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Abstract

Six methods of determining regional values of average annual actual evapotranspiration from a mixed vegetation surface are applied to observations from 20 climatological stations in Malaŵi. Three of the methods are judged unsuitable because they either over or under-estimate substantially or do not exhibit the gradual increase in actual evapotranspiration with increasing rainfall: these methods are equilibrium evaporation and two others, Brutsaert-Stricker and Bouchet, based on the complementary evaporation concept. The remaining three methods are recommended for use in Malaŵi: catchment waterbalance, which is used as a yardstick against which the other methods are compared, gives values of actual evapotranspiration which vary between 39 and 67% of short grass potential evaporation at the same station; soil moisture recharge demonstrates the least scatter but suffers the disadvantage of requiring independent calibration; the last of the methods, a new empirical approach expressing actual evapotranspiration as the difference between the values of the constituent energy and aerodynamic terms of the Penman formula for short grass potential evaporation, gives a countrywide mean 9% lower than that of the catchment waterbalance.

Contents

Notation

e	Actual vapour pressure	millibar
e_s	Saturated vapour pressure at air temperature	millibar
$\frac{n}{\bar{N}}$	Ratio of actual to maximum possible hours of bright sunshine	dimensionless
q	Energy excess in the complementary concept (water equivalent)	mm
r	Albedo	dimensionless
AAE	Average annual actual evaporation estimated from catchment waterbalance method	mm
AAE'	Average annual actual evaporation estimated from soil moisture recharge method	mm
AAR	Average annual rainfall	mm
AAY	Average annual yield estimated from catchment waterbalance method	mm
AAY'	Average annual yield estimated from soil moisture recharge method	mm
AE_j'	Annual value of actual evaporation for year j estimated from soil moisture recharge method	mm
AY_j'	Annual value of yield for year j estimated from soil moisture recharge method	mm
E	Actual evapotranspiration	mm
E_a	Drying power of the air (water equivalent)	mm
E_{BO}	Bouchet actual evapotranspiration	mm
E_{BS}	Burtsaert-Stricker actual evapotranspiration	mm
E_D	Actual evapotranspiration estimated from Difference method	mm
E_E	Equilibrium evaporation	mm
E_{ij}	Monthly potential evaporation for month i and year j	mm
E_o	Penman open water evaporation	mm
E_p	Potential evapotranspiration	mm
E_{PN}	Penman short grass potential evaporation	mm
E_{po}	Evaporative power of the air the absence of advection	mm
E_{PT}	Priestley-Taylor potential evaporation	mm
G	Ground heat flux (water equivalent)	mm
K	Number of years	dimensionless
M_a	Aerodynamic term of Penman short grass potential evaporation	mm
M_e	Energy term of Penman short grass potential evaporation	mm
Q	Large scale advection (water equivalent)	mm
R	Rainfall, precipitation	mm
R_a	Incoming short-wave radiation at the top of the earth's atmosphere (water equivalent)	mm
R_{ij}	Monthly rainfall for month i and year j	mm
R_L	Outgoing long-wave radiation (water equivalent)	mm
R_n	Net radiation (water equivalent)	mm
R_s	Incoming short-wave radiation at the surface	mm
S	Soil moisture recharge	mm
T_a	Mean air temperature	K
U_2	Wind speed at a height of two metres	ms^{-1}

V	Soil moisture storage	mm
W	Groundwater storage	mm
Y	Yield, i.e. surface runoff	mm
α	Empirical constant employed in the Priestley-Taylor potential evaporation formula	dimensionless
γ	Psychrometric constant	millibar K^{-1}
δ	Difference	dimensionless
Δ	Slope of the saturation vapour pressure curve at mean air temperature	millibar K^{-1}
σ	Stefan-Boltzman constant	mm day^{-1} K^{-4}
Σ	Sum	dimensionless

1. Introduction

1.1 TOPOGRAPHY

Malaŵi is located at the southern end of one limb of the East African Rift Valley system which dominates the topography of the country. Lake Malaŵi, the third largest lake in Africa, occupies the northern two thirds of this section of the rift (Figure 1.1). The lake is at an altitude of 470 m and its only outlet, the River Shire, drains southwards to the lower rift valley at 90 m altitude before joining the River Zambezi. In subsequent sections of this report two parts of the rift valley will be mentioned frequently: the region adjacent to Lake Malaŵi is called the 'lakeshore', whilst the region extending southwards from approximately the River Shire's confluence with the River Mwanza is called the 'Lower Shire Valley'.

All rivers in Malaŵi drain eventually into the River Shire (Fig. 1.1), except those in the eastern part of the country. Here there is an extensive catchment area draining into Lake Chilwa, from which there is no outlet, and a smaller area draining into the lakes and rivers of Mozambique.

The topography of Malaŵi is particularly varied (Figure 1.2) but the country may be divided into tour major physiographic zones as follows:

a) plateau
b) highland
c) rift valley plains
d) escarpment

The plateau is at an altitude of between 900 and 1200 m and features broad undulating plains. The underlying rocks are those of the Precambrian Malaŵi Basement Complex. The climate is temperate and the original vegetation is Brachystegia-Julbernadia woodland. These are the most densely cultivated regions of the country and little of the original woodland remains. An important feature of the plateau are the dambos, broad grass-covered swampy valleys which overlie impervious strata and which become saturated with water during the rainy season; they exhibit a peculiar hydrological behaviour which sets them apart from all other types of catchment within the country.

