Current research on crop water balance and implications for the future

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Abstract Insufficient water supply is the most important single factor governing agricultural production in the Sudano-Sahelian zone. Understanding the magnitude and dynamics of different components of the crop water balance is crucial to development of technological options for sustainable management of soil and water resources. In addition to rainfall, a thorough knowledge is required of seasonal values of evaporation, weed and crop transpiration, runoff, deep drainage and soil water storage. Rainfall effectiveness in crop and livestock production can be enhanced by reducing evaporation, runoff, weed transpiration and deep drainage. The objective of soil and crop management is to increase crop transpiration, plant biomass, and the harvest index. Research information on climatic data, water balance and soil hydrological characteristics for the region is grossly inadequate. Major problems with available climatic data include: (a) incomplete, insufficient and discontinuous data; (b) unsatisfactory data obtained by non-standard methods; and (c) data of low scientific credibility. A few lysimetric studies have been conducted to evaluate crop water use and water use efficiency. The water use efficiency depends on time of sowing, tillage methods, residue management, and fertilizer application. Information on rooting characteristics and soil water extraction patterns is not known for any of the major crops. A few experiments conducted to evaluate runoff have been done either on small plots or using a rainfall simulator. Little information exists on soil physical and hydrological properties measured in situ. Hydrological studies, preferably done on agricultural watersheds, are needed for the following: (a) agroclimatic analysis of the existing data to estimate plant available water reserves; (b) integration of climatic data with soil characteristics; (c) application of hydrological theory to benchmark soils; (d) evaluation of components of water balance; and (e) establishment of data banks.

INTRODUCTION

Lack of adequate water supply is a principal constraint to crop production in arid and semiarid regions. Therefore, water management is crucial to alleviating adverse effects of recurring droughts which seriously curtail crop
production in the Sudano-Sahelian zone of Africa. While drought is a natural phenomenon in these regions, its effects and duration can be reduced through judicious management of soil, crop and water. Although irrigated agriculture can be 2 to 3 times more productive than rainfed agriculture, development of irrigation potential in sub-Saharan Africa is also based on the availability of reliable data on water resources. Long term and continuous records of scientifically credible data are a necessary pre-requisite to sustainable development of water resources. Types of data required include the principal components of the water balance.

**WATER BALANCE**

The most commonly used crop-water balance model is given as:

\[ ET = P + I - S - D - R \]  

(1)

where \( ET \) is evapotranspiration, \( P \) is precipitation, \( I \) is irrigation, \( S \) is change in soil water storage, \( D \) is deep drainage and \( R \) is runoff. Components \( ET, P \) and \( I \) are always positive, but the others can be positive or negative. If \( R \) is negative, it implies run on from the surrounding areas. Negative \( S \) indicates depletion of soil-water reserves, and negative \( D \) means upward flow from the groundwater.

In practical terms, equation (1) is better expressed as

\[ P - R - E - T_w - T_c - S - D + I = 0 \]  

(2)

the term \( ET \) of equation (1) has been separated into three components: \( E \) is loss by evaporation from the soil and \( T_w \) and \( T_c \) refer to transpiration by weeds and crops, respectively. The objective of soil and crop management practices is to minimize losses by \( R, E, D, \) and \( T_w \) while maximizing \( T_c \).

While models depicted in equations (1) and (2) are simple, assessment of different components requires careful experimentation and precise measurements. Measurement of \( P \) and \( I \) is usually simple and direct, although a sufficient number of raingauges are needed to obtain reliable estimates over a watershed. In principle, assessment of soil water storage is also simple and direct. In practice, however, obtaining scientifically credible estimates of soil water storage on the field scale is cumbersome, subject to error because of large spatial and temporal variations, and a challenge. Most methods have their specific advantages and disadvantages. Furthermore, instruments used for measuring soil water content are usually accurate only for changes longer than a week or so, unless a large amount of water has been added by rainfall or irrigation. The gravimetric technique, though simple and the most basic, is destructive, labourious and time consuming, and highly subject to spatial variations (Warrick & Nielson, 1980; Campbell & Campbell, 1982). Non-destructive techniques (e.g. neutron moderation) are usually expensive and require careful calibration for all soils and major horizons (Lal,
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1974; 1979a). The neutron probe samples a large volume, but the maintenance of equipment is a problem to be considered for operations in sub-Saharan Africa. Attempts have been made to standardize methods of measurement of \( R \) (Lal, 1988). However, from the standpoint of the practitioner, measurement of \( R \) has remained as much an art as a science. Most methods are based on individual judgement, and are subject to budgetary provisions. Measurement of deep drainage \( (D) \) requires information on moisture potential profile \( (\Phi_{soil}) \), hydraulic conductivity \( (K_{soil}) \), and depth of zero flux. Assessment of these characteristics under field conditions requires careful instrumentation and precise measurements.

