion and extraction of the tubes in dry soil.

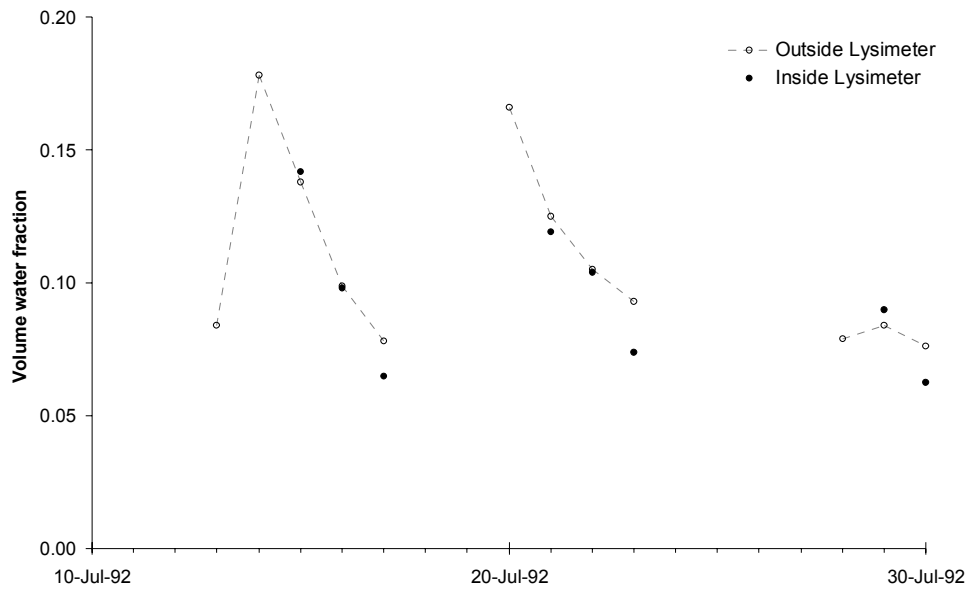


Figure 7-7 Comparison of surface (50 mm) water content inside and outside of the micro-lysimeters at University of Maiduguri Research Farm.

Soil evaporation was measured by the micro-lysimeters over three drying cycles following rainfall between 13 July and 31 July 1992. The drying following wetting can be clearly seen from the change in water content of the surface (0 - 50 mm) soil (Figure 7-7). Immediately following heavy rainfall, the volume water fraction of the surface would rise to 16% - 17%, but would fall rapidly over the following days with evaporation from the surface, however the rate of fall declines with time.

The calculated daily soil evaporation rates are shown in Figure 7-8. On days with rain, or soon after, there is a large standard error in the calculated evaporation rates, but this reduces in the following days.

Measured soil evaporation on days without rain was always less than the potential. This implies that there is no stage 1 evaporation and therefore $U = 0$. The calibrated value of α was found to be $4.6 \text{ mm d}^{-0.5}$.

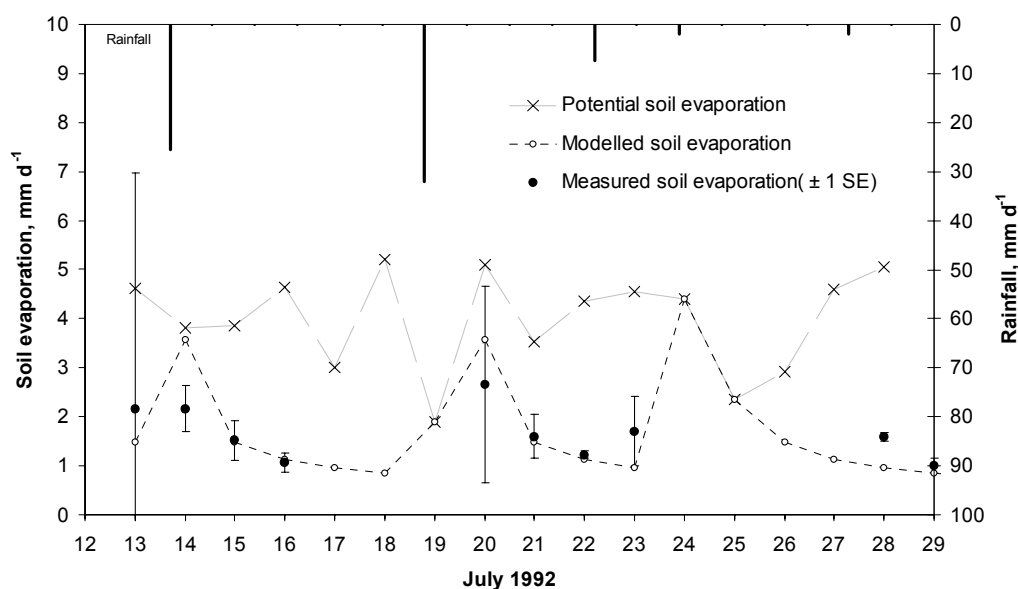


Figure 7-8 Daily soil evaporation calculated from micro-lysimeters showing modelled soil evaporation for two drying periods.

3.1.6. Crop coefficient

Monthly average maximum and minimum temperatures, relative humidities, sunshine duration and wind run were available for 108 growing season months between 1961 and 1991 to allow the calculation of reference evapotranspiration. Figure 7-9 shows that the FAO modified Penman method significantly overestimates reference evapotranspiration in all growing season months. During August, the month of peak cover, the overestimate is 21%, thus the corrected crop coefficient would be 1.21. Following Allen et al., (1998) the maximum crop coefficient for millet under non-advective weather conditions in Maiduguri in August could be up to 1.18. Although the estimated crop coefficient is slightly higher this is probably due to advection in semi-arid conditions.

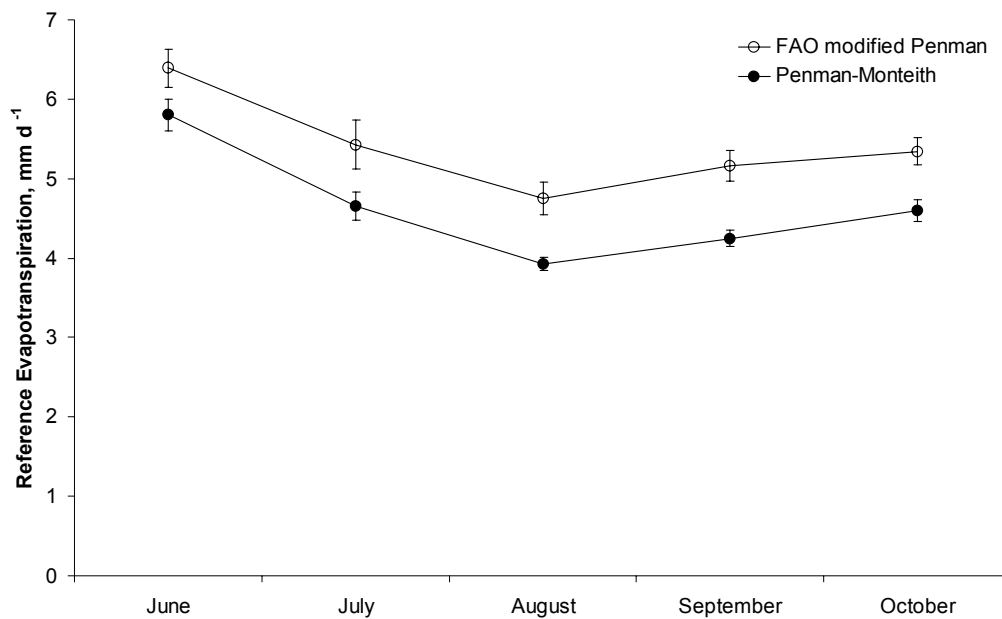


Figure 7-9 Average (1962 – 91) monthly reference evapotranspiration for Maiduguri, Nigeria, calculated by two methods for the growing season months, showing standard errors.

3.1.7. Maximum rooting depth

The maximum root depth for pearl millet in West Africa has been measured between 0.75 m and 1.40 m (Azam-Ali, et al., 1984; Gregory and Reddy, 1982; Payne et al., 1990). As the soil on the experimental site is deep and does not limit root growth, the maximum root depth was taken as 1.3 m.

3.2. Sensitivity and calibration of the model

The comparison between the observed and predicted water contents with the uncalibrated model is shown in Figure 7-10. The model over-estimates the water content in the early part of the season and under-estimates it later. This suggests that soil evaporation is being under-estimated and drainage is over-estimated. The average over-estimate is 15 mm.

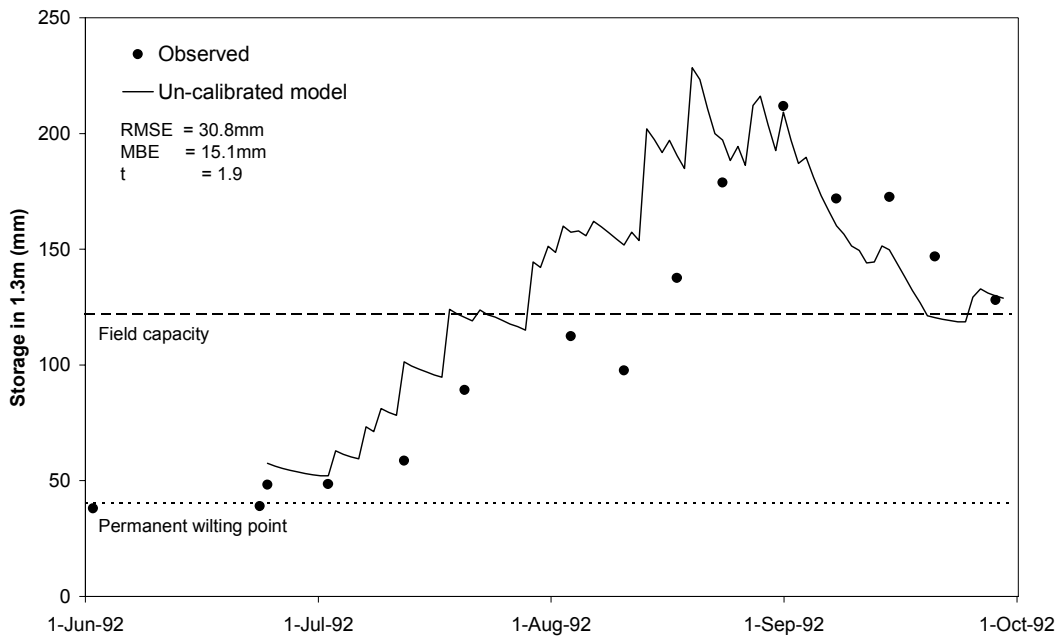


Figure 7-10 Comparison between observed and predicted water contents with the un-calibrated model.

As there are two distinct periods during the season when a) soil evaporation is important and b) drainage is important, the two sets of parameters can be calibrated independently. The soil evaporation parameters were calibrated first. Figure 7-11 shows the sensitivity of RMSE to values of α and U in the bare soil drying model (see 2.1.5 above). There is clearly an interaction as lower values of U can be compensated by higher values of α , however, the model is far more sensitive to U than to α .

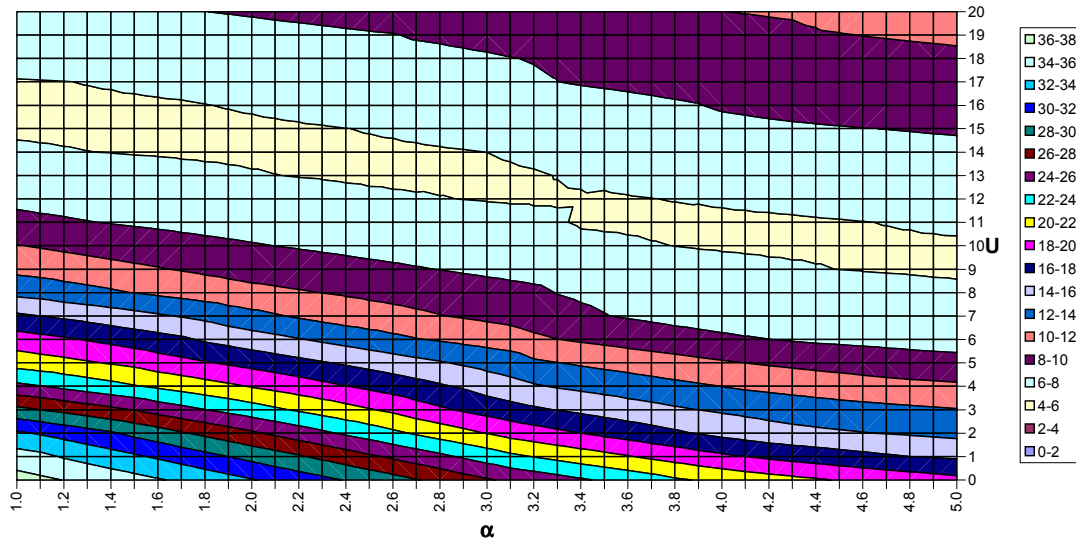


Figure 7-11 Sensitivity of RMSE to values of α and U in the bare soil drying model.