The highland rises abruptly from the plateau reaching altitudes of between 2100 and 3000 m. The underlying rocks are granites, phyllonites or syeno-granites. The climate is cool and the natural vegetation is forest relics and open grassland. These areas are now either forest or game reserves, partly covered with exotic trees.

The plains of the rift valley floor are gently sloping and of very low relief. They extend along parts of the lakeshore and upper River Shire valley at levels of less than 600 m and fall to less than 100 m above sea level in the Lower Shire valley; they are covered mainly by alluvial deposits of the Quaternary Age. The climate is semi-tropical and the original vegetation is mixed savannah woodland. In this zone the most favourable soils have been developed into irrigated rice and sugar schemes.

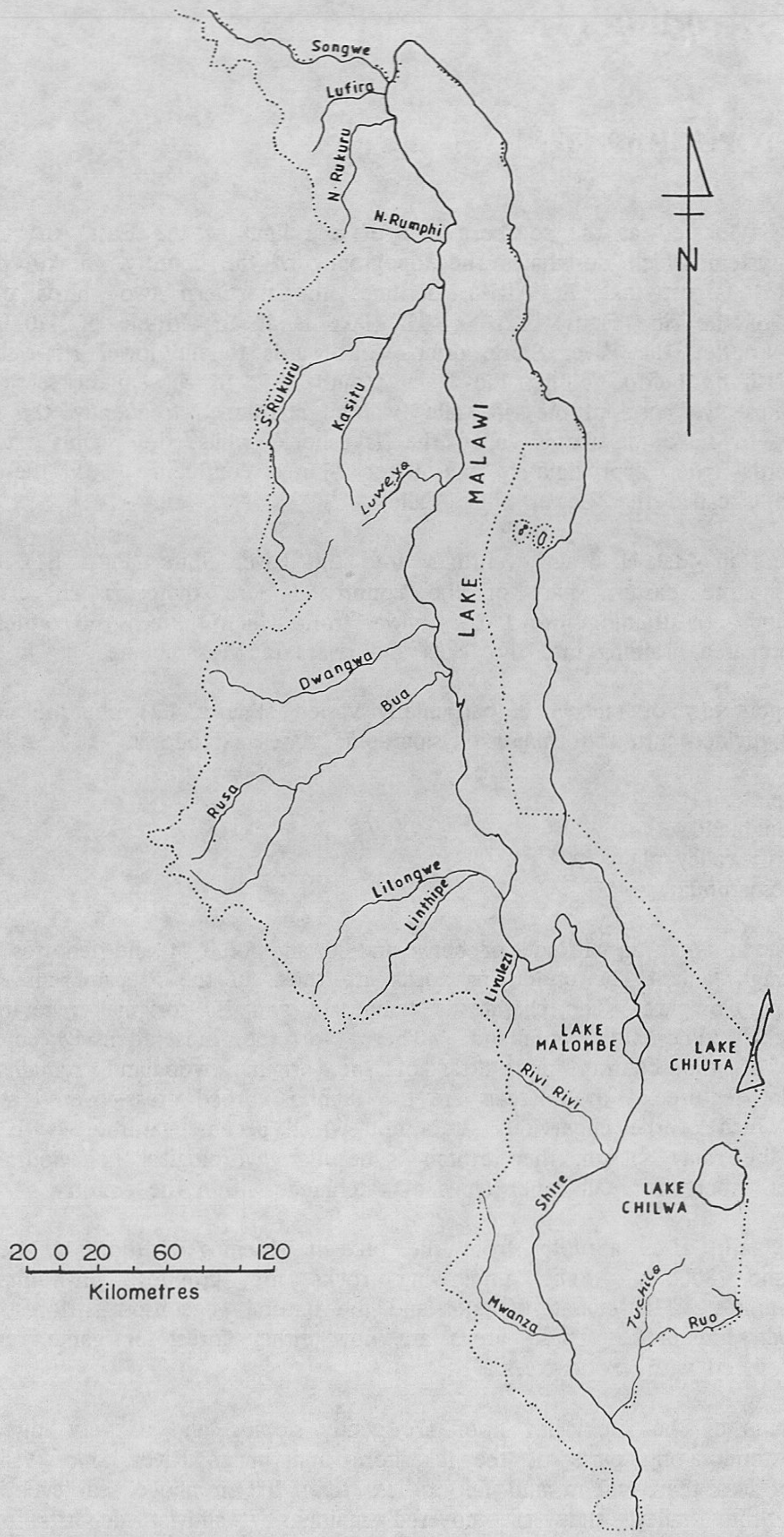

Figure 1.1 Major drainage systems of Malaŵi

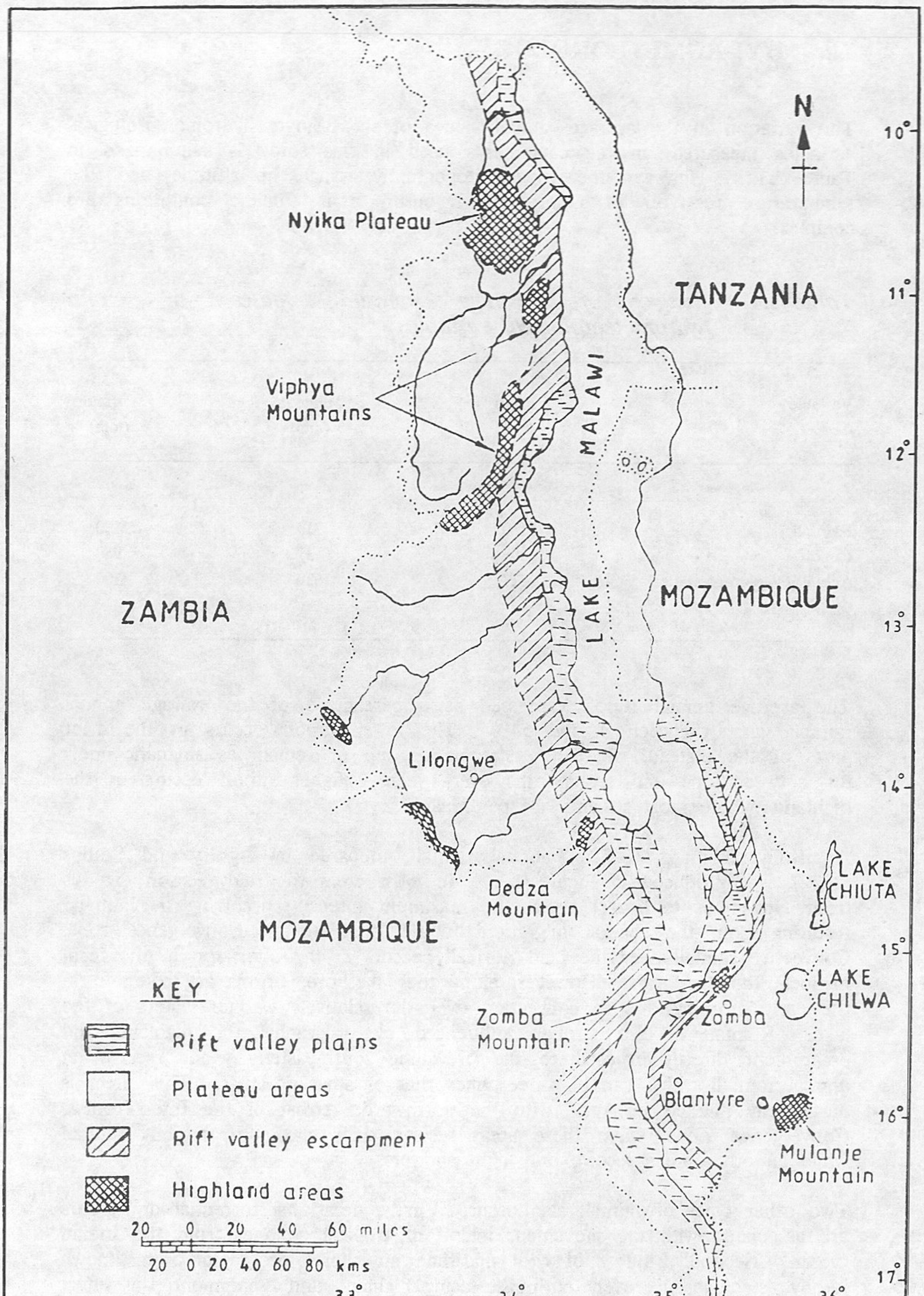

Figure 1.2 Major physiographic zones of Malaŵi (after Smith-Carington and Chilton, 1983)

1.2 HYDROMETEOROLOGY

The variation in the average annual values of the primary hydrometeorological variables measured on the catchments used in this study is summarized in Table 1.1. However the rugged topography, range of altitude and the temperature reservoir of Lake Malaŵi ensure that climatic conditions are complex.

Table 1.1 Range of average annual values of main hydrometeorological variables

Variable	Mean (mm)	Minimum (mm)	Maximum (mm)
Rainfall	1130	710	2100
Runoff	309	37	980
Actual evapotranspiration	817	630	1100