Evapotranspiration \( (ET) \) estimates for equation (1) can be obtained by several different methods. \( ET \) includes all water lost by evaporation from the soil surface and by transpiration from the surfaces of weed and crop plants. Measurement of actual \( ET \) can be done by the lysimetric technique (Harrold & Dreibelbis, 1951). Lysimeters are useful because they allow direct measurement of \( D \), and \( S \) can be accurately evaluated from total weight changes over a known time interval. Nonetheless, direct measurement of \( ET \) is difficult. Indirect estimates are obtained by correlating \( ET \) with climatic conditions (Tanner, 1967; Ritchie, 1972; Jensen, 1973; Kanemasu et al., 1979), and crop yields (Stewart et al., 1977; Hanks, 1974, 1983; Retta & Hanks, 1983; Papendick & Campbell, 1988). In general, dry matter production increases with evapotranspiration. The relationship may be linear (Sorensen et al., 1980). The objective of most models is to increase \( T_c \) and harvestable plant biomass. These two variables are highly correlated. Tanner & Sinclair (1983) developed a relationship between dry matter production \( (Y_t) \), crop transpiration \( (T_c) \) and average vapour deficit of the air during daylight hours \( (\Delta e) \) which is given as:

\[
Y_t = K \frac{T_c}{\Delta e}
\]  

(3)

\( K \) is a constant and is influenced by several factors, e.g. canopy structure, plant composition etc. Total dry matter \( Y_t \) can be sub-divided into its components, e.g. grain \( (Y_g) \), straw \( (Y_s) \) and roots \( (Y_r) \). Another model by Stewart et al. (1977) is designed to correlate yield with \( ET \), i.e.

\[
\frac{Y}{Y_p} = 1 - B(1 - \frac{ET}{ET_p})
\]

(4)

where \( Y \) is yield associated with a given value of \( ET \), \( Y_p \) is potential yield associated with potential evapotranspiration, \( (ET_p) \) and \( B \) is slope of the relative yield \( (Y/Y_p) \) vs. relative evapotranspiration relation \( (ET/ET_p) \). The value of \( B \) is empirically determined. For equations (3) and (4), \( R \) is assumed to be zero, \( D \) must also be known or assumed zero, and \( ET_p \) must be measured or estimated. The model in equation (4) suits lysimetric studies. Another model, proposed by Hanks (1983), can be written as:

\[
\frac{Y}{Y_p} = \frac{T}{T_m}
\]

(5)

where \( T \) and \( T_m \) refer to actual and potential transpiration associated with
the yield $Y$ and $Y_p$ respectively. The practical problem in using equation (5) is to be able to divide $ET$ into $E$ and $T$ components. Hanks (1985) has described methods to achieve this.

The effectiveness of soil and crop management practices in maximizing $Y_t$ and $T_c$ is usually expressed in terms of water use efficiency ($WUE$). In agronomic terms, $WUE$ is a seasonal value defined as:

$$WUE = \frac{\text{yield per unit area}}{\text{total water used}}$$

(6)

Quantitatively, $WUE$ is expressed as:

$$WUE = \frac{Y_t/T_c}{1 + (E/T_c)}$$

(7)

The numerator in equation (7) ($Y_t/T_c$) is the transpiration efficiency. Equation (6) is applicable in situations where the summation of terms $E + T$ equals $P$, and where the $R$ and $D$ components are practically zero (Cooper et al., 1987). If not, the denominator in equation (7) must contain all components expressed in equation (1) as follows (Gregory, 1988a):

$$WUE = \frac{Y_t/T_c}{1 + [(E + R + D + I)/T]}$$

(8)

$T_c$ is crop transpiration and $T$ is the total transpiration including that by weeds. Equations (7) and (8) are extremely useful models because they are indicative of ways in which the $WUE$ of a system can be increased.