Figure 7-12 shows the sensitivity of RMSE to values of τ and field capacity in the drainage model. Again, there is an interaction as lower values of field capacity can be compensated by higher values of τ .

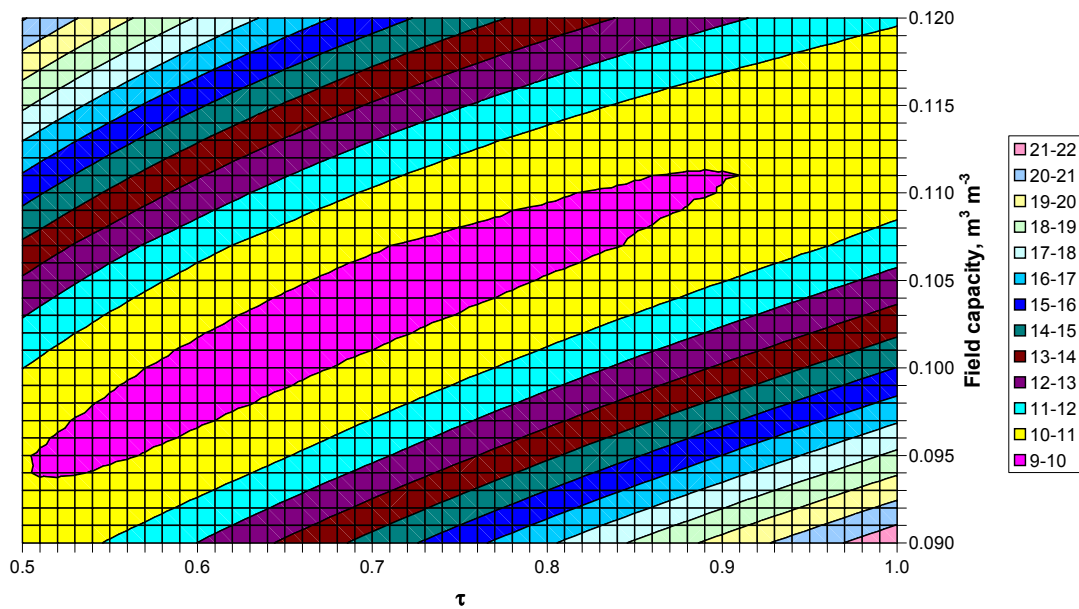


Figure 7-12 Sensitivity of RMSE to values of τ and field capacity in the drainage model.

Finally, α and τ were fixed at 3.3 and 0.7 respectively and the model was optimised for U and field capacity. Figure 7-13 shows that the optimum model fit occurs with values of U and field capacity of 16 and 0.107 respectively.

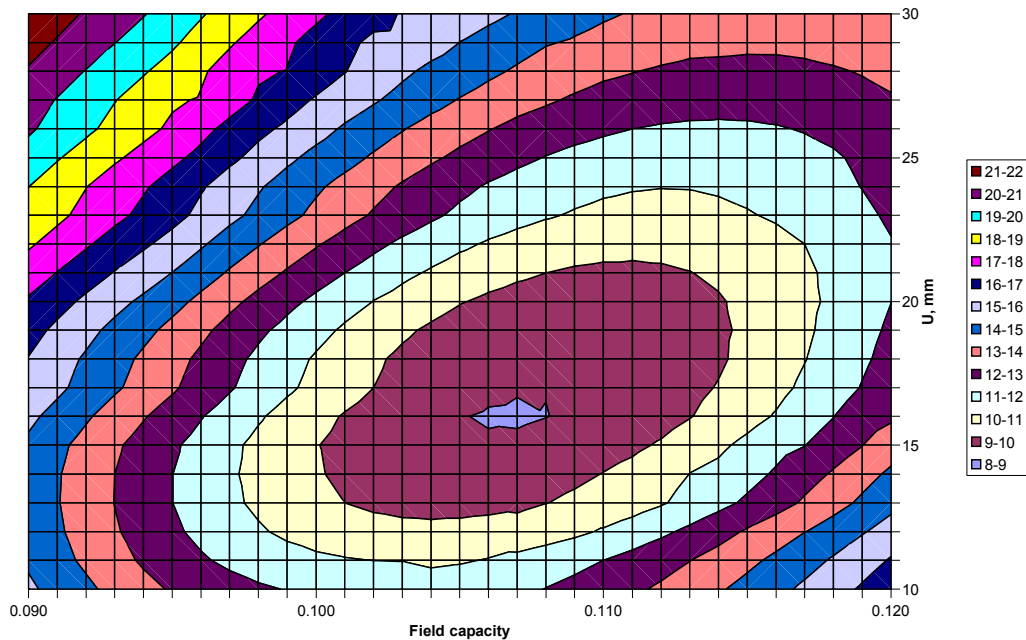


Figure 7-13 Sensitivity of RMSE to values of U and field capacity.

Re-running the model with the calibrated values of the parameters significantly improves the goodness of fit, especially during the early part of the season when bare soil drying is important. The mean bias error is reduced to -0.9 mm.

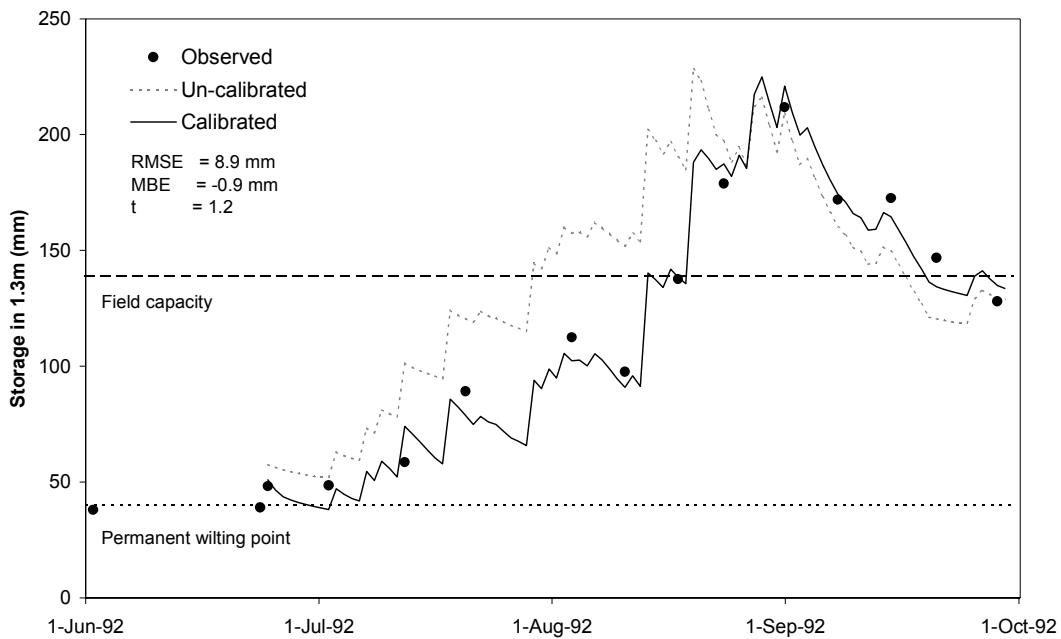


Figure 7-14 Comparison between observed and predicted water contents with the calibrated model showing goodness of fit statistics for the calibrated model (n = 13).

4. DISCUSSION

4.1. Partitioning of evapotranspiration and drainage

Figure 7-15 shows the relationship between the observed and predicted cumulative evapotranspiration and drainage below the root zone for the calibrated model. This demonstrates that there is a close agreement between the observed and predicted soil water storage and also the partitioning of the loss of water from the soil profile into drainage and evapotranspiration.

In the field experiment, no separate measurements of evaporation and transpiration were taken, therefore the validity of the partitioning of evapotranspiration in the model could not be established. However, it may be inferred from the dry matter yield. The dry matter yield can be estimated from (Squire, 1990);

$$W = \epsilon_w D \Sigma_t \tag{5-14}$$

where

W above ground dry matter yield, g m⁻²

ϵ_w is the transpiration efficiency, $\text{g kg}^{-1} \text{kPa}^{-1}$

D daily maximum saturation deficit, kPa

Σ_t transpired water, kg m^{-2}

Furthermore, the transpiration efficiency for pearl millet (expressed in terms of dry matter production per unit saturation deficit per unit of water transpired) has been shown to be quite conservative across a range of environments, and has been estimated at $9.5 \text{ g kPa kg}^{-1}$ (Squire, 1990, p.114). Taking the predicted cumulative transpiration of 176 mm ($= 176 \text{ kg m}^{-2}$) and a mean maximum daily saturation deficit¹⁶ of 2.5 kPa would predict a total above ground dry matter yield of 660 kg m^{-2} . This compares favourably with the observed dry matter yield of 690 kg m^{-2} (Grema & Hess, 1994) and goes some way towards the validation of the partitioning of evapotranspiration.

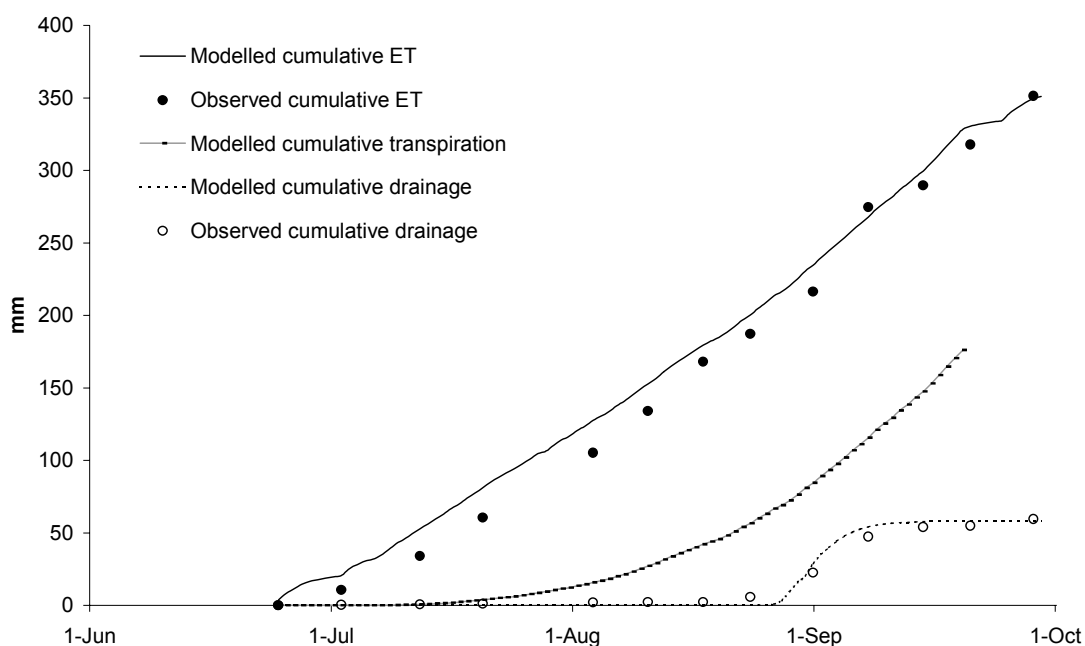


Figure 7-15 Relationship between observed and predicted cumulative evapotranspiration and drainage showing estimated cumulative transpiration.

¹⁶ Average for July – September calculated from the mean daily vapour pressure and the saturation vapour pressure at maximum air temperature.

4.2. Water retention

Table 7.4 shows a comparison between the values determined for θ_{SAT} , θ_{FC} , and θ_{PWP} and those suggested in the BALANCE manual (Hess, 1997). Despite the silt and clay content that would classify the soil as a sandy loam, the water retention properties are closer to the values suggested for a sand textured soil.

Table 7.4. Comparison between BALANCE default and fitted parameters for soil water retention and drainage.

	Texture Class	θ_{sat}	θ_{fc}	θ_{pwp}	AWC mm m ⁻¹	τ
Defaults	Sandy Loam	0.453	0.245	0.095	150	0.37
	Loamy Sand	0.437	0.168	0.055	113	0.51
	Sand	0.437	0.115	0.033	122	0.69
Parameterised		0.429	0.094	0.031	63	0.72
Calibrated		0.429	0.107	0.031	76	0.70

The defaults in BALANCE for saturation and permanent wilting point water contents are based on American soils from Rawls *et al.* (1982). The saturation water content compares well with the observed value as the dry bulk density is typical for soils of this type. There is a large discrepancy with the permanent wilting point water content. The observed value was determined from a disturbed soil sample. However, permanent wilting point is largely a function of soil texture, rather than structure, and should therefore be little affected by disturbance. The lower value was supported by the dry season water contents measured by the neutron probe at depths of >1.0 m shown in Figure 7-4.