The average annual runoff expressed as a percentage of the average annual rainfall varies between 4 and 54%. The lower runoff occurs in the drier parts of the plateau, where the streams dry up or remain as stagnant pools for between one and six months every year. Higher runoff occurs in the highland, where most streams are perennial.

An isohyetal map of mean annual rainfall, prepared by Agnew and Stubbs (1972), is reproduced in Figure 1.3. In most areas the rainy season extends from November to March, with the maximum intensity occurring in January, resulting from the general migration of the Inter-Tropical Convergence zone. Convective rainfall over the land normally occurs in the afternoon in the form of local thunderstorms. However, along the lakeshore, storms are common in the early morning due to convection over the relatively warmer waters of the lake. Rainfall is also strongly influenced by orography; the highland and escarpment directly exposed to the prevailing south-easterly winds receive an annual rainfall which can be three times that of adjacent areas. This effect is particularly marked in April, with the northwards retreat of the Inter-Tropical Convergence Zone, when these areas receive their maximum monthly rainfall while all other areas receive only light showers.

Two other types of rainfall also occur. Firstly, occasional torrential downpours are associated with the movement inland of tropical cyclones from the Indian Ocean. Secondly, inflow of cool maritime air causes orographic rain, known locally as 'chiperoni', over south-east facing highland and escarpment; this effect if particularly apparent when contrasted with the otherwise fine weather of the dry season, which extends from May to October.