All the models described in equations (1) to (8) are simple, and each of the quantities described is considered to be a summation over a cropping cycle. Consequently, these models do not apply under transient conditions with reference to crop transpiration and water uptake at a given point in time. More complex water balance models are available to achieve these objectives (Hanks, 1985).

SOIL AND CLIMATIC CHARACTERISTICS OF SUDANO-SAHELIAN ZONE OF AFRICA

The Sudano-Sahelian zone of Africa is a large area covering semiarid and tropical wet-dry regions of sub-Saharan Africa. The region covers an area from the Atlantic (including the Cape Verde Islands) roughly to Lake Chad, bounded on the north by the southern edge of the Sahara (Steeds, 1985; Barrow, 1987). The Sudano-Sahelian zone refers to the north-south division of the Sahel west of Lake Chad, the geographical extent of which has already been described by Sivakumar & Wallace (1991).

The Sahelian zone is characterized by a rainy season of about 2.5
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months. A short growing season and drought during the crop growth are crucial factors affecting growth and yield. *In situ* conservation of soil and water and supplementary irrigation are important inputs for satisfactory yields. The Sudanian zone has a growing season length of 2.5–7.0 months. The southern part of this zone (rainy season of 5.0–7.0 months) is also the zone of the tsetse fly that hinders pastoral activities and animal-based systems. The mean annual rainfall in the Sudano-Sahelian zone is less than 800 mm, and may be less than 100 mm in the northern regions. Up to 20% of the rainfall may occur in a single day, giving very heavy runoff. Between 1968 and 1974, these zones have suffered repeated cycles of drought.

Predominant soils of these regions are Alfisols, Entisols and Inceptisols. Most soils are of low inherent fertility, low in organic matter content, and have low plant-available water reserves. A large proportion of these soils are characterized by presence of plinthite or hardened iron and manganese concretions. In all concretionary soils cover about 25 million hectares in this zone (Obeng, 1978).

SOIL, WATER AND CLIMATIC DATA NEEDS FOR CROP WATER BALANCE

The major requirements of water balance studies are: (a) rapid and accurate assessment of changes in the soil water profile; (b) measurements of field capacity and permanent wilting point of the root zone; (c) assessment of infiltration capacity, and runoff rate and amount, and (d) data on deep drainage or its estimate by measuring hydraulic conductivity $K(\theta)$ and soil moisture characteristic curves $[\psi(\theta)]$ for different depths. In addition, detailed measurements are also needed on crop growth and climatic parameters. Crop growth measurements should include yield, leaf area index, canopy transpiration rate, root profile and plant water potential. Relevant climatic measurements are daily rainfall and evaporation, net radiation, wind speed and relative humidity. While measurements of crop and climatic parameters are very important, this paper is limited only to the description of relevant soil and hydrological characteristics. Measurements of soil and hydrological characteristics should preferably be done on the basis of well defined watersheds. A watershed, as a biogeophysical entity, is an ideal unit to assess crop water balance. Some examples of the available research information for obtaining different components of crop water balance are briefly described below.

Agroclimatic data

There are several on-going meteorological stations which were established during the 1920s and 1930s. Major problems with the data from these stations are that they are: (a) incomplete, insufficient and discontinuous; (b) unsatisfactory, having been obtained by non-standard methods; and (c) of low scientific credibility. Errors in meteorological data can arise from several sources, e.g. instrument calibration and location, maintenance, reading charts
and conversion of units, data management, etc. Another major problem is that what information exists has not been adequately and systematically utilized. This is not to say that no attempts have been made to collate the available data and interpret it for land use planning. Daily and mean monthly records of routinely measured climatic variables were compiled by Papadakis (1965). In its pioneering work FAO developed the Agroecological Zones map for Africa (FAO, 1978). The agroclimatology section of ICRISAT has compiled the existing data for West Africa into a readily available and usable form (Sivakumar et al., 1984). Attempts have also been made by countries of the region to collate and interpret the existing data, e.g. on semiarid regions of Ghana (Kasei, 1988). Some examples of the application of the database for planning purposes are available (Samani & Hargreaves, 1988).