The largest difference is with the field capacity water content and this relates to the problems of definition of the term. Figure 7-2 shows that 30 days after initial wetting, the volume water fraction at 0.3 m depth is at 0.11. From the soil water release curve, this is equivalent to a tension of 15 kPa. From a practical point of view, this could be considered to be field capacity and corresponds with the default value for a sand soil. However, the water content is still falling, albeit, slowly, and extrapolating the curve in Figure 7-2 would result in no further drainage at a volume water fraction of 0.094.

Using a field capacity of 0.094 resulted in an over-estimation of drainage, and hence under-estimation of water content in the un-calibrated model. To overcome this the value of field capacity water content had to be increased to 0.107 and the value of τ reduced slightly to 0.70. It may have been that, during the field test outlined in 2.1.2, water was being lost from the measured profile by lateral movement to the dry soil outside of the prepared plot in addition to downward drainage. In terms of water potential, the calibrated field capacity value is equivalent to the water content at 17 kPa, (compared to 18.9 kPa for the parameterised value).

4.3. Soil evaporation

The results of the soil evaporation tests are less satisfactory. Table 7.5 shows that the two field tests generated quite different values for the two parameters.

Table 7.5. Comparison between soil evaporation parameters determined by two field methods and calibrated.

Experiment	U mm	α mm d ^{-0.5}
Micro-lysimeter	0	4.6
Water balance	22	3.3
Calibrated	16	3.3

In the micro-lysimeter test, there appeared to be no energy limited stage. This may be due to the much smaller amounts of water added by natural rainfall (7.5 – 32.1 mm) than added to the water balance experiment (\approx 150 mm). Also, the constant for the supply limited stage 4.6 mm d^{-0.5} is higher than expected. The lower surface water contents inside than outside the micro-lysimeters suggests that the micro-lysimeters may be restricting the upward movement of water, and hence reduce the amount of evaporation. Allen (1990) and Daamen *et al.* (1993), found that micro-lysimeters performed well during rain-free periods, but under-estimated evaporation when rain occurred.

The water balance test was carried out during the dry season. Although this removed the problem of rainfall occurring during the test and gave a long period of uninterrupted drying, it created an artificial situation in the experimental plot.

Although this was well wetted, the surrounding land was dry and there could have been significant advection of energy from the surrounding land. This would account for the evaporation in excess of net radiation during the first, energy-limited stage. The constant for the supply-limited stage, $3.3 \text{ mm d}^{-0.5}$, was close to that observed by other sources.

5. CONCLUSION

The comparison between the calibrated model output and field observations shows that the BALANCE model can provide a good simulation of the soil water balance under a millet crop, grown on a sandy soil in this environment, and correctly partitions the components of the water balance. However, attempts to parameterise components of the model by independent field trials may not be entirely successful.

The study has shown that the model predictions of soil water content are particularly sensitive to the estimation of the field capacity water content and the duration of the first stage of bare soil evaporation.

Although the field capacity value of the soil may be considered as a hydrological parameter, it is more appropriate to think of it as an empirical parameter, which, therefore only has a meaning in the context of the model to which it is being applied. Attempting to calibrate the field capacity value in an artificially wetted soil resulted in an under-estimation of its value. Although the difference was small in terms of water potential, the gradient of the soil water characteristic curve at low suctions (6 – 50 kPa) results in a large difference in volume water fraction. This may have been due to water losses other than by drainage.

Similarly, attempting to parameterise the limit of the first stage of bare soil drying by two methods resulted in quite different results. The micro-lysimeters appeared to under-estimate the rate of bare soil evaporation. The water balance experiment produced results much closer to the calibrated values, but over-estimated evaporation during the energy limited stage, possibly due to advection from surrounding dry soil.

Given the above, it appears that the best way to determine the values for the key parameters is through simultaneous fitting to observed soil water data. By this

method, the following parameter set (Table 7.6) could be used in the BALANCE model to simulate pearl millet grown in a sandy loam soil in North East Nigeria.

Table 7.6. Suggested parameter set for BALANCE to be applied to millet cropping in a sandy soil in the North East Arid Zone of Nigeria.

Parameter	Symbol	Value	Units
Volume water fraction at saturation	θ_{SAT}	0.429	
Volume water fraction at field capacity	θ_{FC}	0.107	
Volume water fraction at permanent wilting point	θ_{PWP}	0.031	
Fraction of total available water that is readily available	p	0.6	
Drainage constant	τ	0.70	
Maximum, cumulative energy-limited soil evaporation	U	16	mm
Constant for supply-limited soil evaporation	α	3.3	mm d ^{-0.5}
Crop coefficient at full cover	Kc	1.21	
Maximum root depth		1.40	m

6. ACKNOWLEDGEMENTS

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7. REFERENCES

- Abdulummin, S. and Misari, S. M., 1990. Crop coefficients of some major crops of the Nigerian semi-arid tropics. *Agricultural Water Management* 18:159-171.
- Adams J. E., Arkin, G. F. and Ritchie, J. T., 1976. Influence of row spacing and straw mulch on first stage drying. *Soil Sci. Soc. Am. J.* 40:436-442
- Allen S. J., 1990. Measurement and estimation of evaporation from soil under sparse barley crops in Northern Syria *Agric. For. Met.* 49:291-309
- Allen, R. G., Smith, M., Perrier, A. and Pereira, L. S., 1994. An update for the definition of reference evapotranspiration. *ICID Bulletin*, 43: 1-34.
- Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper 56*. FAO, Rome. pp300.

- Arkin G. F., Ritchie, J. T. and Adams, J. E., 1974. A method for measuring first-stage soil water evaporation in the field *Soil Sci. Soc. Am. Proc.* 38:951-954
- Azam-Ali, S.N., Gregory, P.J. and Monteith, J.L. 1984. Effects of plating density on water use and productivity of pearl millet (*Pennisetum typhoides*) grown on stored water. I. Growth of roots and shoots. *Experimental Agriculture.* 20:213-204.
- Black T. A., Gardner, W. R. and Thurtell, G. W., 1969. The prediction of evaporation, drainage and soil water storage for a bare soil. *Soil. Sci. Soc. Am. Proc.* 33:655-660
- Boast C. W. and Robertson, T. M., 1982. A 'micro-lysimeter' method for determining evaporation from bare soil: Description and laboratory evaluation. *Soil Sci. Soc. Am. J.* 46:689-696
- Boesten J. J. T. I. and Stroosnijder, L., 1986. Simple model for daily evaporation from fallow tilled soil under spring conditions in a temperate climate. *Netherlands J of Agric. Sci.* 34:75-90
- British Standards Institution, 1990. British standard methods of test for soils for civil engineering purposes. Part 2. Classification tests. BSI, London.
- Daamen, C. C., Simmonds, L. P., Wallace, J. S., Laryea, K. B. and Sivakumar, M. V. K. 1993. Use of microlysimeters to measure evaporation from sandy soils. *Agricultural and Forest Meteorology* 65:159-173.
- Dancette C. and Hall, A. E., 1979. Agroclimatology applied to water management in the Sudanian and Sahelian zones of Africa. *Ecological Studies* 34:98-118
- Doorenbos, J. and Pruitt, W.O., 1977. Crop water requirements. FAO irrigation and drainage paper 24. FAO. Rome.
- Folorunso, O. A., 1986. Distribution of field measured steady state infiltration rate for Borno State soil. *Annals of Borno (Maiduguri)* 3:193-204.

- Gregory, P.J. and Reddy, M.S. 1982. Root growth in an intercrop of pearl millet / groundnut. *Field Crops Research*, 5:241-252.
- Grema, A.K. and Hess, T.M., 1994. Water balance and water use of pearl millet-cowpea intercrops in north east Nigeria. *Agricultural Water Management* 26:169-185.
- Grema, A.K., 1994. Productivity of pearl millet-cowpea intercrops in North-East Nigeria. Unpublished PhD thesis. Silsoe College, Cranfield University, UK.
- Hess, T. M., 1997. BALANCE – A soil water balance model. Unpublished, Silsoe College, Cranfield University, UK.
- Hess, T. M., 1998. Trends in reference evapo-transpiration in the North East Arid Zone of Nigeria, 1961–91. *Journal of Arid Environments*, 83:99-115.
- Jacovides, C. P. and Kontoyiannis, H., 1995. Statistical procedures for the evaluation of evapotranspiration computing models. *Agricultural Water Management*, 365-371.
- Kassam, A. H. and Kowal, J. M., 1975. Water use, energy balance and growth of gero millet at Samaru, Northern Nigeria. *Agricultural Meteorology*, 15:333-342.
- Landon, J. R., 1991. (ed.) Booker tropical soil manual. Longman Scientific and technical, Harlow.
- Lascano R. J. and van Bavel, C. H. M., 1986. Simulation and measurement of evaporation from a bare soil *Soil Sci. Soc. Am. J.* 50:1127-1133
- Martin D. L., Klocke, N. L. and DeHaan, D. L., 1985. Measuring evaporation using mini-lysimeters. In *Advances in evapotranspiration. Proc. of a conference at Chicago, IL. Am. Soc. Agric. Eng., St. Joseph, MI*, pp231-240.
- Nachabe, M. H., 1998. Refining the definition of field capacity in the literature. *Journal of Irrigation and Drainage Engineering*, 124:230-232.

- Payne, W.A., Wendt, C.W. and Lascano, R.J. 1990. Root zone water balances of three low-input millet fields in Niger, West Africa. *Agronomy Journal* 82:813-819.
- Rawls, W J, Brakensiek D L and Saxton K E 1982. Estimation of soil water properties. *Trans. ASAE* 25:1316-1320
- Rayar, A. J., 1984. University of Maiduguri farm development planning report for Faculty of Agriculture, Annex A; Soil survey details. Unpublished. University of Maiduguri.
- Ritchie J. T., 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Res.*, 8:1204-1213.
- Rockström, J., Jansson, P. E. and Barron, J., 1998. Seasonal rainfall partitioning under runoff and runoff conditions on sandy soil in Niger. On-farm measurements and water-balance modelling. *Journal of Hydrology*, 210:68-92.
- Shawcroft R. W. and Gardner, H. R. 1983. Direct evaporation from soil under a row crop canopy. *Agric. meteorol.* 28:229-238.
- Squire, G.R., 1990. *The physiology of tropical crop production*. C.A.B International, Wallingford, UK.
- Stroosnijder L., 1987. Soil evaporation: test of a practical approach under semi-arid conditions. *Netherlands J. of Agric. Sci.* 35:417-426.
- Villalobos F. J. and Fereres, E., 1990. Evaporation measurement beneath corn, cotton and sunflower canopies. *Agron. J.* 82:1153-1159
- Walker G. K., 1983. Measurement of evaporation from soil beneath crop canopies. *Can. J. Soil Sci.* 63:137-141
- Walker G. K., 1984. Evaporation from wet soil surfaces beneath plant canopies. *Agric. For. Met.* 33:259-264

Appendix I

Neutron probe calibration check

The validity of the manufacturer's calibration was checked against gravimetrically determined water contents. Two sets of data were used.

Firstly, neutron probe readings were routinely taken at 0.20m depth and the calculated volume water fractions were compared with the mean of gravimetric samples at 0.15 and 0.25 m depth converted to a volumetric water content using a dry bulk density of 1.41 g cm^{-3} . This is more realistic than comparison with a single point from 0.2 m depth as the neutron probe gives an average reading of a layer of soil, rather than a point reading. The results are shown in Figure 7-16. A paired t-test was carried out on the measured (gravimetric) water content and the water content measured by the neutron probe with the standard calibration equation. The probability of $P = 0.12$ implies no significant difference between the two sets of data.