Temperature is closely related to altitude; latitude has much less significance.

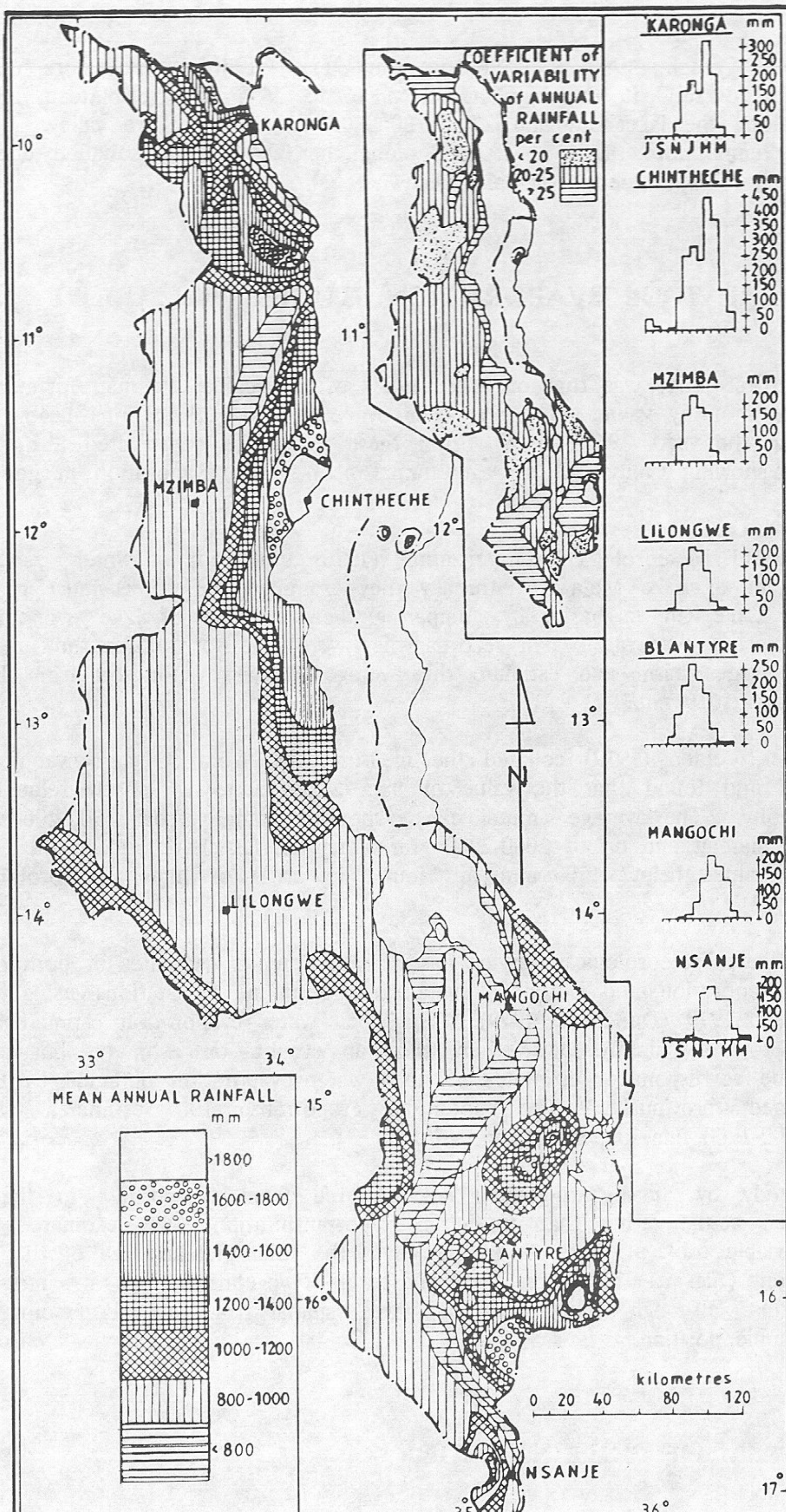

Figure 1.3 Mean annual rainfall (after Agnew and Stubbs, 1972)

Van der Velden (1980) showed that the mean monthly temperature ranges from 10 to 16°C in the highland, from 16 to 26°C on the plateau, 20 to 29°C along the lakeshore and 21 to 30°C in the Lower Shire valley. The annual temperature range at stations along the lakeshore is subdued due to the ameliorating influence of Lake Malaŵi.

1.3 PREVIOUS EVAPORATION STUDIES IN MALAŴI

The earliest study was that of Pike (1962) who used the Penman formula to estimate monthly values of open water evaporation at 23 stations using data spanning the years 1952-1961. From these results he constructed a map of Malaŵi showing isolines of average annual open water evaporation in imperial units.

The World Meteorological Organization (1976) undertook a water resources assessment of Lake Malaŵi. Initially they examined the waterbalance of the smaller Lake Chilwa basin; by comparing their estimate of lake evaporation with adjacent evaporation pan records, they were able to transfer their results to the larger basin and estimate the average annual evaporation from Lake Malawi as 1610 mm.

Van der Velden (1979) collated the measurements from 38 pan evaporation stations and found that the value of pan evaporation was closely related to topography. The average annual pan evaporation ranges from 1500-2000 mm on the plateau and up to 2000-2200 mm along the lakeshore and in the Shire Valley; values below 1500 mm are found in areas of high and prolonged rainfall.