While the frequency and intensity of data collection should be strengthened to improve continuity and scientific credibility, it is important that the available information is adequately used. Development of a more detailed monthly climatic database for predominant ecological zones of the region is strongly recommended. Basic information required includes solar radiation, air temperature, humidity, wind speed and rainfall. More specific information is needed for rainfall intensity, kinetic energy and drop size distribution of rain. The climate data should be used to calculate probabilities of onset of assured rains, and occurrence of drought of different durations during the critical stages of crop growth. Methodologies are available to use the data for obtaining information required for planning farm operations. Kanemasu et al. (1988) reported that growing season duration, the growing season rainfall and crop yield depend significantly on the onset date of the assured rains. Information of this nature derived from climatic data is a powerful planning tool, and must be used toward planning for sustainable development of land and water resources.

Crop water use and water use efficiency

There are precious few systematic and long term studies of crop water use and water use efficiency. Some of the earlier studies in the region were conducted by Institut de Recherches Agronomiques Tropicales et Des Cultures Vivrières (IRAT) at Bambey and Safa in Senegal (Dancette, 1973). Lysimetric measurements were made to assess actual and potential evapotranspiration for different grasses. At Samaru, northern Nigeria, Kowal & Kassam (1978) measured evapotranspiration and crop water use for maize (*Zea mays*), millet (*Pennisetum typhoides*) and other crops using weighing lysimeters.

At the ICRISAT Sahelian Center in Niamey, Wallace et al. (1988) measured components of *ET* (soil evaporation (*E*) and crop transpiration (*T*<sub>c</sub>) for millet) using small lysimeters and an eddy correlation technique (Shuttleworth et al., 1988). They observed that the ratio of actual to potential evaporation ranged from 0.6 to 0.3 while the crop was present, and decreased even further after harvest. These authors also computed the crop
factor for millet as defined by Doorenbos & Pruitt (1977). The crop factor averaged 0.38 for the 10 days before harvest and 0.15 for a similar period after harvest.

Measurement of WUE is an important tool for selection of yield-enhancing soil and crop management technologies, e.g. date of sowing, methods of seedbed preparation, residue management, fertilizer application and cropping system. A few systematic studies have been carried out to assess WUE in relation to cultural practices. In Niamey, Long & Persaud (1988) assessed the influence of neem (Azadirachta indica) windbreaks on WUE of millet. The data in Table 1 indicate that protection by windbreaks increased WUE by 27.3 and 67.7% for grain and dry matter production, respectively. Despite the significant benefits, however, agronomic yields were rather low. An example of the effect of fertilizer application on WUE of millet is shown by the data in Table 2. At Sadoré and Dossa in Niger, fertilizer application increased the WUE of millet by 90.5 and 75.6% respectively. It is apparent that nutrient availability is an important factor in improving the rainfall effectiveness in enhancing crop production.

### Table 1 Water use efficiency (WUE) of millet as influenced by windbreaks (Long & Persaud, 1988)

<table>
<thead>
<tr>
<th>WUE (Mg ha⁻¹ m⁻¹ of H₂O)</th>
<th>Grain</th>
<th>Dry matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>With windbreak</td>
<td>1.4</td>
<td>10.4</td>
</tr>
<tr>
<td>Without windbreak</td>
<td>1.1</td>
<td>6.2</td>
</tr>
</tbody>
</table>

* Yields are averages of fertilized and unfertilized treatments.