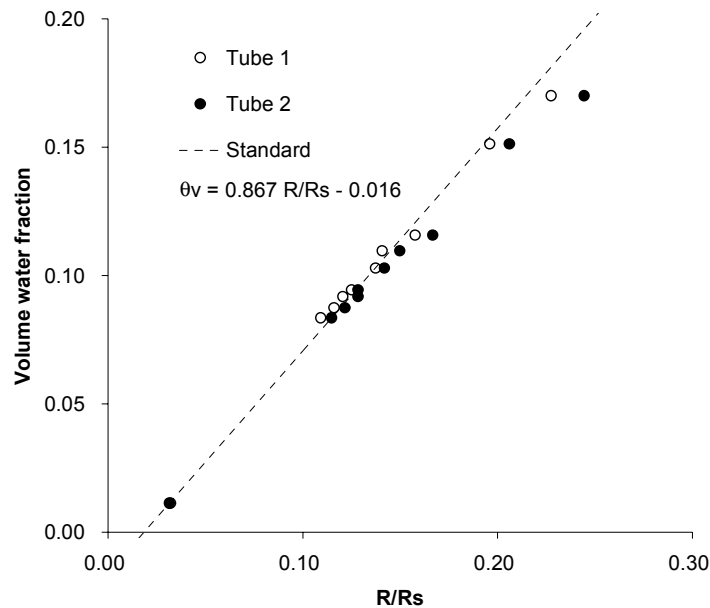


Figure 7-16 Neutron probe calibration check at 20cm

Secondly, on three occasions, neutron probe readings were taken at 0.2 m depth intervals and a layer of more or less constant water content was identified. Five 64 s readings were taken at this depth, then the soil was excavated to the same depth and five samples were taken for gravimetric determination. The results are shown in

Figure 7-17. The wide variability of the gravimetric results demonstrates the sensitivity of this method to sampling error and precise depth determination. However, the best-fit line is not significantly different from the 1:1 line, confirming that the manufacturer's calibration equation is suitable.

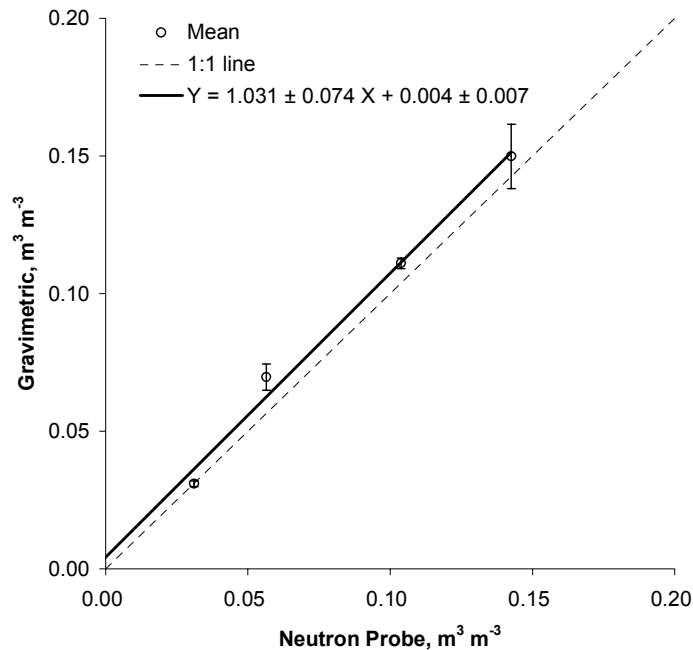


Figure 7-17 Neutron probe calibration check at >0.2 m.

Both sets of data show close agreement between the neutron probe readings and the gravimetric results suggesting no reason to reject the manufacturer's calibration. This equation will continue to be used.

References

British Standards Institution (1996) BS 7755 / ISO 10573 Soil quality. Part 5. Physical methods. Section 5.2 Determination of water content in the unsaturated zone – neutron depth probe method. British Standards Institution, London.

CHAPTER EIGHT. THE IMPACT OF CHANGING RAINFALL PATTERNS ON THE EFFICIENCY OF RAINFALL UTILISATION IN MILLET AND MILLET-COWPEA FARMING SYSTEMS IN N E NIGERIA¹⁷

1. INTRODUCTION

The North East Arid Zone of Nigeria comprises the northern parts of Yobe and Borno States between 12° N and the Niger border. Within the floodplain of the Yobe River (*fadama*), the farming systems can utilise the seasonal flood water or shallow groundwater for irrigation, however, in the uplands, agriculture is predominantly rain fed.

The uplands (*tudu*) are characterised by hummocky sand plains formed on relic sand dunes. The soils developed on these deposits are deep and very sandy. The rainfall regime is characterised by a single peak; the rainy season starting in May, reaching a maximum in August, and finishing quite abruptly in September / October. The rest of the year is virtually dry. Mean annual rainfall is highest (over 650 mm) in the South West and lowest in the North East (less than 350 mm) where the length of the growing season is correspondingly shorter. However, there is considerable year-to-year variability in rainfall amount and successful cropping requires the efficient utilisation of the limited rainfall.

1.1. Upland cropping systems

The traditional staple food crop of the area is pearl millet (*Pennisetum typhoides* (S&H)) which is grown as a rain fed crop in many semi-arid regions, and is the most important crop in the Sahel south of the 250mm isohyet. It is grown extensively throughout the uplands of the North East Arid Zone. It grows well in dry areas with low relative humidities and will germinate with less moisture than almost any other

¹⁷ This chapter is based on a re-working of a paper published as Hess, T M and Grema, A K (1994) The impact of changing rainfall patterns on the efficiency of rainfall utilisation in pearl millet - cowpea intercropping system in N E Nigeria. Aspects of Applied Biology 38:231-238.

crop. It requires light, but evenly distributed rain through the growing season as it cannot remain dormant during drought (Purseglove, 1972). It does well in loams and sandy soils but cannot tolerate waterlogging.

There are two main types of millet grown in the North East Arid Zone: Maiwa millet is a long season (120 -180 days), photoperiodic crop; Gero millet is a short season (75 - 100 days), non-photoperiodic crop. Gero millet is usually rain fed and in W Africa is grown south of the 200 - 250 mm/year isohyet. In the North East Arid Zone it is generally preferred as it is less susceptible to drought than the longer duration Maiwa millet and thrives best on the light soils. Most local varieties are short season (40 - 100 days) Gero millets, which are planted at a low density (2 - 3 plants per hill and hills spaced approximately 1m x 1m). Planting takes place soon after the beginning of the rains and the crop matures around the time of the end of the rains.

Nearly all Gero millet in the savanna is grown in mixtures with other crops, especially cowpea (*Vigna unguiculata* L. (Walp)) (Kowal and Kassam, 1978) which is the main cash crop of the area. The cowpea is grown both for its seeds, which are used for human consumption, and for its leaves, which are used as fodder for livestock. It is quick growing, nitrogen fixing and drought tolerant. Cultivars of cowpea vary in maturity between 60 and 100 days and short season varieties can often be grown on residual soil moisture. Cowpea requires bright, sunny weather during maturing. Cowpeas can extract water from up to 1m and there is a linear relationship between water use and total dry matter production. Water use efficiency is improved by moderate deficits during the vegetative stage, and too much water tends to reduce the proportion of dry matter partitioned to seed (Pandey and Ngarm, 1985).

Locally, the cowpea is sown as an intercrop between millet rows, two to six weeks after the establishment of the millet (Grema, 1994). Local cowpea cultivars (e.g. cv. *Borno Local*, '40 days', *Yarkaraduwa* (erect) and *Kananado* (early maturing)) are generally photoperiod sensitive, spreading and late maturing. They are therefore adapted to the lower light intensities in intercrops (Kowal and Kassam, 1978) and mature up to one month after the millet harvest.

Yields of cowpea grown as intercrops are considerably reduced compared to sole crops due to shading by the millet. Tests carried out by IITA and ICRISAT (Niger) show that cowpea and millet yields in intercrops are partly dependant on cowpea plant type. Early maturing (60 - 70 days) cowpea varieties showed less reduction in millet yields, however, a medium maturing variety (80 - 90 days) produced higher cowpea grain and fodder yields (Ntare, 1989). Early planting of the cowpea produces higher yields, but conflicts with labour requirement for the millet (Muleba and Ezumah, 1985). The cowpea is generally grown as a *bonus* in addition to the staple millet crop. When the rainfall is average or above, sufficient residual moisture remains in the soil after the millet harvest to support the production of both seeds for human consumption and fodder for livestock. However when the rains are poor, the cowpea may run short of water before the seeds develop and it may produce only fodder (Grema, 1994).

1.2. Intercropping and water conservation

Intercropping has been shown to provide many benefits to the farmer over sole cropping in terms of efficiency of utilisation of land and labour (Kowal and Kassam, 1978), however it also ensures more efficient use of rainfall. Studies in Niger (Sivakumar and Wallace, 1991; Rockström, et al., 1998) have found that in an average year in widely spaced millet systems, soil evaporation accounts for 30% - 50% of the annual rainfall. As dry matter production is related to transpiration only, this could be considered unproductive use of rainfall. Studies of the water balance of intercropping systems (Natarajan and Willey, 1986; Grema and Hess, 1994) have shown that an intercrop can use water that would otherwise have been lost by soil evaporation. The presence of the cowpea between the millet rows, therefore, does not significantly increase the total water use of the system. The traditional upland millet-cowpea intercropping system has evolved in such a way as to make efficient use of the limited rainfall.

Over the period 1961 – 90, there has been an unpredictable, yet significant decline of 8 mm year⁻¹ in the mean annual rainfall (Hess, et al., 1995). In the latter years, local farmers observed that the traditional cowpea cultivars grown as intercrops performed less well than expected. It is the objective of this paper to explore, through agro-

climatic modelling, the extent to which changing rainfall patterns have affected the viability of the traditional millet and millet-cowpea intercropping systems.

2. MATERIALS AND METHODS

2.1. Water balance modelling

In the absence of long term monitoring, the impact of the recorded change in rainfall regime can only be assessed by modelling the soil water balance. The daily root zone soil water balance, for a freely draining upland soil can be written as;

$$\Delta S = P - E - T - D - R_o$$

where

ΔS change on soil water content

P precipitation

E evaporation from bare soil

T plant transpiration

D drainage below the root zone

R_o net runoff

Precipitation is generally measured and available for a long time series. More problematic is the estimation of evaporation and transpiration. Three main approaches have been use to model the evapotranspiration from sparse vegetation in arid environments from meteorological data (Wallace, 1991):

- a) The use of empirical crop factors to relate reference or potential evapotranspiration to actual evapotranspiration (e.g. Agnew, 1991). This method is difficult to apply due to the difficulty in defining crop factors especially in the early stages of crop development when actual evapotranspiration is dominated by soil evaporation (Wallace, et al., 1993).
- b) Models that attempt to partition crop transpiration from soil evaporation and model each separately (e.g. Ritchie, 1972). A major advantage of such a model over the simple crop factor models (Wallace, et al., 1993), is that they can be used to estimate crop yield which is more closely related to transpiration than evapotranspiration.

- c) Separate models of crop transpiration and soil evaporation (e.g. Rockström, et al., 1998) and those that allow for the interaction between the two (e.g. Shuttleworth and Wallace, 1985). These require a detailed knowledge of the resistances to evaporation at the leaf and the soil surface.

Drainage cannot generally be measured, but has to be modelled from root zone soil water content. Runoff may be significant on sloping land where no water conservation measures are used. To accurately simulate runoff, rainfall data are required at a high temporal resolution, however, often, only daily rainfall data are available. Daily runoff can be estimated using the US NRCS 'Curve Number' method (USDA, 1986).

2.2. Application of the model

The BALANCE model (see Chapter Six) was used to simulate the daily soil water balance. The model was parameterised and calibrated for a typical upland soil and an 88 day Gero millet (see Chapter Seven). The calibrated water balance model was run for the growing seasons from 1961 to 1993 to estimate:

- a) the partitioning of annual rainfall into plant transpiration, bare soil evaporation, runoff and drainage;
- b) the seasonal plant transpiration from a millet crop; and,
- c) the depth of residual available water at the time of the millet harvest (residual storage); and subsequent rainfall until the end of October (late rainfall). The sum of these two represents water that could be used by the intercropped cowpea (available water).

Daily rainfall data from the meteorological station at Nguru (12.53 °N, 10.28 °E, alt. 343 m) were used for the simulation. During that period there were few months when all the parameters necessary to calculate ETo were recorded. Over the period 1961 – 90 there has been no significant trend in reference evapotranspiration at Nguru (Hess, 1998), therefore, long-term average monthly means of temperature, humidity, wind speed and sunshine duration were used to calculate mean daily ETo for each month. Linear interpolation was used to estimate average daily ET_o, ensuring that the mean

of the daily values was equivalent to the monthly means. The soil water content on 1st June each year was assumed to be at permanent wilting point.

An appropriate ‘curve number’ for a row crop, grown on a sandy soil in straight rows and poor hydrologic condition was chosen from USDA (1986) for the simulation of daily runoff in the BALANCE model.

The planting of the millet crop is dependent upon the rainfall distribution in a given year. Local practice is to plant when sufficient rain has fallen to wet the topsoil to the ‘the width of a hand’ (say ≈100mm). In the model, planting was triggered when the water content of the topsoil layer had reached a critical level, θ_{crit} . Where,

$$\theta_{crit} = 100\text{mm} \times \text{the volume water fraction at field capacity} = 10.7\text{mm}$$

Subsequent ground cover and root development rates were taken to be constant each year.