The Malaŵi Meteorological Service has derived Penman estimates of both open water evaporation and potential evapotranspiration at 19 stations using data from 1972-1979 (Dandaula, 1979). The open water evaporation estimates are similar to, but slightly lower than, the pan evaporation estimates but differ from the corresponding estimates of open water evaporation obtained by Pike, mentioned previously. The potential evapotranspiraton estimates range from1100-1700 mm, depending on altitude.

The study by Smith-Carington (1983) differed from the others in that it examined actual rather than potential evapotranspiration. She estimated that this variable took a value of 780 mm over the total plateau area of the Bua catchment (Fig. 1.1) based on a consideration of vegetation types and moisture conditions, although there will be large spatial variations depending on topographic position.

1.4 AIM OF PRESENT STUDY

The aim of this study is to provide methods for estimating actual evapotranspiration in Malaŵi. In this report justification is provided to support the application of these methods only under the following restraints:

a) the evaporating surface is mixed vegetation as described in Section 1.1 (a mixture of cultivated fields, open grassland, pockets of woodland, small irrigation schemes etc.); a continuous vegetation surface, such as a forest canopy, has not been examined

b) the estimate is of annual values of actual evapotranspiration - although all the proposed methods use monthly observed data as input (and several of the methods can provide monthly estimates of actual evapotranspiration) all the comparisons and supporting evidence described in this report have been directed towards examining average annual values

c) the estimate is primarily a regional, rather than a site-specific, value of actual evapotranspiration - although the comparison between the methods is undertaken using a definitive network of climatological stations, the most reliable method, against which the others are adjudged, is based on a non-site-specific catchment waterbalance.

The majority of previous evaporation studies in Malaŵi have been directed towards estimating open water evaporation and potential evapotranspiration; actual evapotranspiration has not been examined in any depth.

Open water evaporation estimates, derived from either climatological station or evaporation pan data, are used to compute evaporative losses from large open-water surfaces, such as lakes or reservoirs. Potential evapotranspiration estimates are used to determine water use, i.e. evapotranspiration, or irrigated or rainfed crops. Irrigation engineers and agricultural hydrologists have devised various empirical methods for relating actual evapotranspiration to potential. However, because of the moisture deficit which builds up in the soil during the long dry season in Malaŵi, values of actual evapotranspiration of non-irrigated vegetation will, in practice, be of the order of half those of potential evapotranspiration in the same region.

It would prove extremely useful to possess reliable methods for estimating actual estimating actual evapotranspiration directly from observed data. Such methods could be used to determine:

a) the water use of rainfed and irrigated crops, without the use of empirical factors

b) the waterbalance of catchments; the difference between the rainfall and actual evapotranspiration, is the sum of the surface runoff and the recharges to soil moisture and groundwater storages.

1.5 METHODS OF ANALYSIS

The study commences with a review of the variation of potential evapotranspiration estimated from observations drawn from a network of 20 climatological stations spread throughout the country. This leads to a classification of the stations according to the respective sizes of the average annual value of their energy and aerodynamic terms, constituents of the Penman formula for estimating short grass potential evaporation.

In the main body of the report, the suitability of six methods of estimating actual evapotranspiration, for use under the soil-vegetation complex of this region of Central Africa, is examined. Of these, five are well-established methods, the last is a new method first proposed in this study.

The first method is a simplified catchment waterbalance applied to rainfall and runoff data from 38 catchments in Malawi (Drayton *et al.*, 1980). Neglecting annual changes in groundwater and soil moisture storage enables average annual actual evapotranspiration to be expressed in terms of the average annual rainfall. The second method introduces the concept to soil moisture recharge (Thornthwaite, 1948), which is applied to monthly rainfall data and potential evapotranspiration; the value of soil moisture recharge is found ideally from an independent field survey.

The remaining four methods determine actual evapotranspiration directly from climatological data, expressing it in terms of the constituent energy and aerodynamic terms of the Penman formula for short grass potential evaporation; one of the methods also requires values of the outgoing long-wave radiation. One of these methods is that of equilibrium evaporation (Denmead and McIlroy, 1970); the other three are based on the concept of complementary evaporation, and include the methods of Bouchet (1963), Brutsaert and Stricker (1979), and the new so-called Difference method.

Values of average annual actual evapotranspiration were determined using each of the six methods for data observed at the 20 climatological stations. Accuracy of all methods was assessed by comparing their results with those of the catchment waterbalance, which was considered the most reliable.

2. Rainfall and potential evaporation

This section will examine the variability of rainfall and potential evaporation throughout the country, prior to investigating the different methods of estimating actual evaporation in the main body of the report.

2.1 CLIMATOLOGICAL STATIONS

The basic records used in this study to estimate evaporation are drawn from observations, established by the Malaŵi Meteorological Service, which are situated throughout the country (Figure 2.1) at altitudes ranging from 58 m at Makhanga to 1633 m at Dedza (Figure 2.2). The latitude, longitude and altitude listed in Table 2.1 are provided by the Meteorological Service. In his study on pan evaporation in Malaŵi, Van der Velden (1979) lists the same statistics; these show slight differences in latitude and longitude and larger differences in some of the altitudes. As latitude and altitude form an important input to the calculation of potential evaporation, these discrepancies should be resolved in future to improve the accuracy of the estimates.

