Water Balance in a Moist Semi-Deciduous Forest of Ghana

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Abstract

The hydrological cycle has been studied in temperate regions for many years, but only few measurements of its components have been made in tropical areas. The water balance is important for agriculture and forestry, and available soil water is an essential requirement to evaluate plant growth potential. Hence, the moist semi-deciduous forest of Ghana was selected for this study because most food and export crops are grown there. Available water capacity (AWC) was determined for three typical soils selected on a catena in the forest of Kade. Monthly actual evapotranspiration (AET) was calculated by using the Penman formula and the temporal variation and magnitude of deep percolation was assessed. Available water capacity was high for all soil types averaging about 170 mm m^{-1}. It was found that available soil water is important both for the amount of deep percolation and AET during the year. AET was highly variable on monthly basis but, on average, it was about 1200 mm $year^{-1}$. Deep percolation was found to be 16% - 18% of annual average rainfall. This study suggests that a simple water balance model can be used in place of complicated models in the determination of soil water balance in the tropics.

Key words: water balance, Ghana, forest, soil

Introduction

The moist semi-deciduous forest is being exploited in many places of the world (Palo *et al.*, 1996), and this adversely affects the forest hydrology on a local and global scale. In Ghana, for example, this forest occupies approximately 20% of the land area. In order to evaluate the impact of human activities on the forest, it is necessary to have a basic knowledge of natural hydrological processes. The water balance is useful for forestry, agriculture and engineering hydrological studies. Ledger (1975), Calder *et al.* (1986), Shuttleworth (1988), Hodnett *et al.* (1995), Veenendaal et al. (1996) and Cook *et al.* (1988) have used the water balance in the study of the hydrology in the humid tropics.

The water balance which is a simple way to assess inputs and outputs of the water cycle may be expressed as follows:

$$P = AET + DP + A + DS$$

where P is precipitation, AET is actual evapotranspiration, DP is deep percolation, A is overland flow, and DS is change in soil moisture storage of the root zone.

AET is the most difficult parameter to estimate accurately in the hydrological cycle. Hitherto, AET has been determined by rather complex micro-meteorological and soil physical methods (Shuttleworth, 1988; Hodnett *et al.*, 1995). The micro-meteorological technique often used is the eddy correlation or the Bowen ratio method, where several climatological parameters are measured on towers placed above the forest canopy (Shuttleworth, 1988). Soil moisture measurements are done with neutron probes (Calder *et al.*, 1986) or tensiometers (Veenendaal *et al.*, 1996) or both (Hodnett *et al.*, 1995). A combination of micro-meteorological, soil physical and ground water chemical measurements has also been introduced (Cook *et al.*, 1998).

Simpler methods have been presented where approximate estimates of AET are calculated based on potential evapotranspiration (PET) (Veenendaal *et al*, 1996). Penman's formula is a well known method to estimate PET. Potential evapotranspiration can be sustained until a critical soil moisture deficit is reached (Novak, 1989). Thereafter, a linear decrease from PET is often predicted. However, a more simple way to determine AET when soil moisture is limited is to assume an abrupt decrease in evapotranspiration to a fixed value. The critical value is difficult to determine because it is dependent on soil, plant and atmospheric conditions. Usually, relations have been determined for agricultural crops. AET does not fall below PET until 20 to 40% of available water content (AWC) is reached (Ritchie, 1973; Nkederim & Hailey, 1973; Rockström *et al.*, 1997). Assuming an abrupt decrease occurs, a fixed AET value of 1.5 mm d^{-1} can be estimated (Cook *et al.*, 1998; Hodnett *et al.*, 1995).

Overland flow has been measured with troughs (Bonell & Gilmour, 1978) or by hydrochemical tracers (Hensel & Elsenbeer, 1997). In recent years, a combination approach had been used where both hydrometric and hydrochemical methods are applied (Elsenbeer & Lack, 1996). Overland flow is often neglected in water balance studies. It is assumed that in such studies all water infiltrates the soil. The presence and absence of overland flow have been found in forest zones (Elsenbeer & Lack, 1996; Bonell & Gilmour, 1978; Fujieda *et al.*, 1997).