### Table 2 Water use efficiency (WUE) of millet crop in 1984 at Sadoré and Dosso, Niger as affected by fertilizer application (Gregory, 1988b)

<table>
<thead>
<tr>
<th>Location</th>
<th>Fertilizer</th>
<th>Shoot dry matter</th>
<th>Grain yield</th>
<th>E + T (mm)</th>
<th>WUE (kg ha⁻¹ mm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(N + P + K)</td>
<td>Mg ha⁻¹</td>
<td>Mg ha⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sadoré</td>
<td>With</td>
<td>4.75</td>
<td>0.41</td>
<td>165</td>
<td>28.2</td>
</tr>
<tr>
<td></td>
<td>Without</td>
<td>2.42</td>
<td>0.29</td>
<td>163</td>
<td>14.8</td>
</tr>
<tr>
<td>Dosso</td>
<td>With</td>
<td>5.00</td>
<td>1.12</td>
<td>247</td>
<td>20.2</td>
</tr>
<tr>
<td></td>
<td>Without</td>
<td>3.10</td>
<td>0.48</td>
<td>270</td>
<td>11.5</td>
</tr>
</tbody>
</table>

Extensive and in-depth studies of this nature are needed for different soils, crops and cropping systems for major ecological regions of the Sudano-Sahelian zone. The linear relationship that normally exists between
Dry matter production and evapotranspiration has not been established for any crop, soil type or ecological zone of the Sudano-Sahelian region. Such information is also not available for harvest index in relation to $ET$ or $T_c$. Several agronomic studies are currently under way by international organizations and national research centers. These studies are designed to relate crop yields to cultural practices, e.g. tillage methods, weed control measures, plant population, date of sowing, etc. The usefulness of these studies can be drastically enhanced if measurements on crop yields are related to crop transpiration and consumptive water use. These measurements, made on the same plots designed for assessment of agronomic yields, would enable extrapolation of data to other soils and environment and facilitate transfer of technologies to regions with similar edaphological characteristics.

### Plant water extraction, root growth, and plant water characteristics

Principles of water infiltration, redistribution, and uptake by plant roots are well established. A plant undergoing drought stress exhibits decreased plant water potential, stomatal closure, leaf rolling and wilting. However, little or no research information exists regarding responses of major crops of the Sudano-Sahelian region (millet (*Pennisetum typhoides*), sorghum (*Sorghum bicolor*), groundnut (*Arachis hypogea*) or pigeon pea (*Cajanus cajan*)) to soil water deficits under field conditions. The response can be measured in terms of leaf or root water potential, leaf diffusive resistance, net photosynthetic rate, crop or canopy temperature, etc.. Plant water potential and diffusive resistance changes are usually detectable at low soil moisture levels, which can be quickly attained in the coarse-textured soils of low water holding capacity commonly found in the African Sahel. Plant response to water deficit is also exhibited in patterns of root growth and water extraction. Depth of rooting must also be known to evaluate the zone of active water absorption. An example of depth of root penetration of millet for three sites in Niger is given by Payne *et al.* (1988). Zaongo *et al.* (1988) also related soil water use by sorghum and millet to the root distribution. They observed that the contour strip rainfall harvesting technique increased rooting depth and soil water storage. Root distribution is an elusive but useful parameter that needs to be assessed for a reliable water balance assessment.

### Runoff

In most water balance studies, runoff ($R$) and deep drainage ($D$) are assumed zero. While this may be true on small plots, these components may be major factors under field conditions. Soils of the arid and semiarid regions are low in organic matter content, contain predominantly low-activity clays, and are prone to crusting and formation of a surface seal. Under high intensity monsoonal storms, a large proportion of rain is lost as runoff especially at the onset of rains when ground cover is scarce. The data in Table 3 from
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Table 3 Effects of tillage methods on runoff at Nino, Mali (Stroosnijder & Hoogmoed, 1984)

<table>
<thead>
<tr>
<th>Year</th>
<th>Rainfall</th>
<th>Runoff (mm)</th>
<th>Runoff (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(Surface storage = 1.0 mm)</td>
<td>(Surface storage = 10.0 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No-till</td>
<td>Till</td>
</tr>
<tr>
<td>1977</td>
<td>368</td>
<td>155</td>
<td>76</td>
</tr>
<tr>
<td>1978</td>
<td>271</td>
<td>104</td>
<td>49</td>
</tr>
<tr>
<td>1979</td>
<td>361</td>
<td>141</td>
<td>80</td>
</tr>
<tr>
<td>Mean</td>
<td>333</td>
<td>133</td>
<td>68</td>
</tr>
</tbody>
</table>