Six of the stations lie close to the shore of Lake Malaŵi and together with two further stations, Ngabur and Makhanga located in the Lower Shire Valley, form the group of stations described as in the 'rift Valley'. The remaining 12 stations, all at higher altitudes, form the group of stations on 'upland' areas.

2.2 ESTIMATING POTENTIAL EVAPORATION

Potential evaporation (E_p) was estimated by the well-known Penman formula:

$$E_p = \frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} f\ (U_2)\ (e_s - e) \qquad (2.1)$$

All symbols are explained in the Notation at the beginning of the report.

In this study the semi-empirical formula for the estimation of net radiation (R_n) is used. This has been applied by de Bruin and Stewart (1983); they, in turn, adopted it from Doorenbos and Pruitt (1977) who proposed a relationship between sunshine hours and solar radiation suitable for tropical latitudes. It reads:

$$R_n = R_a(1 - r)\ (0.25 + 0.50 \frac{n}{N} - \sigma T_a^4\ (0.1 + 0.9 \frac{n}{N})\ (0.34 - 0.44 \sqrt{e}) \qquad (2.2)$$

To estimate Penman short grass potential evaporation ($E_p = E_{PN}$) the albedo r was set equal to 0.25. To estimate Penman open water evaporation ($E_p = E_o$) the albedo was set to 0.05.

The wind function $f(U_2)$ is the same as that applied by Brutsaert and Stricker

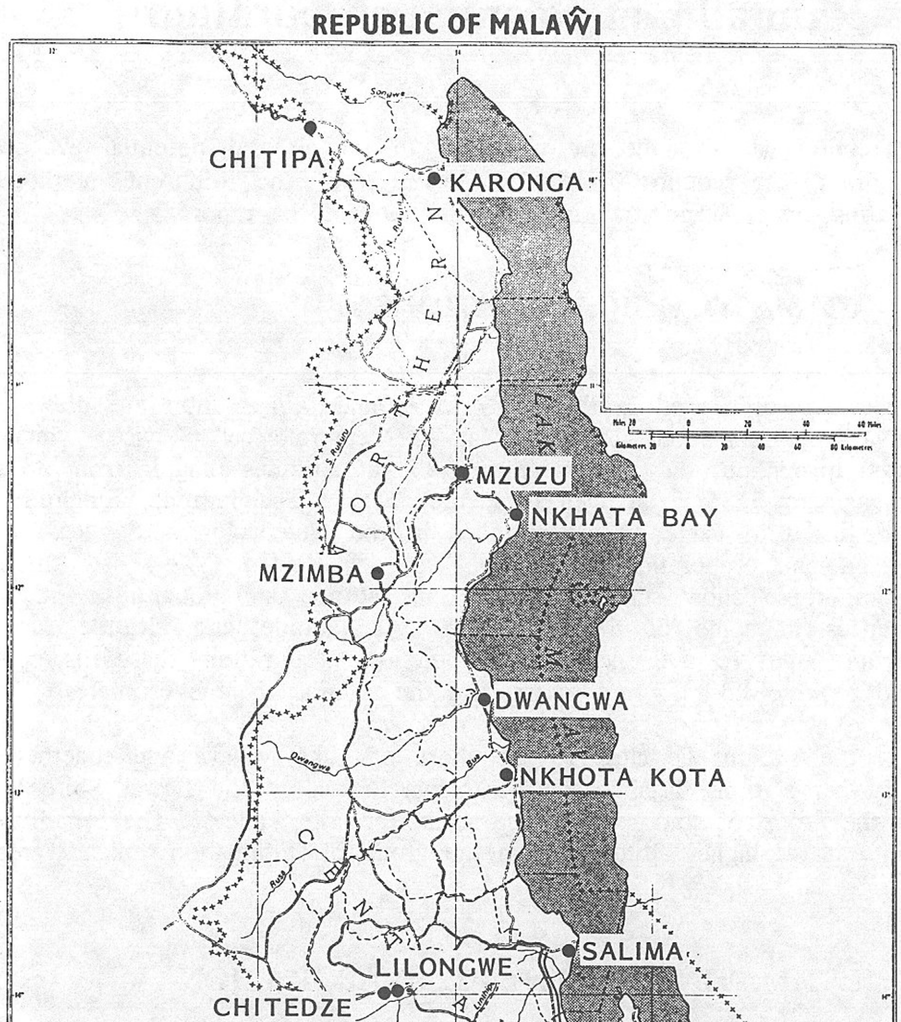

Figure 2.1 Location of climatological stations

Table 2.1 Climatological stations (records published by Malâwi Meteorological service)