AWC is defined as the difference in soil moisture between field capacity (FC) and permanent willing point (PWP). Empirical relations such as regression equations have been used for determining the soil moisture content based on particle size distribution, bulk density, and percentage carbon. For soils consisting predominantly of low activity clays, such relationships are rare (Van den Berg *et al.*, 1997). Although most roots are found in the top of forest soils, an average effective root depth of 1 m can be used for the determination of soil moisture storage (Hodnett *et al.*, 1995). If dry periods exist, vegetation may extract water from deeper soil layers (Calder *et al.*, 1986; Hodnett *et al.*, 1995). In this study, primary focus is on the water balance determination and no empirical model for AWC determination is used.

Deep percolation is usually neglected in water balance studies (Veenendaal *et al.*, 1996), but this will often result in overestimating of AET. At low soil water suctions, macropore flow is present and water leaves the root zone by gravity. Downward movement of water ceases when field capacity is reached (McGowan & Williams, 1980).

The main aim of the study is to (i) determine AWC of three soils on one of the typical toposequences in the moist semi-deciduous forest zone of Ghana and (ii) present a simple water balance method from a combination of climatological and soil physical measurements.

Materials and methods

The study was carried out at the Agricultural Research Station at Kade in Ghana (6° 05' N; 0° 05' W) 90 km NW of Accra. The site is about 0.3 km^2 and about 150 m above sea level. It is located in the moist semi-deciduous forest zone.

According to Lawson *et al.* (1970), it falls into the *Antiaris-Chlorophora* association. The profiles are part of the Bekwai/Nzima-Oda association of the Ghanaian soil classification system. The soils at the upper and middle part of the catena belong to the

Bekwai, Nzima, and Kokofu series (Adu, 1992). According to World Reference Base (ISSS/ISRIC/FAO 1998) they are alumic acrisol, chromic acrisol and haplic lixisol, respectively. Bekwai is a Typic Paleudults, Nzima is a Kandic Paleudalf, and Kokofu is a Udic Kandiudalf according to Soil Taxonomy (Soil Survey Staff; 1998). The average slope of the catena is 4-5% and the area is drained by the seasonal Kadepon stream. Ahn (1970), Lawson *et al.* (1970), and Owusu-Bennoah *et al.* (2000) have earlier conducted various experiments on this catena but their focus has predominantly been on soil and vegetation studies and little attention has been paid to water balance analysis.

The texture of the soil profiles ranges from clay in the summit soils to clay loam and loam in the middle slope and in the valley bottom. The summit soils, Bekwai and Nzima, are clay soils of sedentary origin. They are red/brown, concretionary, acid, well drained clays. The middle slope soil, Kokofu, is slightly acid, yellowish brown clay loam developed in colluvial deposits. All three soils are formed over Birrimian rock with phyllite and intrusions of quartz as the main constituents (Wills, 1962). Saprolite and soft rock are found at 150-200 cm depth. Kaolinite is the predominant soil clay mineral. Physical and chemical soil properties are described in Owusu-Bennoah *et al.* (2000).

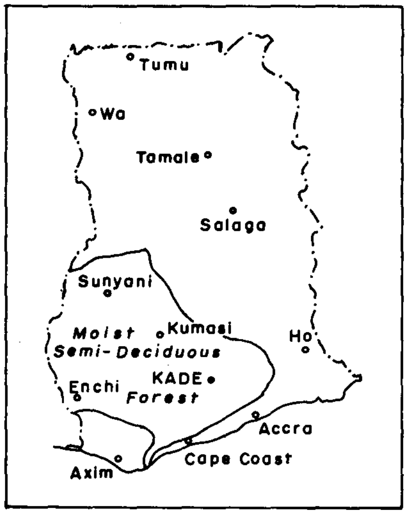

Fig. 1. Location of the catena at The Agricultural Research Station, Kade, Ghana.