3. RESULTS

3.1. Partitioning of rainfall

Table 8.1 shows the predicted partitioning of annual rainfall into the various components of the water balance.

Table 8.1. Predicted partitioning of annual rainfall for Nguru for the years 1961 – 1993.

	Soil Evaporation	Transpiration	Drainage	Runoff	Water remaining at 31 December
Lowest	39%	14%	0%	0%	0%
Mean	52%	42%	1%	1%	3%
Highest	85%	58%	10%	5%	13%

The predicted partitioning of seasonal rainfall into its water balance components suggests an increased proportion directed to crop transpiration, and a concomitant lower proportion being lost to drainage and runoff than has been measured in some trials in the Sahel. Rockström, et al. (1998), for example, estimated plant transpiration at only 4 – 9% of annual rainfall over three years in Niger (with rainfall

between 488 – 596 mm year⁻¹). The difference may be due to the high degree of soil crusting in the Niger trials, which resulted in significantly greater runoff (25 – 30% of annual rainfall) than was predicted in the present study (0 – 5% of annual rainfall).

3.1.1. Transpiration and evaporation

The primary consumption of water is in evapotranspiration which can itself be partitioned into plant transpiration and soil evaporation.

Ninety-two percent of the variation in annual crop transpiration could be explained by seasonal rainfall (Figure 8-1). In years with more than 500 mm of rainfall during the growing season, total transpiration remains stable suggesting that this is the minimum rainfall required for maximum millet transpiration. With less rainfall, annual transpiration reduces. Soil evaporation is less affected by the amount of rainfall and only 61% of the variation could be explained by rainfall. The proportion of total rainfall that is lost to soil evaporation is, therefore, inversely related to the seasonal rainfall total (Figure 8-2).

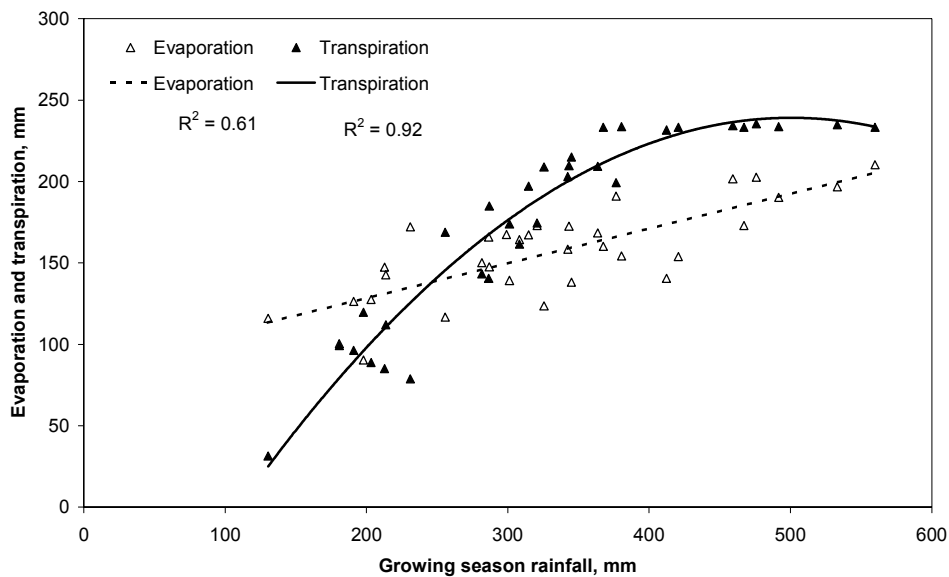


Figure 8-1 Predicted relationship between growing season (planting – harvest) rainfall and crop transpiration and soil evaporation for Nguru, 1961 to 1993.

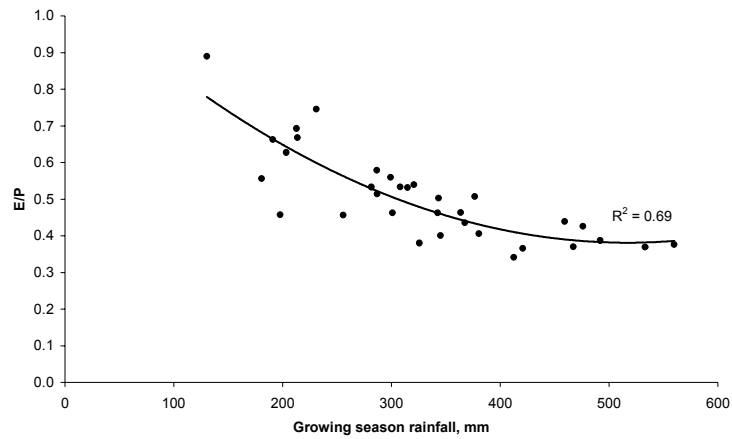


Figure 8-2 Predicted relationship between the ratio of soil evaporation (E) to rainfall (P) during the growing season

3.1.2. Drainage, residual moisture and runoff

With less than 400 mm seasonal rainfall, there is negligible runoff, drainage of water below the root zone or residual water remaining in the soil profile (Figure 8-3). All the rainfall is utilised by evapotranspiration. With extra rainfall, drainage, residual soil water and runoff increase in a similar manner.

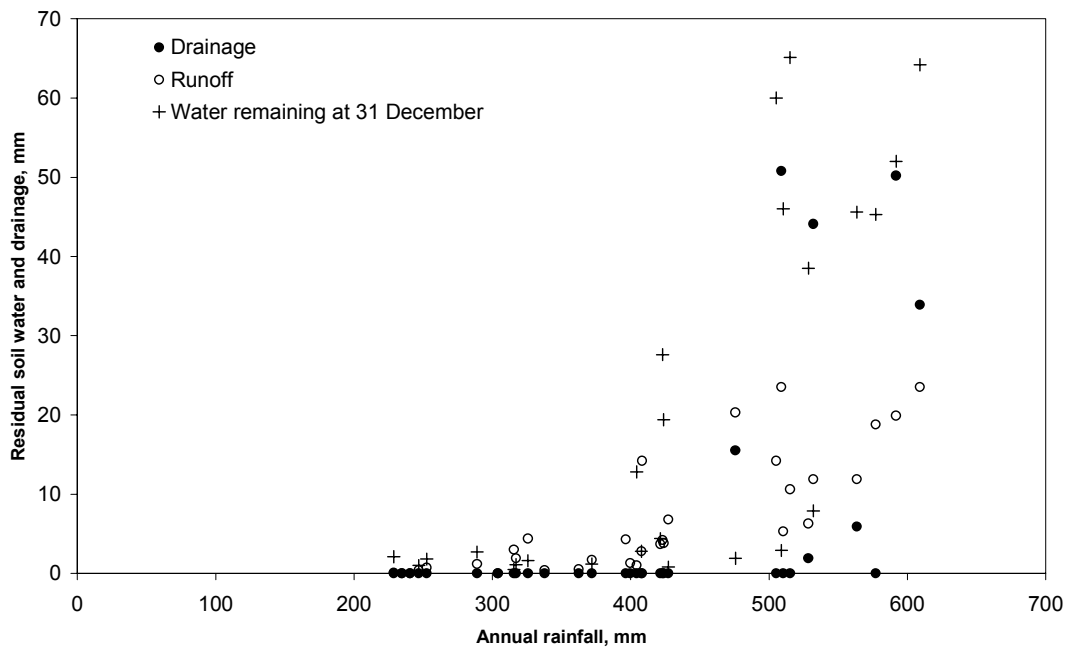


Figure 8-3 Predicted relationship between annual rainfall and crop drainage and residual soil water for Nguru, 1961 to 1993.

Total drainage ranges from zero in a dry year to a maximum of 10% of annual rainfall and runoff ranges from zero to 5%.

The water remaining at 31 December ranges from zero to 13%. Although the model would predict that this moisture would remain in the root zone until the following season, observations in the field¹⁸ suggest that this moisture would be lost before the onset of the rains. Whether this is by continued, slow drainage (despite the soil being drier than field capacity) or soil evaporation is unsure.

3.2. Trends in the partitioning of rainfall

Over the period 1961 – 1993, annual rainfall ranged from 229 mm (1972) to 609 mm (1961) and there has been a general decline in the seasonal total that has been particularly pronounced since 1980. Comparing 1961 – 80 with 1981 – 93, average annual rainfall has fallen by 29% ($p < 0.01$).

Figure 8-4 shows the predicted partitioning of the seasonal rainfall into soil evaporation, crop transpiration, drainage below the root zone and residual storage (at 31 December) for upland millet systems in Nguru for the period 1961 to 1993.

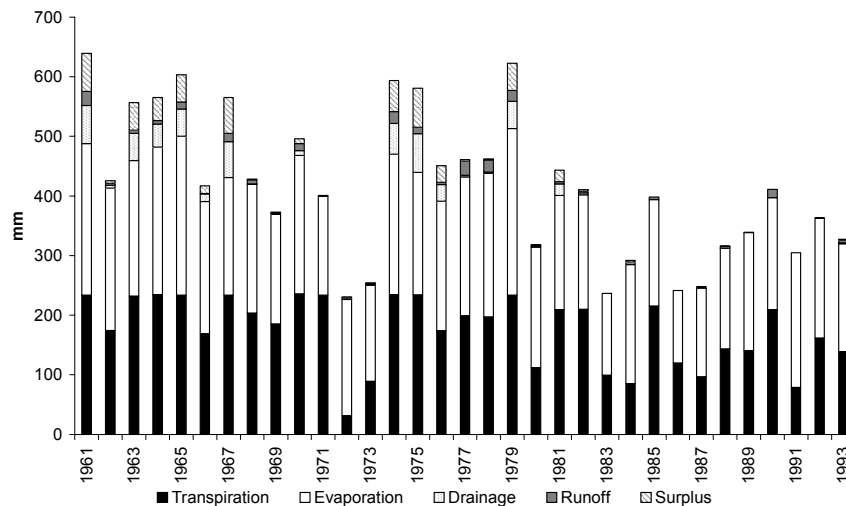


Figure 8-4 Predicted evaporation, transpiration, drainage, runoff and residual storage (at 31 December) for Nguru, 1961 to 1993.

¹⁸ Augering to 5m before the onset of the rains in 1991 found the entire profile to be at permanent wilting point despite high rainfall on fallow land in the previous season. Similar observations were made in Niger (C Daamen, pers. comm.).

Prior to the early 1980s the predicted crop transpiration remained fairly stable (with the exception of notable drought years such as 1972 and 1973). Since then, there has been a decline in transpiration of 24% ($p = 0.02$). Soil evaporation has not changed significantly and total evapotranspiration has fallen by 18% ($p = 0.02$) (Table 8.2).

Table 8.2. Predicted average crop transpiration, soil evaporation and total evapotranspiration, 1961 – 1980 and 1981 – 1993.

Period	Crop transpiration (T) mm/season	Soil evaporation (E) mm/season	Evapotranspiration (ET) mm/season
pre-1981	194	163	357
post 1980	147	145	292
P =	0.02	0.09	0.02
Reduction %	24%		18%

4. DISCUSSION

4.1. Impact of rainfall trends on farming systems

4.1.1. *Millet cropping*

Years with low rainfall are associated with reduced rainfall totals and a reduction in the number of rain days in the middle of the rainy season (i.e. August) (Hess, et al., 1995; Tarhule and Woo, 1998). Tarhule and Woo (1998) suggested that rain-fed farming systems may have been relatively unaffected by the decline in seasonal rainfall total. However, given the close linear correlation between crop transpiration and dry matter yield (Squire, 1990) the modelled reduction in crop transpiration suggests that since 1981 crop yields may also have declined by 24%. It is likely that the longer intervals between rain days has meant that the crop has increasingly run short of water during the mid-season growth stage when potential water use is at its maximum.

The reduction in soil evaporation is insignificant ($p > 0.05$). At this time the millet crop is at its maximum ground cover and soil evaporation is at its lowest due to shading from the millet crop. The reduction in rainfall has therefore reduced the

availability of water to the millet crop, but has had little impact on the bare soil evaporation.

4.1.2. Potential for cowpea intercrops

The water use of sole and intercropped systems is similar, therefore, although the model simulated a sole millet crop, the results could also be applied to intercropped situations up to the time of millet harvest.

The traditional long-duration cowpea varieties rely on residual soil moisture and rainfall after the millet harvest in order to mature. Figure 8-5 shows the annual series of available residual soil moisture at the time of the millet harvest and rainfall after harvest that could be utilised by a cowpea intercrop. Over the time period under consideration there was an increase in the proportion of rainfall used by evapotranspiration during the millet growing season, whilst the proportion available for use by the cowpea after the millet harvest (residual storage and late rain) has fallen.