Climatological Station	Latitude (South)	Longitude (East)	Altitude (m)	Period of record used
Bvumbwe	15° 55'	35° 04'	1147	1970-78
Chichiri	15° 47'	35° 02'	1134	1970-78
Chileka	15° 41'	34° 58'	769	1970-78
Chitedze	13° 59'	33° 38'	1150	1970-78
Chitipa	09° 42'	33° 16'	1279	1970-78
Dedza	14° 19'	34° 16'	1633	1970-78
Dwangwa	12° 29'	34° 05'	489	1973-74
Karonga	09° 57'	33° 54'	529	1970-78
Lilongwe	13° 58'	33° 42'	1135	1970-78
Makhanga	16° 31'	35° 09'	58	1970-78
Makoka	15° 31'	35° 13'	1029	1970-78
Mangochi	14° 26'	35° 15'	485	1970-78
Mimosa	16° 05'	35° 35'	653	1970-78
Mzimba	11° 54'	33° 36'	1353	1970-78
Mzuzu	11° 26'	34° 01'	1254	1970-78
Ngabu	16° 30'	34° 57'	102	1973-78
Nkhata Bay	11° 36'	34° 18'	500	1970-78
Nkhota Kota	12° 56'	34° 19'	501	1970-78
Salima	13° 45'	34° 35'	520	1970-78
Thyolo	16° 09'	35° 13'	820	1970-78

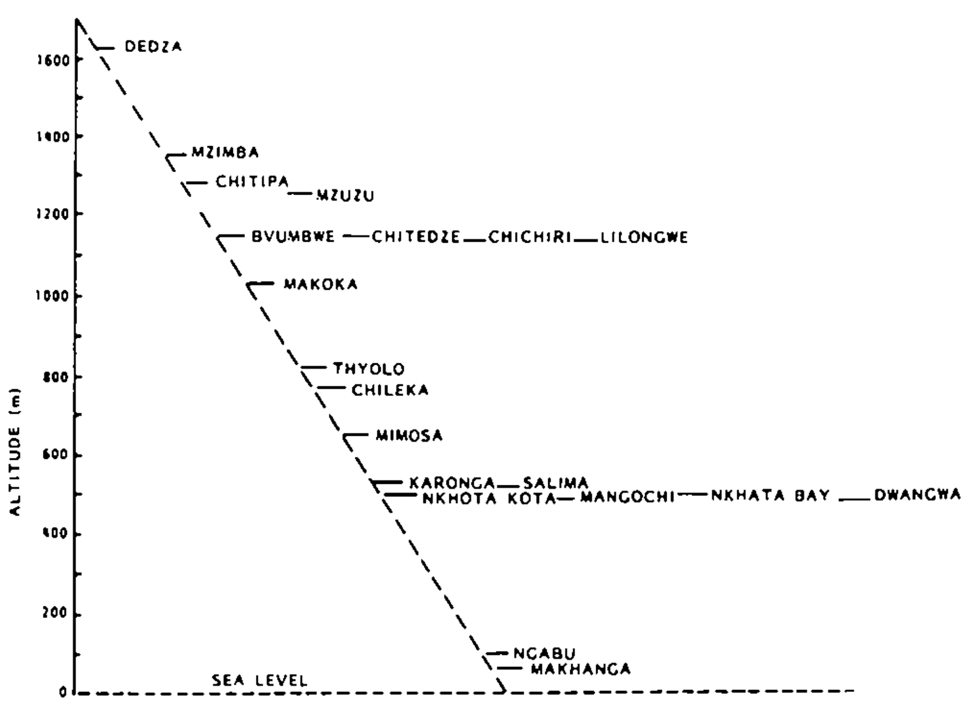

Figure 2.2 Altitude of climatological stations

(1979) in one of their versions of the Penman formula. Expressed in units of W m^{-2} mb^{-1} the exact expression used was:

$$f(U_2) = 7.4\ (1.0 + 0.54\ U_2) \qquad (2.3)$$

where U_2 is the wind speed (m s^{-1}) at a height of 2 m. The monthly mean wind run over 24 hours was used, with no additional modification incorporating the ratio between day and night-time wind speeds. Before substitution in Equation 2.1 the units of $f(U_2)$ were converted to mm day^{-1} mb^{-1} to make them compatible with the net radiation term expressed as a water equivalent.

Appendix 1 contains in greater detail the practical background to the calculation of potential evaporation for Malaŵi; it discusses how certain minor variable were calculated, anomalies discovered and corrections made to the data before processing.

The four types of basic data required for using Penman's formula are temperature, humidity, wind run and sunshine hours. Monthly mean climatological data of this form, together with rainfall, are published by the Malaŵi Meteorological Service (1970-1978). When this study began there were nine years of records (1970-1978) for all stations except Ngabu which had records for six years (1973-1978) and Dwangwa which had records only for 1973 and 1979 and which was subsequently closed.

Monthly values of E_{PN} and E_o were estimated by Equation 2.1 using the appropriate value of albedo. Average annual values of R, E_{PN} and E_o, calculated over the nine years of record, are listed in Table 2.2 Average monthly values of the same variables for each of the 20 stations are given in Appendix 2. Variations in average annual values of rainfall and potential evaporation, and also the energy term and aerodynamic term are shown in Appendix 3.

2.3 VARIATIONS IN RAINFALL

Average annual values of rainfall (R) taken from Table 2.2 are also shown in Figure A3.1. For upland stations R varies without major inconsistencies from a low of 898 mm at Lilongwe to 1544 mm at Mimosa. Amongst rift valley stations low values are recorded to the south of the lake, the lowest value being 722 mm at Makhanga. In contrast, along the western lakeshore, rainfall demonstrates considerable variation, ranging from 1147 mm at Karonga to 1759 mm at Nkhota Kota, but without any smooth progression from north to south.