The climate is humid tropical with bimodal precipitation pattern. The maximum monthly rainfall is 150-200 mm in May/June and September/October. Little rainfall is registered in December and January. The average rainfall is 1300-1400 mm per year (Wills, 1962). The potential evapotranspiration varies between 3 and 5 mm daily in the rainy and dry season, respectively, and may reach an annual value of 1400 mm. Temperature varies little during the year. The monthly average temperature reaches a maximum of 28-29 °C in February and March, and a minimum of 25-26 °C in July/August. The soil temperature regime is isothermic and the soil moisture regime is udic according to Soil Survey Staff (1998).

Soil sampling and analysis

Profiles were excavated in 1998 and soil samples taken from the major horizons (Table 1). Five undisturbed soil cores of diameter 6 cm and height 3.5 cm, were collected for each of the four horizons (A,E, Bt1, Bt2) of Bekwai, Nzima, and Kokofu series. Disturbed samples were taken from all horizons for determining texture, organic matter and pH.

The soil samples were air dried and gently passed through a 2 mm sieve. Coarse fragment content (>2 mm) was measured on a mass basis by sieving a minimum of 500 g of soil through a 2 mm sieve. Based on an assumed mass density of coarse fragments of 2650 kg m^{-3}, the volumetric coarse fragment content was calculated.

Particle size distribution was determined by sieving and by sedigraph 5100 (Micrometrics Instrument Corporation). The total carbon was determined by dry combustion. Organic matter content was determined from the carbon content assuming a C content of 58%. The pH was determined potentiometrically in 0.01 *M* $CaCl_2$ at a soil solution ration of 1:2.5.

Soil moisture retention was determined using the pressure plate apparatus with suctions of 10 kPa for undisturbed and 1500 kPa for disturbed samples as described in Smith and Mullins (1991). The values of dry bulk density and porosity were based on the weight of dry undisturbed samples and values are given as averages. The value of the volumetric coarse fragment content was used for the determination of volumetric water content at 1500 kPa as shown in Van Wesemael et al. (1995). The volumetric moisture content between 10 kPa (FC) and 1500 kPa (PWP) was used to calculate AWC in percent by volume and converted to root zone capacity (RZC) in mm assuming an effective root depth of 1 m.

Determination of the water balance

Precipitation was measured three kilometres from the catena at the meteorological station of the Agricultural Research Station at Kade. A standard rain gauge was used for daily measurements that were added up to give monthly totals.

Precipitation was assumed to fall at the beginning of every month if a soil water deficit existed. Potential evapotranspiration was calculated using the Penman formula:

$$PET = \frac{\Delta * (Rn + G)}{Lv * (\Delta + \gamma)} + \frac{\gamma * f(u) * (Pm - Pa)}{(\Delta + \gamma)}$$

where PET is potential evapotranspiration (mm d^{-1}), Δ is slope of vapour pressure curve (Pa $°C^{-1}$), Rn is net radiation and G is soil heat storage (kJ m^{-2} d^{-1}), Lv is latent heat of vaporisation (kJ kg^{-1}), γ is psychrometric constant (66.7 Pa $°C^{-1}$), pm and pa is mean saturated and mean actual vapour pressure, respectively (Pa), u is mean wind speed at 2 m height (m s^{-1}), and f (u) is the wind function (f(u) = 0.00263 * (0.5 + 0.54 * u)) (mm H_2O m^{-1} d^{-1}).

From sunshine hours, net radiation was calculated from the radiation balance (Oke, 1987). Short-wave incoming radiation was estimated by Angsrom's formula (Hutjes et al, 1990). In situations where sunshine hour data were unavailable, an average of existing data was calculated to replace the missing number. Short-wave outgoing radiation was determined, assuming an albedo of 0.2 for forest (Cook *et al.*, 1998; Oke, 1987).

Long-wave outgoing radiation was obtained by Stefan-Boltzmann's formula (Oke, 1987). Surface temperature was replaced by average air temperature. Long-wave incoming radiation was fixed to 80% of long wave outgoing radiation (Oke, 1987). Data of relative humidity and temperatures at 3 p.m and 6 a.m. were available. Maximum and minimum vapour pressure deficits were found, and an average was used as a monthly mean vapour pressure deficit. It was assumed that actual evapotranspiration did not exceed potential evapotranspiration. Soil and canopy heat storage was not considered. AWC was used as initial soil moisture value in July 1992. Fig. 2 shows the relation between AET/PET and AWC for the PET values 3 and 4 mm per day.