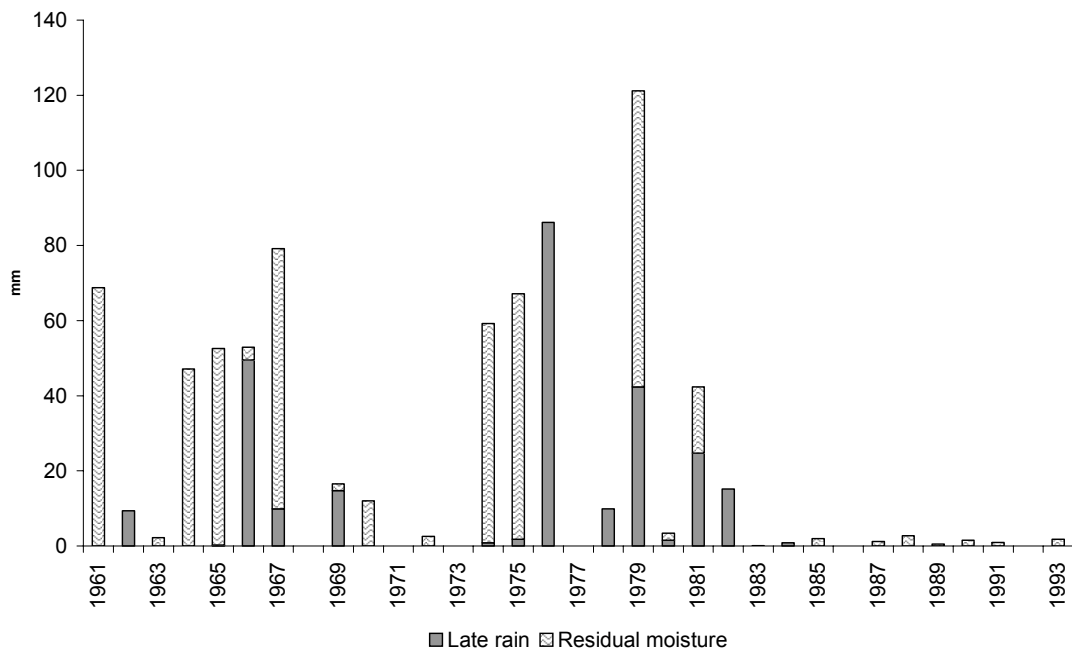


Figure 8-5 Predicted late rain and residual soil moisture for Nguru, 1961 to 1993.

Although the timing of the end of the rains has not changed significantly low rainfall years are associated with a later onset and reduced mid-season rainfall (Hess et al., 1995). Therefore the millet harvest is generally later in drier years and the millet consumes most of the available soil water up to harvest. Prior to 1983 there was late rainfall or residual soil moisture in most years that would have contributed towards a cowpea crop, however, since that date, there has been no available water after the millet harvest.

5. CONCLUSION

The traditional system of growing a long duration cowpea as an intercrop with pearl millet has been an effective way of increasing the efficiency of utilisation of limited rainfall in the North East Arid Zone of Nigeria by a) substituting cowpea transpiration for non-productive soil evaporation and b) utilising water remaining in the soil profile after the millet harvest for the maturing of the cowpea. This system ensures that priority is given to the staple millet crop, with the opportunity of producing cowpea fodder and in wetter years, seed. However, over the period 1961 to 1993, the region has suffered a significant decline in the annual rainfall.

The predicted reduction in millet water use of 24% since 1980, is likely to have led to a similar reduction in millet yields, however, the trends in rainfall will have had a major impact on the amount of water available to the intercropped cowpea crop after the millet harvest. Prior to 1980, there was frequently sufficient water remaining after the millet harvest, in addition to late rain, to produce useful yields of cowpea, however, from 1981 to 1993 this has rarely been the case.

This analysis has been based on the assumption that the water use from an intercropped system is equivalent to that of a sole millet crop. Whilst this has been shown to be the case in wetter years, it may not hold true in the drier years. As the main characteristic of the change in rainfall regime has been a reduction of mid-season rainfall, the high millet canopy cover at that time would mean that both soil evaporation or cowpea transpiration would be low and therefore the total water use should be similar for sole or intercropped systems.

If the rainfall patterns of the 1980s persist, then the traditional, long duration cowpea cultivars may no longer be appropriate to the region and attention should be given to

new, short season cultivars which mature around the same time as the millet (at the end of the rains). This would still make effective use of the rainfall during the rainy season, but would not be reliant upon a surplus remaining after the millet harvest.

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7. REFERENCES

- Agnew, C. 1991. Evaluation of a soil water balance model for the analysis of agricultural drought in the Sahel. In Sivakumar M V K, Wallace J S, Renard C, Giroux C (eds) (1991) Soil water balance in the Sudano-Sahelian zone. (Proc. Int. Workshop, Niamey, Niger, February 1991). IAHS Bull. no. 199. IAHS Press, Institute of Hydrology, Wallingford, UK.
- Chiroma, A. M. (1996) The farming system of Futchimiram, Yobe State, Nigeria. Soils, cultivars and livelihoods in North East Nigeria. Working Paper No. 4. Department of Geography, University of Cambridge UK / Bayero University Kano, Nigeria. Unpublished.
- Grema, A. K., 1994. Productivity of pearl millet-cowpea intercrops in north-east Nigeria. PhD thesis. Cranfield University, Silsoe College, UK. Unpublished.
- Grema, A. K., Hess, T. M., 1994. Water balance and water use of pearl millet-cowpea intercrops in North East Nigeria. Agricultural Water Management.
- Hess, T. M., William Stephens, Maryah, U. M., 1995. Rainfall trends in the North East Arid Zone of Nigeria 1961 - 1990. Agricultural and Forestry Meteorology.
- Hess, T. M., 1998. Trends in reference evapo-transpiration in the North East Arid Zone of Nigeria, 1961-91. Journal of Arid Environments. 38: 99-115.
- Kanamasu, E. T., Singh, P. and Chaudhuri, U. N., 1984. Water use and water-use efficiency of pearl millet and sorghum. In, Virmani, S.M. and Sivakumar, M. V. K., Eds. Agrometeorology of sorghum and millet in the semi-arid tropics:

- Proceedings of the international symposium, 15-20 Nov. 1982. ICRISAT Centre, Patancheru, A.P. 502324, India: ICRISAT. p175 – 181.
- Kowal, J. M. and Kassam, A. H., 1978. *Agricultural ecology of savanna*. Oxford University Press, Oxford
- Muleba, N. and Ezumah, H. C., 1985. Optimizing cultural practices for cowpea in Africa. In Singh, S. R. and Rachie, K. O. (eds). *Cowpea research, production and utilisation*. John Wiley & sons, Chichester, UK. pp289-295.
- Natarajan, M, and Willey, R. W., 1980. The effects of water stress on yield advantages of intercropping systems. *Field crops research*. 13:117-131.
- Ntare, B. R., 1989. Intercropping cowpeas with millet. *IITA research briefs* 9(4):5.
- Pandey, R. K. and Ngarm, A. T., 1985. Agronomic research advances in Asia. In Singh, S. R. and Rachie, K. O. (eds). *Cowpea research, production and utilisation*. John Wiley & sons, Chichester, UK. pp 297-306
- Purseglove, J. W., 1972. *Tropical Crops – Monocotyledons*. Longman Scientific & Technical, Harlow.
- Ritchie, J. T., 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Res.*, 8:1204-1213.
- Rockström, J., Jansson, P. E. and Barron, J., 1998. Seasonal rainfall partitioning under runoff and runoff conditions on sandy soil in Niger. On-farm measurements and water-balance modelling. *Journal of Hydrology*, 210:68-92.
- Shuttleworth, W. J. and Wallace, J. S., 1985. Evaporation from sparse crops – an energy combination theory. *Quarterly Journal of the Royal Meteorological Society*, 111:839-855.
- Sivakumar, M. V. K. and Wallace, J. S., 1991. Soil water balance in the Sudano-Sahelian zone: need, relevance and objectives of the workshop. In Sivakumar M V K, Wallace J S, Renard C, Giroux C (eds) (1991) *Soil water balance in*

the Sudano-Sahelian zone. (Proc. Int. Workshop, Niamey, Niger, February 1991). IAHS Bull. no. 199. IAHS Press, Institute of Hydrology, Wallingford, UK.

Squire, G. R., 1990. The physiology of tropical crop production. CAB International, Wallingford, UK.

Tarhule, A. and Woo, M-K., (1998) Changes in rainfall characteristics in Northern Nigeria. *International Journal of Climatology*. 18:1261-1271.

United States Department of Agriculture, Natural Resources Conservation Service. 1986. National Engineering Handbook. Second edition. June, 1986. U.S. Government Printing Office.

Wallace, J. S., 1991. The measurement and modelling of evaporation from semiarid land. In Sivakumar M V K, Wallace J S, Renard C, Giroux C (eds) (1991) Soil water balance in the Sudano-Sahelian zone. (Proc. Int. Workshop, Niamey, Niger, February 1991). IAHS Bull. no. 199. IAHS Press, Institute of Hydrology, Wallingford, UK.

Wallace, J. S., Lloyd, C. R. and Sivakumar, M. V. K., 1993. Measurements of soil, plant and total evaporation from millet in Niger. *Agricultural and Forest Meteorology*, 63:149-169.

CHAPTER NINE. THE IMPACT OF CLIMATIC VARIABILITY OVER THE PERIOD 1961- 1990 ON THE SOIL WATER BALANCE OF UPLAND SOILS IN THE NORTH EAST ARID ZONE OF NIGERIA

1. CLIMATIC VARIABILITY

The most significant change in the climate of the North East Arid Zone of Nigeria over the period 1961 – 90, has been a decline in annual rainfall totals. Although there is large year-to-year variability, an underlying trend of -8 mm year^{-1} was identified at the four synoptic stations in the region. This is in-line with similar trends identified elsewhere in northern Nigeria (Tarhule and Woo, 1998; Onyebuchi, 1998). Although years of lower rainfall are generally associated with a late rainfall onset, the relationship is poor and there is little evidence of a progressive change in the average duration of the rainy season. The average rainfall amount per day has not changed, rather, the declining rainfall total is attributed to a reduction in the number of rain-days in the middle of the growing season (August – September).

The analysis of rainfall trends has been based on an arbitrary 30-year time period (chosen to reflect the standard meteorological reporting period) which is reflected in the statistical results. Whilst the decline in annual rainfall is undisputed, the trend of -8 mm year^{-1} is an artefact of the time period chosen. Tarhule and Woo (1998) considered a longer time period and concluded that the change in rainfall regime was characterised by an abrupt jump that occurred between 1964 and 1972 across northern Nigeria. After the change point the decline in rainfall total has been more gradual at -1 to -3 mm year^{-1} .

The analysis of other climatic parameters is complicated by long periods of missing data and concerns over data quality. However, the available data suggest that there has been a gradual increase in minimum and, to a lesser extent maximum, air temperatures during growing season over the period under study. This has resulted in an increase in mean air temperature of about $1.5 \text{ }^{\circ}\text{C}$ from 1961 – 1990. Sunshine duration, vapour pressure and wind speed have remained stable over this period, and the increase in temperature alone has resulted in a small, and generally insignificant, increase in reference evapotranspiration of about 30 mm year^{-1} .

2. SOIL WATER BALANCE MODEL

A parsimonious soil water balance model has been developed and parameterised for a sandy soil and millet cropping system that is typical of the North East Arid Zone of Nigeria. Although an attempt was made to parameterise the model by independent experiments, it was shown that difficulties in isolating soil hydrological processes and measuring them under artificial conditions meant that the model fit was not good compared to field observations. Simultaneous calibration of key parameters resulted in an excellent fit, whilst still maintaining the values of the parameters within acceptable ranges. The calibrated model provided a good simulation of soil water contents and rates of drainage, evaporation and transpiration.

3. TRENDS IN SOIL WATER BALANCE

The calibrated soil water balance was used to simulate the water balance of a sandy soil under pearl millet and millet-cowpea intercrops for the period 1960 – 1993. The results show that the decline in rainfall totals has led to an alteration of the partitioning of annual rainfall into its various water balance components. Prior to the early 1980s (with the notable exception of the drought years of the early 1970s) the rainfall was generally sufficient in amount, and adequately distributed, to meet the needs of a typical pearl millet crop, with sufficient remaining after harvest to contribute towards a cowpea intercrop. In the drier years there was generally less residual moisture available after the millet harvest and cowpea intercrops would have produced little, if any, seed and been used mainly for fodder. The millet-cowpea intercropping systems was therefore well suited to the climate, with sufficient rainfall in all but drought years, to ensure a good millet harvest and the bonus of cowpea seed in wetter years.