Mali show that the mean annual runoff loss for a 1.0 mm surface storage capacity was 39.3% for a no-till treatment and 19.3% for a tilled treatment. For a 10.0 mm surface storage capacity, the mean annual runoff was 14.7 and 7.0% for no-till and tilled treatments, respectively. In northern Nigeria, Kowal (1970) estimated runoff losses ranging from 29 to 57% (Table 4), and

Table 4 Effects of tillage methods on runoff in northern Nigeria (Kowal, 1970)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Seasonal runoff:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm</td>
</tr>
<tr>
<td>Bare fallow (non-ridged land)</td>
<td>4.45</td>
</tr>
<tr>
<td>Maize planted on flat</td>
<td>4.29</td>
</tr>
<tr>
<td>Maize planted on ridges</td>
<td>5.46</td>
</tr>
<tr>
<td>Maize planted on alternately tied-ridges</td>
<td>2.92</td>
</tr>
<tr>
<td>Maize planted on flat with residue incorporated</td>
<td>3.05</td>
</tr>
<tr>
<td>Maize planted on flat with residue mulch on surface</td>
<td>2.79</td>
</tr>
<tr>
<td>Catchment basis</td>
<td>4.04</td>
</tr>
</tbody>
</table>

in Senegal, Charreau (1970) estimated runoff losses ranging between 16.6 and 39.5% (Table 5); runoff losses of 15 to 25% are common (Table 6). With the exception of a few lysimetric measurements made in Senegal and Nigeria, there are virtually no data on the magnitude of deep drainage (D). In addition to the scarcity of data, the quality of data is also an issue to be considered. Most of the measurements on runoff are made either on small plots or under simulated rains. Although these data are useful, measurements

Table 5 Effect of vegetation cover on water runoff in Senegal (Charreau, 1970)

<table>
<thead>
<tr>
<th>Vegetation cover</th>
<th>Runoff (mm)</th>
<th>% of rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation fallow</td>
<td>200</td>
<td>16.6</td>
</tr>
<tr>
<td>Cultivated</td>
<td>264</td>
<td>21.2</td>
</tr>
<tr>
<td>Bare soil</td>
<td>456</td>
<td>39.5</td>
</tr>
</tbody>
</table>
of runoff and deep drainage should be made on agricultural watersheds large enough to facilitate normal farm operations. Long term studies of this nature were conducted at the International Institute of Tropical Agriculture (IITA), Ibadan (Lai & Russell, 1981).

Soil physical and hydrological characteristics

Soil physical properties exert a dominant effect on soil-water balance, crop production, and water use efficiency especially in regions prone to drought stress. Important soil properties are infiltration capacity, plant-available water reserves, computed on the basis of upper and lower limits of water availability assessed from soil moisture characteristic \( (p^F) \) curves, and saturated and unsaturated hydraulic conductivity. These properties should be determined either \textit{in situ} or on undisturbed cores. Despite the severe problem of recurring drought, and neglect and mismanagement of soil resources, there is a notable scarcity of reliable data on physical and hydrological characteristics of major soils of the Sudano-Sahelian zone. The reliability of available data is also questionable. Indirect or simulated estimates of \( p^F \) curves made from soil texture may not be always reliable (Mellaart, 1988). The data such as those shown in Table 7 for soils of northern Nigeria are rare, and are needed for

**Table 7** Soil moisture characteristics of some soils of northern Nigeria (recalculated from Lawes, 1965); FC = field capacity and PWP = permanent wilting point