Actual evapotranspiration (AET) is set equal to potential evapotranspiration (PET) until actual soil moisture storage constitutes 20% of AWC. This method was used in the

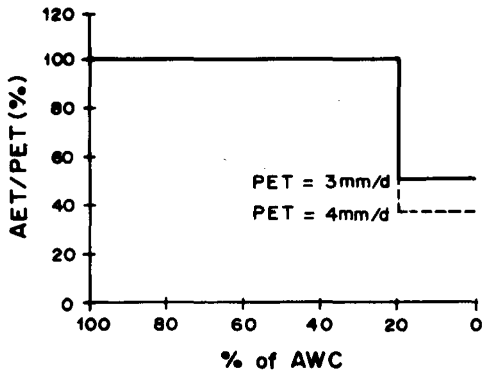

Fig.2. Relation between AET/PET and AWC for two typical PET values.

following to make a simple water balance determination. A value of 20% of AWC was used as critical value because the vegetation type is permanent semi-deciduous forest and roots are assumed well distributed. From PET and actual soil moisture storage, the number of days was calculated, where PET was maintained. For the remaining days of the month, an AEP of 1.5 mm per day was assumed (Cook *et al.,* 1998; Hodnett et al., 1995).

Results and discussion

Soils and soil water retention

Table 1 presents depths of horizons, particle size distribution, organic matter, and pH ($CaCl_2$). It should be noted that the coarse fragment content is included in the particle size distribution so that clay, silt, sand, gravel, stones, and organic matter equal 100%.

For all soil types, a humus A horizon is observed with an alluvial E horizon below. In all profiles, clay content increases with depth, and soils are supposed to be prone to clay migration which introduce a Bt horizon. Concretions are found in the E-horizon of Bekwai series, and in the Bt1 horizon of Nzima series. No coarse fragments of significance are found in Kokofu. Organic matter content is about 5% in the surface horizons. In the deepest horizons the soils are very acid with pH-values ranging between 3.7 and 4.4. In the upper horizons the pH values are markedly higher. This shows that the soils are strongly leached and the vegetation has accumulated exchangeable base cations in the uppermost soil layers. This has resulted in a slight increase in pH in the topsoil as compared with the subsoil. The soil pH has some impact on root development, because at low pH toxic conditions for the roots may develop. The effective root depth is often set at the depth of one meter because of lack of data, and this value will be used in this paper. But due to highly acid conditions in the subsoils of the three investigated soils, 1 meter may be an overestimated effective root depth. Table 2 shows the moisture content at different suctions and AWC for Bekwai, Nzima, and Kokofu.

Porosity is about 50% in the surface horizons decreasing with depth, but increases in Bt2 for all soil types. Soil bulk density reaches a maximum of 1.73 g cm^{-3} in Nzima, Bt1, but rather low in the humus A-horizons (1.2-1.3 g em^{-3}) and Bt2 horizons (1.3-1.5 g cm^{-1}). The low soil bulk density in the top horizon could be explained by high organic matter content and high biological activity. A better soil structure due to high carbon content also increases the available pore space and thereby lowering the bulk density.

Organic matter content is known to increase moisture content especially at low suctions. This effect was recognised in all surface horizons. High clay content means high surface area and high soil moisture retention, but much of this water will be unavailable for the plants. Whenever coarse fragment content is significant, soil moisture content is lowered. This was observed in Bekwa E-horizon and in Nzima Bt1 horizon.

TABLE 1.

Particle size distribution determined by sieving and sedigraph 5100 (Micrometric Instrument corporation), organic matter content (OM) in %, and pH (from Owusu-Bennoah et al, 2000). Coarse fragment content and dry soil bulk density are included. n is number of samples.