Since the early 1980s the rainfall has generally been fully utilised by the millet crop and there has rarely been a surplus for cowpeas after the millet harvest. In addition, the full water requirements of millet have not been met in most years and yields would have been affected by water stress.

The changing partitioning of rainfall will also have had impacts on the hydrology of the region, with reduced aquifer recharge from drainage and reduced runoff contributing to river flows. These impacts are beyond the scope of this study.

The initial intention was to use the field observations of the soil water balance under pearl millet and an independent validation of the soil water balance model, however, the poor fit of the model required the use of this data set for calibrated. As a result there was no independent data set, with sufficiently detailed records, against which to validate the model. Additionally, the observed water balance was from one year only, when rainfall was slightly above average for the period 1961 – 1990 and the performance of the model in low rainfall years was not assessed.

The BALANCE model was developed for use with a minimum of plant and soil parameters and daily rainfall data. The simplifications inherent in the conceptual model mean that although it provides an estimate of the impact of climate on agrohydrology, agronomic impacts can only be extrapolated with caution. In particular the feedback of low rainfall on crop development and transpiration was not included in the BALANCE model and may have resulted in an over-estimation of the amount of water consumed in transpiration in dry years.

4. MANAGEMENT INTERVENTIONS TO OFFSET THE IMPACT OF REDUCED RAINFALL REGIMES

Studies elsewhere in the Sahel have shown that a large proportion of annual rainfall can be lost as surface runoff. Rainfall intensities are frequently high and the soils are prone to capping. Where this is the case, runoff conservation techniques could be used to minimise the runoff and maximise infiltration. In addition, water harvesting could be used to increase infiltration above and beyond the natural rainfall depth. It is clear that either may not necessarily produce yield benefits in all years and the degree of benefit will depend as much upon the distribution of rainfall as on the amount.

As the causes of increased aridity in the North East Arid Zone of Nigeria are not fully understood, it is difficult to extrapolate the trends observed during the period 1961 – 90 to the future. Certainly, there is no suggestion of a linear decrease in rainfall totals continuing and the early 1990s contained a series of relative ‘wet’ years. This study shows that agro-hydrological models can be useful in explaining observed qualitative impacts of climatic variability on agriculture and for examining the sensitivity of physical and agronomic interventions to climate. Such models could be used to evaluate the sustainability of agricultural technologies designed to alleviate the impacts of aridity under alternative future climatic scenarios.

5. REFERENCES

- Onyebuchi, C.C., 1998. Land use change in Makurdi area of Benue State, Nigeria: assessment by remote sensing, GIS and rapid rural appraisal (RRA). PhD thesis, Silsoe College, Cranfield University, UK. Unpublished.
- Tarhule, A. and Woo, M-K., 1998. Changes in rainfall characteristics in Northern Nigeria. *International Journal of Climatology*. 18:1261-1271.

FULL REFERENCE LIST

- Abdalla, J. D., 1994. The evaluation of satellite imagery in a geographic information system (GIS) for monitoring land cover changes in a semi-arid area of North-Eastern Nigeria. PhD thesis. Silsoe College, Cranfield University. Unpublished.
- Abdulmumin, S. and Misari, S.M., 1990. Crop coefficients of some major crops of the Nigerian semi-arid tropics. *Agricultural Water Management* 18:159-171.
- Adams, J.E., Arkin, G.F. and Ritchie, J.T., 1976. Influence of row spacing and straw mulch on first stage drying. *Soil Sci. Soc. Am. J.* 40:436-442
- Adams, W.M. and Mortimore, M.J., 1997. Agricultural intensification and flexibility in the Nigerian Sahel. *The Geographical Journal*, 163:150-160.
- Adderley, W.P., Jenkins, D.A., Sinclair, F.L., Stevens, P.A. and Verinumbe, I., 1997. The influence of soil variability on tree establishment at an experimental agroforestry site in North East Nigeria. *Soil Use and Management*, 13:1-8.
- Agnew, C.T., 1982. Water availability and development of rainfed agriculture in south west Niger, West Africa. *Transactions of the Institute of British Geographers* 7:419-457.
- Agnew, C.T., 1991. Evaluation of a soil water balance model for the analysis of agricultural drought in the Sahel. In Sivakumar M. V. K., Wallace J. S., Renard C, Giroux C. (eds) 991) Soil water balance in the Sudano-Sahelian zone. (Proc. Int. Workshop, Niamey, Niger, February 1991. IAHS Bull. no. 199. IAHS Press, Institute of Hydrology, Wallingford, UK.
- Akintola, J.O., 1986. Rainfall distribution in Nigeria 1892 - 1983. Impact Publishers, Ibadan, Nigeria.
- Allen, S. J., 1990. Measurement and estimation of evaporation from soil under sparse barley crops in Northern Syria *Agric. For. Met.* 49:291-309
- Allen, R.G. and Pruitt, W.O., 1986. Rational use of the FAO Blaney-Criddle formula. *Journal of the Irrigation and Drainage Division, ASCE* , 112: 139-155.

- Allen, R.G., 1996. Assessing the integrity of weather data for reference evapotranspiration estimation. *Journal of Irrigation and Drainage Engineering*, ASCE, 22: 97-106.
- Allen, R.G., Smith, M., Pereira, L.S. and Perrier, A., 1994. An update for the calculation of reference evapotranspiration. *ICID Bulletin*, 43: 35-92.
- Allen, R.G., Wright, J.L. and Burman, R.D., 1989. Operational estimates of evapotranspiration. *Agronomy Journal*, 81.
- Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome. pp300.
- Arkin, G.F., Ritchie, J.T. and Adams, J.E., 1974. A method for measuring first-stage soil water evaporation in the field *Soil Sci. Soc. Am. Proc.* 38:951-954
- Armbrust, D.V., 1990. Rapid measurement of crop canopy cover. *Agronomy Journal* 82:1170-1171.
- Azam-Ali, S.N., Gregory, P.J. and Monteith, J.L., 1984. Effects of plating density on water use and productivity of pearl millet (*Pennisetum typhoides*) grown on stored water. I. Growth of roots and shoots. *Experimental Agriculture*. 20:213-204.
- Baker, E.F.I. and Norman, D.W., 1975. Cropping patterns in northern Nigeria. Proc. South and East Asia Cropping Systems Network Workshop, IRRI, 13-20 March 1975. Los Baños, Philippines.
- Benoit P., 1977. The start of the growing season in Northern Nigeria. *Agricultural Meteorology* 18:91-99.
- Black, T.A., Gardner, W.R. and Thurtell, G.W., 1969. The prediction of evaporation, drainage and soil water storage for a bare soil. *Soil. Sci. Soc. Am. Proc.* 33:655-660

- Boast, C.W. and Robertson, T.M., 1982. A 'micro-lysimeter' method for determining evaporation from bare soil: Description and laboratory evaluation. *Soil Sci. Soc. Am. J.* 46:689-696
- Boesten, J.J.T.I. and Stroosnijder, L., 1986. Simple model for daily evaporation from fallow tilled soil under spring conditions in a temperate climate. *Netherlands J of Agric. Sci.* 34:75-90
- British Standards Institution, 1990. British standard methods of test for soils for civil engineering purposes. Part 2. Classification tests. BSI, London.
- Bunting, A.H., Dennett, M.D., Elston, J. and Milford, J.R., 1976. Rainfall trends in West African Sahel. *Quarterly Journal of the Royal Meteorological Society* 102:59-64.
- Chiroma, A.M., 1996. The farming system of Futchimiram, Yobe State, Nigeria. Soils, cultivars and livelihoods in North East Nigeria. Working Paper No. 4. Department of Geography, University of Cambridge UK / Bayero University Kano, Nigeria. Unpublished.
- Cisse, L. and Vachaud, G., 1988. Influence d'apports de matiere organique sur la culture de mil et d'arachide sur un sol sableux du Nord-Senegal. 1. Bilans de consommation, production et developpement racinaire. *Agronomie* 8:315-326.
- Daamen, C.C., Simmonds, L.P., Wallace, J.S., Laryea, K.B. and Sivakumar, M.V.K., 1993. Use of microlysimeters to measure evaporation from sandy soils. *Agricultural and Forest Meteorology* 65:159-173.
- Dancette, C. and Hall, A.E., 1979. Agroclimatology applied to water management in the Sudanian and Sahelian zones of Africa. *Ecological Studies* 34:98-118
- Doorenbos, J. and Pruitt, W.O., 1977. Guidelines for predicting crop water requirements. (FAO Irrigation and Drainage Paper 24). Food and Agriculture Organisation of the United Nations (FAO) Rome .
- Duffie, J.A. and Beckman, W.A., 1991. Solar engineering of thermal processes. (2nd. ed.). John Wiley and sons New York .

- FAO, 1984. Agroclimatological data for Africa. Vol. 1 Countries north of the equator. Food and Agriculture Organisation. Rome.
- FAO, 1984. Agroclimatological data for Africa. Vol. 2. FAO plant production and protection series. No. 22. Rome: Food and Agriculture Organisation of the United Nations.
- Folland, C.K., Palmer, T.N. and Parker, D.E., 1986. Sahel rainfall and worldwide sea temperatures, 1901-85. *Nature*. 320:602-607.
- Folorunso, O.A., 1986. Distribution of steady state infiltration rate for Borno Soil. *Annals of Borno* 3:193-204.
- Frevert, D.K., Hill, R.W. and Braaten, B.C., 1983. Estimation of FAO evapotranspiration coefficients. *Journal of the Irrigation and Drainage Division, ASCE* , 109: 265-270.
- Geiger, S.C. and Manu, A., 1993. Soil surface characteristics and variability in the growth of millet in the plateau and valley region of Western Niger. *Agriculture, Ecosystems and Environment* 45:203-211.
- Goutorbe, J.P., Dolman, A.J., Gash, J.H.C., Kerr, Y.H., Lebel, T., Prince, S.D. and Stricker, J.M.M., 1997. HAPEX-Sahel. Elsevier Science, 1088pp.
- Gregory, P.J. and Reddy, M.S., 1982. Root growth in an intercrop of pearl millet / groundnut. *Field Crops Research*, 5:241-252.
- Grema, A.K., 1994. Productivity of pearl millet-cowpea intercrops in north-east Nigeria. PhD thesis. Cranfield University, Silsoe College, UK. Unpublished.
- Grema, A.K. and Hess, T.M., 1994. Water balance and water use of pearl millet-cowpea intercrops in North East Nigeria. *Agricultural Water Management*.
- Hansen, E.V., Israelsen, O.W. and Stringham, G.E., 1980. *Irrigation Practices* (4 ed.). Wiley. New York .
- Hargreaves, G.H. and Samani, Z.A., 1982. Estimating potential evapotranspiration. *Journal of the Irrigation and Drainage Division, ASCE* , 108: 225-230.

- Hess, T.M., 1998. Trends in reference evapo-transpiration in the North East Arid Zone of Nigeria, 1961–91. *Journal of Arid Environments*, 83:99-115.
- Hess, T.M., Stephens, William and Maryah, U.M., 1995. Rainfall trends in the North East Arid Zone of Nigeria 1961 - 1990. *Agricultural and Forest Meteorology*, 74: 87-97.
- Hulme, M., 1992. Rainfall changes in Africa 1931-1960 to 1961-1990. *International Journal of Climatology* 12:685-699.
- Hulme, M., 1996. Recent climate-change in the worlds drylands. *Geophysical Research Letters*, 23: 61-64.
- Hulme, M. and Kelly, M., 1993. Exploring the links between desertification and climate change *Environment*. July/August 1993. pp5-45.
- IWACO B.V., 1985. Study of the water resources in the Komadougou - Yobe basin. Nigeria - Niger Joint Commission for Cooperation, Niamey, Niger Republic.
- Jacovides, C.P. and Kontoyiannis, H., 1995. Statistical procedures for the evaluation of evapotranspiration computing models. *Agricultural Water Management*, 365-371.
- Jensen, M.E. and Haise, H.R., 1963. Estimating evapotranspiration from solar radiation. *Journal of the Irrigation and Drainage Division, ASCE* , 89: 15-41.
- Jensen, M.E., Burman, R.D. and Allen, R.G., 1990. Evapotranspiration and irrigation water requirements. (ASCE Manuals and Reports on Engineering Practice No. 70). American Society of Civil Engineers New York .
- Kanamasu, E.T., Singh, P. and Chaudhuri, U.N., 1984. Water use and water-use efficiency of pearl millet and sorghum. In, Virmani, S.M. and Sivakumar, M.V.K., Eds. *Agrometeorology of sorghum and millet in the semi-arid tropics: Proceedings of the international symposium, 15-20 Nov. 1982. ICRISAT Centre, Patancheru, A.P. 502324, India: ICRISAT. p175 – 181.*
- Kassam, A.H. and Kowal, J.M., 1975. Water use, energy balance and growth of gero millet at Samaru, Northern Nigeria. *Agricultural Meteorology*, 15:333-342.