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Makwaye series: FC</th>
<th>PWP</th>
<th>Samaru series: FC</th>
<th>PWP</th>
<th>Bassawa series: FC</th>
<th>PWP</th>
<th>Bomo series: FC</th>
<th>PWP</th>
<th>Kurmi series: FC</th>
<th>PWP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15</td>
<td>30.2</td>
<td>8.2</td>
<td>27.5</td>
<td>11.0</td>
<td>27.0</td>
<td>7.8</td>
<td>24.3</td>
<td>8.1</td>
<td>30.2</td>
<td>9.7</td>
</tr>
<tr>
<td>15-30</td>
<td>26.9</td>
<td>10.2</td>
<td>29.7</td>
<td>15.2</td>
<td>28.0</td>
<td>11.7</td>
<td>28.5</td>
<td>13.4</td>
<td>29.1</td>
<td>10.4</td>
</tr>
<tr>
<td>30-45</td>
<td>30.6</td>
<td>14.7</td>
<td>32.3</td>
<td>17.5</td>
<td>31.1</td>
<td>15.9</td>
<td>29.9</td>
<td>17.6</td>
<td>29.8</td>
<td>30.4</td>
</tr>
<tr>
<td>45-60</td>
<td>31.6</td>
<td>17.4</td>
<td>34.2</td>
<td>18.5</td>
<td>33.8</td>
<td>19.4</td>
<td>33.5</td>
<td>18.9</td>
<td>32.7</td>
<td>15.9</td>
</tr>
<tr>
<td>60-75</td>
<td>32.3</td>
<td>18.1</td>
<td>34.3</td>
<td>18.6</td>
<td>34.0</td>
<td>19.8</td>
<td>33.1</td>
<td>18.9</td>
<td>34.8</td>
<td>17.6</td>
</tr>
<tr>
<td>75-90</td>
<td>31.9</td>
<td>17.6</td>
<td>34.6</td>
<td>19.1</td>
<td>33.5</td>
<td>19.7</td>
<td>34.6</td>
<td>20.4</td>
<td>33.4</td>
<td>18.6</td>
</tr>
<tr>
<td>90-105</td>
<td>30.7</td>
<td>16.6</td>
<td>33.2</td>
<td>19.0</td>
<td>33.4</td>
<td>18.8</td>
<td>33.1</td>
<td>18.8</td>
<td>33.4</td>
<td>18.3</td>
</tr>
<tr>
<td>105-120</td>
<td>32.0</td>
<td>16.5</td>
<td>32.7</td>
<td>18.9</td>
<td>31.8</td>
<td>17.6</td>
<td>33.4</td>
<td>18.9</td>
<td>32.6</td>
<td>17.9</td>
</tr>
</tbody>
</table>
land use planning. Most of the available data from northern Nigeria by Lawes (1962) and Kowal (1968, 1969), and from Senegal by Dancette (1971) indicate that measurements of plant available moisture reserves must be made in situ under field conditions. In Niger, Charoy (1974a,b) reported that in situ soil moisture characteristics could be measured using a combination of neutron moisture meter technique and tensiometric measurements. Although the neutron moisture meter has several advantages, it has limitations for use in heterogeneous soils. For highly variable soils, it is difficult to obtain a single calibration curve. Furthermore, obtaining reliable tensiometric measurements on gravelly soils can be difficult (Lal, 1979b). Most soils which are coarse-textured and contain low levels of soil organic matter are characterized by low levels of water retention.

CONCLUSIONS

While drought is a natural phenomenon in the Sudano-Sahelian zone, its effects are accentuated by the lack of knowledge of the hydrological characteristics of soil, crop, and environment. Given sufficient scientifically credible information, water conservation practices can be developed to compensate for non-uniformities and inadequacies in the amount and distribution of rainfall. The efficient use of rainfall is crucial to sustainable productivity of rainfed agriculture. It is important to understand rainfall characteristics, e.g. probability of occurrences of a certain amount of assured rains at a given time. Evaluation of different components of water balance is a necessary pre-requisite to maximize crop-water use and minimize losses due to evaporation, weed competition and surface runoff. Hydrological studies, preferably on well-defined agricultural watersheds as biogeophysical units, are needed for the following:

(a) agroclimatic analysis to determine plant-available water reserves for different soils, regions and cropping systems;
(b) integration of climatic data with soil characteristics, and strengthening of data bases by the systematic evaluation of soil properties and climatic characteristics;
(c) assessment and application of hydrological and soil water theory to benchmark soils, predominant ecological environments and major crops of the region;
(d) evaluation of the components of the water balance (e.g. runoff, soil water storage, soil evaporation, crop transpiration) in relation to cultural practices of soil and crop management; and
(d) establishment of data banks based on long term, continuous and scientifically credible climatic records.

Theoretical principles so developed should be translated into simple technologies that can be used by resource-poor farmers. Small landholders of the Sudano-Sahelian zone cannot accept technology if it is complex, labour demanding or capital intensive.
REFERENCES