Profile Horizon	*Depth cm*	*<2 µm %*	*2-63 µm %*	*63-2000 µm %*	*>2000 µm %*	*OM %*	*pH (CaCl$_2$)*	*Dry soil bulk Density±1SD g/cm³ n=5*
Bekwai								
A	0-7	37.7	22.1	18.7	16.5	5.0	5.4	1.30±0.25
E	7-34	38.2	18.4	19.0	23.3	1.1	3.9	1.46±0.03
Bt1	34-71	56.1	22.1	12.5	8.4	0.9	3.8	1.34±0.06
Bt2	71-119	56.0	27.3	9.5	6.5	0.6	3.7	1.26±0.05
Nzima								
A	0-8	41.6	27.4	23.5	0.8	6.7	5.9	1.22±0.12
E	8-23	40.6	25.8	29.9	1.6	2.1	4.6	1.53±0.04
Bt1	23.60	39.9	15.9	16.6	26.8	0.8	4.3	1.73±0.12
Bt2	60.113	58.1	20.1	10.7	10.3	0.8	4.4	1.47±0.11
Kokofu								
A	0-7	30.4	41.7	23.3	0.4	4.2	4.8	1.22±0.18
E	7-39	28.6	38.2	32.2	0.1	0.8	4.1	1.62±0.05
Bt1	39-82	36.1	34.4	28.1	0.8	0.5	4.2	1.65±0.06
Bt2	82-120	43.9	27.6	27.5	0.4	0.6	4.4	1.50±0.19

This is due to the fact that coarse fragments decrease the total porosity. The standard deviations of the moisture content were high for Nzima and Bekwai compared to Kokofu. A varying amount of coarse fragments can be the reason for that.

The water content at field capacity (10 kPa) varies between 30 to 45 percent by volume except for the two horizons with a high content of concretions. The FC values are close to the results obtained by Pidgeon (1972) who studied moisture content of non-swelling clay soils in Uganda. In general, for the subsoils the water content at the permanent wilting point (1500 kPa) follows the clay content.

AWC of the different soil horizons in Bekwai is rather constant whereas available water capacity of Kokofu is highest in the top horizon and decreases with depth. Nzima shows a decrease in available water capacity with depth until the concretionary horizon (Bt) after which it increases. The AWC-values for the Bekwai is almost similar to the results of Lawson *et al.*, (1970), who also studied the soil water retention properties of the catena. On the contrary, the AWC found in Nzima did not correspond well with Lawson's *et al.* (1970) findings. This might be due to differences in soil morphology for example the depth of the concretion layers, and the fact that the samples in Lawson's study were not undisturbed samples as is the case in this study. On the other hand, the results of AWC in the present study are similar to other forest soils in the region (Obi, 1974). Assuming an

TABLE 2.
Porosity, field capacity, permanent wilting point, and AWC in volumetric % for Bekwai, Nzima, and Kokofu with one standard deviation (SD). Number of samples = 5.

Soil	*Depth* cm	*Porosity±1SD* %	*10 kPa ±1SD* %	*1500 kPa±1SD* %	*AWC±1SD* %
Bekwai					
A	0-7	49.1±10	30.2±4.6	13.6±0.6	16.6±4.0
E	7-34	46.2±0.9	27.9±2.5	9.9±0.2	18.0±2.3
Bt1	34-74	51.4±2.3	40.7±2.0	23.9±0.5	16.8±1.5
Bt2	71-119	54.5±1.7	39.1±8.1	21.2±1.0	17.9±7.1
Nzima					
A	0-8	51.5±4.7	43.4±4.7	23.1±3.5	20.3±1.2
E	8-23	42.1±1.6	39.3±1.5	22.2±1.1	17.0±0.5
Bt1	23-60	36.4±4.4	26.1±3.8	11.7±0.4	14.4±3.4
Bt2	60-113	46.5±3.9	45.2±3.1	22.9±0.4	22.3±2.7
Kokofu					
A	0-7	52.4±7.0	36.6±1.2	12.9±1.0	23.6±0.3
E	7-39	38.9±1.8	31.2±1.6	13.5±1.0	17.7±0.6
Bt1	39-82	38.2±2.3	31.7±1.2	18.1±0.3	13.6±0.9
Bt2	82-120	43.9±7.0	30.8±3.0	19.6±0.6	11.2±2.4

effective root depth of 1 m, the root zone capacity (RZC) is 174 mm for Bekwai, 184 mm for Nzima, and 152 mm for Kokofu.