- Klaij, M.C. and Vachaud, G., 1992. Seasonal water balance of a sandy soil in Niger, cropped with pearl millet, based on profile moisture measurements. *Agricultural Water Management* 21:313-330.
- Kowal, J.M. and Kassam A.H., 1978. *Agricultural ecology of Savanna*. Oxford University Press, Oxford.
- Kowal, J.M. and Knabe D.T., 1972. *An agroclimatological atlas of the Northern states of Nigeria*. Ahmadu Bello University Press, Zaria, Nigeria.
- Kundiri, A.M., Jarvis, M.G. and Bullock, P., 1997. Traditional soil and land appraisal on fadama lands in northeast Nigeria. *Soil Use and Management* 13:205-208.
- Landon, J.R., 1991. (ed.) *Booker tropical soil manual*. Longman Scientific and technical, Harlow.
- Lascano, R.J. and van Bavel, C.H.M., 1986. Simulation and measurement of evaporation from a bare soil. *Soil Sci. Soc. Am. J.* 50:1127-1133
- Le Houérou, H.N., 1996. Climate change, drought and desertification. *Journal of Arid Environments* 34:133-185.
- Leeuw, P.N. and Tuley, P., 1972. Vegetation. In, *The land resources of North East Nigeria*. Volume 1. The environment. Land Resources Division / Overseas Development Administration / Foreign and Commonwealth Office. Surbiton. England.
- Ley, T.W., Allen, R.G. and Hill, R.W., 1996. Weather station siting effects on reference evapotranspiration. *Evapotranspiration and irrigation scheduling*. Proc. of the International Conference. 3-6 November 1996. San Antonio, Texas. American Society of Agricultural Engineers.
- Maduakor, H.O., 1991. Physical and hydraulic properties of soils of Sudano-Sahelian regions of Nigeria. In Sivakumar, M.V.K., Wallace, J.S., Renard, C. and Giroux, C. (eds), 1991. *Soil water balance in the Sudano-Sahelian zone*. Proc. Int. workshop, Niamey, Niger, February 1991. IAHS publication no. 199. IAHS Press, Institute of Hydrology, Wallingford, UK.

- Makkink, G.F., 1957. Testing the Penman formula by means of lysimeters. *Journal of the Institution of Water Engineers.*, 11: 277-288.
- Martin, D.L., Klocke, N.L. and DeHaan, D.L., 1985. Measuring evaporation using mini-lysimeters. In *Advances in evapotranspiration. Proc. of a conference at Chicago, IL. Am. Soc. Agric. Eng., St. Joseph, MI*, pp231-240.
- Monteith, J.L., 1981. Evaporation and surface temperature. *Quart. J. Royal Met. Soc.*, 107: 1-27.
- Monteith, J.L., 1991. Weather and water in the Sudano-Sahelian zone. *Soil Water Balance in the Sudano-Sahelian zone. IAHS Publ. no. 199 February 1991. Niamey, Niger. (pp. 11-29). IAHS Press. Institute of Hydrology, Wallingford, UK.*
- Mortimore, M.J., 1989. *Adapting to drought: farmers, famines, and desertification in West Africa. Cambridge University Press, Cambridge. 299pp.*
- Muleba, N. and Ezumah, H.C., 1985. Optimizing cultural practices for cowpea in Africa. In In Singh, S. R. and Rachie, K. O. (eds). *Cowpea research, production and utilisation. John Wiley & sons, Chichester, UK. pp289-295.*
- Nachabe, M.H., 1998. Refining the definition of field capacity in the literature. *Journal of Irrigation and Drainage Engineering*, 124:230-232.
- Natarajan, M, and Willey, R.W., 1980. The effects of water stress on yield advantages of intercropping systems. *Field crops research*. 13:117-131.
- Nicholson, S.E., 1989. Long-term changes in African rainfall. *Weather* 44:46-56.
- Nieuwolt, S., 1977. *Tropical climatology. An introduction to the climates of the low latitudes. John Wiley & Sons. Chichester. pp.207.*
- Nouri, M. and Reddy, K.C., 1991. Utilisation de l'eau par le millet et le niébé en association et de culture pure. In: M.V.K. Sivakumar, J.S. Wallace, C. Renard and G. Girous (editors), *Soil water balance in the Sudano-Sahelian zone. Proc. Niamey Workshop Feb. 1991. IAHS Publ. no. 199 IAHS Press, Institute of Hydrology, Wallingford, UK. pp. 421-429*

- Ntare, B.R., 1989a. Intercropping cowpeas with millet. IITA research briefs 9(4):5.
- Ntare, B.R., 1989b. Evaluation of cowpea cultivars for intercropping with pearl millet in the Sahelian zone of West Africa. *Field Crops Research* 20:31-40.
- Ntare, B.R. and Williams, J.H., 1992. Response of cowpea cultivars to planting pattern and date of sowing in intercrops with pearl millet in Niger. *Experimental Agriculture* 28:41-48.
- Nwadialo, B.E., 1991. The estimation of reference crop evapotranspiration with minimum data in tropical climate. *Beitr. Trop. Landwirtsch. Vet.Med.*, 175-182.
- Ojanuga, A.G., 1987. Characteristics of soils of the semi-arid region of Nigeria. In Sagua, V. O., Ojanuga, A. U., Enabor, E. E., Mortimore, M., Kio, P. R. O., and Kalu A. E., (eds) 1987. *Ecological disasters in Nigeria: drought and desertification*. Proc. Nat. Workshop, Kano, December 1985, 64-77. Federal Ministry of Science and Technology, Lagos, Nigeria.
- Olsson, L., 1993. On the causes of famine - drought, desertification and market failure in the Sudan. *Ambio* 6:395-403.
- Pandey, R.K. and Ngarm, A.T., 1985. Agronomic research advances in Asia. In Singh, S. R. and Rachie, K. O. (eds). *Cowpea research, production and utilisation*. John Wiley & sons, Chichester, UK. pp 297-306
- Payne, W.A., Lascano, R.J. and Wendt, C.W., 1991. Annual soil water balance of cropped and fallowed millet fields in Nigeria. In: M.V.K. Sivakumar, J.S. Wallace, C. Renard and G. Girous (editors), *Soil water balance in the Sudano-Sahelian zone*. Proc. Niamey Workshop Feb. 1991. IAHS Publ. no. 199 IAHS Press, Institute of Hydrology, Wallingford, UK. pp401-411.
- Payne, W.A., Wendt, C.W. and Lascano, R.J., 1990. Root zone water balances of three low-input millet fields in Niger, West Africa. *Agronomy Journal* 82:813-819.

- Priestley, C.H.B. and Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation. *Monthly Weather Review*, 106: 81-92.
- Purseglove, J.W., 1972. *Tropical Crops – Monocotyledons*. Longman Scientific & Technical, Harlow.
- Rawls, W.J., Brakensiek, D.L., and Saxton, K.E., 1982. Estimation of soil water properties. *Transactions of ASAE* 25:1316-1320
- Rayar, A.J., 1984. University of Maiduguri farm development planning report for Faculty of Agriculture, Annex A; Soil survey details. Unpublished. University of Maiduguri.
- Rayar, A.J., 1987. Studies on some physio-chemical parameters of the soils of Borno State. *Annals of Borno (Maiduguri)* 4:283-291.
- Ritchie, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Res.*, 8:1204-1213.
- Rockström, J., Jansson, P.E. and Barron, J., 1998. Seasonal rainfall partitioning under runoff and runoff conditions on sandy soil in Niger. On-farm measurements and water-balance modelling. *Journal of Hydrology*, 210:68-92.
- Savenije, H.H.G., 1995. New definitions for moisture recycling and the relationship with land-use changes in the Sahel. *Journal of Hydrology*. 167:57-78.
- Shackel, K.A. Hall, A.E., 1984. Effect of intercropping on the water relations of sorghum and cowpea. *Field Crops Research* 8:341-387
- Shawcroft, R.W. and Gardner, H.R., 1983. Direct evaporation from soil under a row crop canopy. *Agric. meteorol.* 28:229-238.
- Shuttleworth, W.J., 1992. Evaporation. In D. R. Maidment (Editor), *Handbook of hydrology*. (Chapter 4). New York: McGraw-Hill.
- Shuttleworth, W.J. and Wallace, J.S., 1985. Evaporation from sparse crops – an energy combination theory. *Quarterly Journal of the Royal Meteorological Society*, 111:839-855.

- Singh, S.R. and Rachie, K.O. (eds), 1985. Cowpea research, production and utilisation. John Wiley & sons, Chichester, UK.
- Sivakumar, M.V.K., 1988. Predicting rainy season potential from the onset of rains in Southern Sahelian and Sudanian climate zones of West Africa. *Agricultural and Forest Meteorology* 42:295-305.
- Sivakumar, M.V.K., 1990. Exploiting rainy season potential from the onset of rains in the Sahelian zone of West Africa. *Agricultural and Forest Meteorology* 51:321-332.
- Sivakumar, M.V.K., 1992. Empirical analysis of dry spells for agricultural applications in West Africa. *Journal of Climate* 5:532-539.
- Sivakumar, M.V.K. and Wallace, J.S., 1991. Soil water balance in the Sudano-Sahelian zone: need, relevance and objectives of the workshop. In Sivakumar M.V.K., Wallace, J.S., Renard, C. and Giroux, C. (eds) 1991) Soil water balance in the Sudano-Sahelian zone. (Proc. Int. Workshop, Niamey, Niger, February 1991. IAHS Bull. no. 199. IAHS Press, Institute of Hydrology, Wallingford, UK.
- Smith, M., 1991. Report on the expert consultation on revision of FAO methodologies for crop water requirements. Land and water development division. FAO. Rome. (unpubl.)
- Smith, M., Allen, R.G. and Pereira, L.S., 1996. Revised FAO methodology for crop water requirements. Evapotranspiration and irrigation scheduling. Proc. of the International Conference. 3-6 November 1996. San Antonio, Texas. (pp. 116-123). ASAE / Irrigation Association / ICID.
- Squire, G.R., 1990. The physiology of tropical crop production. CAB International, Wallingford, UK.
- Stern, R.D., Dennett, M.D., and Dale, I.C., 1982. Analysing daily rainfall measurements to give agronomically useful results. I. Direct methods. *Experimental Agriculture* 18:223-236.

- Stroosnijder, L., 1987. Soil evaporation: test of a practical approach under semi-arid conditions. *Netherlands J. of Agric. Sci.* 35:417-426.
- Tarhule, A. and Woo, M-K., 1998. Changes in rainfall characteristics in Northern Nigeria. *International Journal of Climatology.* 18:1261-1271.
- United States Department of Agriculture, Natural Resources Conservation Service, 1986. *National Engineering Handbook*. Second edition. June, 1986. U.S. Government Printing Office.
- Usman, H., 1994. Soils susceptible to erosion in northeastern Nigeria. *Arid Soil Research and Rehabilitation.* 8:217-225.
- van Apeldoorn, G.J., 1981. *Perspectives on drought and famine in Nigeria*. George Allen & Unwin. London. 184pp.
- Villalobos, F.J. and Fereres, E., 1990. Evaporation measurement beneath corn, cotton and sunflower canopies. *Agron. J.* 82:1153-1159
- Walker, G.K., 1983. Measurement of evaporation from soil beneath crop canopies. *Can. J. Soil Sci.* 63:137-141
- Walker, G.K., 1984. Evaporation from wet soil surfaces beneath plant canopies. *Agric. For. Met.* 33:259-264
- Wallace, J.S., 1991. The measurement and modelling of evaporation from semiarid land. In Sivakumar M V K, Wallace J S, Renard C, Giroux C (eds) 1991) *Soil water balance in the Sudano-Sahelian zone*. (Proc. Int. Workshop, Niamey, Niger, February 1991. IAHS Bull. no. 199. IAHS Press, Institute of Hydrology, Wallingford, UK.
- Wallace, J.S., Lloyd, C.R. and Sivakumar, M.V.K., 1993. Measurements of soil, plant and total evaporation from millet in Niger. *Agricultural and Forest Meteorology*, 63:149-169.
- Wright, J.L. and Jensen, M.E., 1972. Peak water requirements of crops in southern Idaho. *Journal of the Irrigation and Drainage Division, ASCE* , v96: n IR1 193-201.

Xue, Y.K., 1997. Biosphere feedback on regional climate in tropical north Africa.
Quarterly Journal of the Royal Meteorological Society. 123:1483-1515.