Water balance

The water balance was calculated for five years, 1992-1997, beginning in July 1992. At that time of the year it is assumed that the soil water content is at field capacity because July is just at the end of the major rainy season. Thus AWC will be at its maximum value. AET was calculated from actual soil moisture storage in the previous month and precipitation in the month in question as explained in the materials and methods section. AET was subtracted from precipitation while surface runoff was neglected. Although measurements indicate surface runoff coefficients of up to 15% at this particular site during the rainy season, surface runoff was neglected in all months. If a surplus of water existed which exceeded AWC, deep percolation was assumed. Differences in AWC between Bekwai and Nzima were small. Therefore, only a water balance for Nzima and Kokofu was calculated. The monthly water balance of Kokofu is shown in figure 3, and Table 3 shows the water balance on annual basis for Nzima and Kokofu.

During the period of January 1993 to December 1997, a total rainfall of 7226 mm was recorded. On yearly basis the precipitation ranged between 1321 mm in 1994 and 1623 mm in 1996. The rainfall shows a bimodal pattern with particularly wet months in June and October. Maximum monthly precipitation was 348 mm in June 1997. The maximum potential evapotranspiration was 157 mm in November 1997 and the minimum was 66 mm in July 1993. On annual basis PET was about 1300 mm. The actual evapotranspiration became less than potential evapotranspiration during January, February, and March. The minimum AET was 29 mm in January 1995. On monthly basis, AET ranged between 24% and 100% of PET, on annual basis between 85% and 99%. Soil moisture deficit varied between no deficit and the RZC. Whenever soil moisture deficit was zero, any additional precipitation was assumed to infiltrate to become deep percolation. On monthly basis, deep percolation was between zero and 266 mm for both Nzima and Kokofu. The latter value was obtained when maximum rainfall was measured in June 1997. Deep percolation occurred mostly in June/July and September/October and in some years in

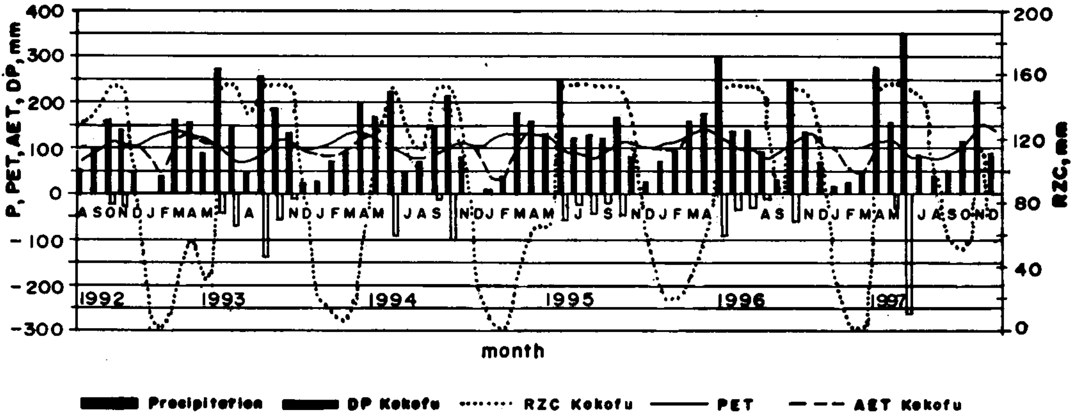

Fig. 3. The water balance of Kokofu from August 1992 to December 1997.

TABLE 3.
Annual water balance for Nzima and Kokofu

Profile	*Year*	*Precipitation mm*	*PET mm*	*AET mm*	*ΔS mm*	*Deep percolation mm*
Nzima	1993	1477	1300	1175	-7	309
	1994	1321	1267	1198	-65	188
	1995	1364	1318	1150	28	186
	1996	1623	1345	1329	70	224
	1997	1441	1304	1219	-48	270
average		**1445**	**1307**	**1214**	**-4**	**235**
Kokofu	1993	1477	1300	1150	-9	336
	1994	1321	1267	1168	-58	211
	1995	1364	1318	1123	23	218
	1996	1623	1345	1309	68	246
	1997	1441	1304	1190	-51	302
average		**1445**	**1307**	**1188**	**-5**	**263**

May, August, and November. The deep percolation ranged between 15% to 20% of the annual precipitation, and the maximum deep percolation was calculated to be 336 mm in 1993.

The method presented gives a quantitative indication of vertical movement of water of the represented soil types, although horizontal water movement was neglected. Precipitation is usually underestimated due to splashing, wetting, intensity, and aerodynamic factors. In this paper, the precipitation error is considered to be less that 5% due to low wind speed and rather high rainfall intensities (Allerup and Madsen, 1979). Furthermore, the precipitation measurements were taken at a distance from the catena, which introduced an additional error that is difficult to quantify.

Most of the rainfall is lost as AET. The calculations show that on monthly basis, AET is equal to PET in wet months and about 25% of PET in dry months. These findings are in line with Cook et al. (1998), who found AET to range between 90 and 35% of PET. According to Shuttleworth (1988), actual evapotranspiration in a humid tropical forest is 100 mm month^{-1}. On the average, the AET was also about 100 mm month^{-1} in this study. Low AET occurs in periods with limited soil moisture. If the forest can extract water from layers deeper than the effective root depth as indicated by Hodnett et al. (1995), AET may be higher than assumed. In that case, the period with growth limit due to water shortage may be shorter.

Deep percolation amounts are smaller for Nzima compared to Kokofu. This is due to a higher available water capacity of Nzima. The highest rainfall amount does not necessary result in maximum deep percolation because the soil can be dry at that time, and the precipitation water is then used to fill up soil water storage capacity. The temporal rainfall distribution is an important parameter for the determination of deep percolation. Two successive months with high precipitation in the wet season lead to high deep percolation amounts.

On annual basis, the AET calculations give about 1200 mm, which are similar to the values of Ledger (1975) and Veenendaal et al. (1996) who in their studies of water balances in West Africa got annual values of AET on 1146 mm and 1128 mm, respectively.

Annual deep percolation was calculated to be 16 and 18% of annual rainfall in the investigated period. Uncertainties on measurements are assumed to remove completely any differences between soil types. The percentage of the rainfall that is deep percolated is slightly higher than the values obtained in a study in Australia by Cook et al. (1998). There the deep percolation was estimated to be 12% of the total precipitation of 1720 mm. Differences in RZC and rainfall distribution could be the explanation of the small differences between the two environments. Deep percolation may be of little interest to a farmer but the amount is important with respect to leaching of nutrients.

Conclusion

The soils belonging to the Bekwai, Nzima, and Kokofu series, typical for the summit and middle part of the catenas in the tropical semi-deciduous forests in Ghana, show high AWC values which is due to high clay (and carbon) content. Concretionary horizons at shallow depth limit soil water content. For future water balance studies, field measurements of the soil water content will strengthen the calculations because it will be possible to obtain data on the drying of the soils. The estimation of the effective root depth is very important for the determination of the water balance as it is one of the key parameters for the calculation of the root zone capacity. Thus, further investigations on that issue are important.

The calculations showed an average AET of about 100 mm per month. Generally, AET is less than PET in January, February, and March. Calculations also show that 15-20% of precipitation is lost as deep percolation. Deep percolation is highly variable depending on the amount and time distribution of rainfall. The water balance can be divided into a wet and dry period. In the wet period, surplus water is present, and deep percolation takes place from June to November. In the dry period, the available water capacity is depleted.

Surplus rainfall means leaching of the soils and this correspond with the appearance and acidity of the soils. Lateral water movement should be included in future studies, because surface runoff measurements indicate that this parameter is significant in this area during the rainy season.

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