The coefficients of variation listed in Table 2.2 should provide a measure of the variation of the annual values of rainfall at each station; in general, rainfall varied considerably from year to year. Fig. A3.2 shows that these coefficients are consistent both for the two stations located in the Lower Shire Valley and for all the upland stations except Chitedze and Chileka which have low and high values respectively. Along the lakeshore Nkhota Kota and Nkhata Bay, which have the highest values of average annual rainfall, show

Table 2.2 Average annual values of rainfall R, Penman short grass potential evaporation E_{PN} and Penman open water evaporation E_o

Climatological Station	R Mean (mm)	R CV (%)	E_{PN} Mean (mm)	E_{PN} CV (%)	E_o Mean (mm)	E_o CV (%)
Bvumbwe	1122	23.6	1430	3.0	1820	2.8
Chichiri	1141	21.2	1512	5.3	1914	4.6
Chileka	912	30.0	1816	4.2	2244	3.9
Chitedze	983	8.5	1558	3.9	1975	3.7
Chitipa	953	17.3	1769	1.2	2201	1.2
Dedza	943	16.7	1472	2.8	1874	2.6
Dwangwa*	1265	33.6	1618	5.1	2065	4.8
Karonga*	1147	32.9	1835	2.4	2297	2.1
Lilongwe	898	22.2	1578	3.8	1992	3.6
Makhanga**	722	15.4	1784	3.0	2239	2.8
Makoka	1060	15.6	1506	3.7	1907	3.5
Mangochi*	856	28.3	1806	3.3	2261	3.1
Mimosa	1544	25.3	1404	2.5	1804	2.5
Mzimba	925	19.2	1513	2.8	1939	2.7
Mzuzu	1182	16.0	1316	1.9	1710	2.0
Ngabu**	859	19.0	1840	3.7	2288	3.4
Nkhata Bay*	1740	18.8	1534	2.7	1968	2.6
Nkhota Kota*	1759	16.2	1759	2.8	2208	2.7
Salima*	1426	31.0	1816	4.2	2276	4.0
Thyolo	1229	24.4	1427	2.4	1830	2.5
Mean	1130	21.8	1610	3.2	2040	3.1

CV Coefficient of variation
* Rift Valley Stations - Lakeshore
** Rift Valley Stations - Lower Shire Valley
Others are Upland Stations

year-to-year variation similar to that of upland stations. However lakeshore stations with lower rainfall show much higher year-to-year variation.

2.4 VARIATIONS IN POTENTIAL EVAPORATION

The spatial variation over Malaŵi of average annual values of evaporation estimates, (E_{PN} and E_o) taken from Table 2.2 are shown in Figures A3.3 and A3.4. In general higher values of Penman short grass potential evaporation,

(E_{PN}) are recorded along the rift valley floor with a maximum of 1840 mm at Ngabu; lower values are found on the upland areas, with a minimum of 1316 mm at Mzuzu. Exceptions to these general trends are lower values of 1618 and 1534 mm at Dwangwa and Nkhata Bay, and higher values of 1769 and 1816 mm at Chitipa and Chileka.

Since the formula for Penman open water evaporation (E_o) and that for E_{PN} differ only to the extent of the value of the albedo chosen, their values show a similar pattern of spatial variability, but with maximum and minimum estimated values for E_o of 2297 mm at Karonga and 1710 mm at Mzuzu. Values of E_{PN} expressed as a fraction of the corresponding value of E_o for each climatological station vary between 76 and 81%; because of this small range, some of the comments made in subsequent sections about properties of E_{PN} will also hold for E_o. However, to avoid considerable repetition, comments will be confined to E_{PN} in the remainder of this report and the reader, armed with corresponding values of E_{PN} and E_o in either Table 2.2 or Appendix 2, is encouraged to deduce the similar relationships for E_o.

The small coefficients of variation listed in Table 2.2 indicate that there is very little change from year to year in annual values of E_{PN} and E_o. Chitipa station is notable in possessing particularly low variation, which may be a symptom of a very stable climate.

2.5 THE CONSTITUENT ENERGY AND AERODYNAMIC TERMS

To look more closely at the variability of the Penman short grass potential evaporation estimate (E_{PN}) it is useful to break it down into its constituent components:

$$E_{PN} = M_e + M_a \tag{2.4}$$

where M_e, the energy term, is defined as:

$$M_e = \frac{\Delta}{\Delta + \gamma} R_n \tag{2.5}$$

and M_a, the aerodynamic term, is defined as:

$$M_a = \frac{\gamma}{\Delta + \gamma} f(U_2)(e_s - e) \tag{2.6}$$

For each climatological station, average annual values of M_e and M_a are listed in Table 2.3 (see also Figures A3.5 and A3.6); average monthly values are given in Appendix 2. The mean average annual values of M_e and M_a for the two main groups of stations are given in Table 2.4.

Examination of the spatial variation of M_e showed that all the higher values were found at rift valley stations; for this group the range is small, 1250 to 1291 mm, and there is no discernible difference in values between lakeshore and Lower Shire Valley stations. The mean value of M_e for upland areas is 11% less than that of the rift valley (Table 2.4), and individual values exhibit rather more spatial variation ranging from 1075 to 1170 mm. The coefficients

Table 2.3 Average annual values of the energy term M_e and aerodynamic term M_a constituents of the Penman short grass potential evaporation E_{PN}

Climatological Station	M_e Mean (mm)	M_e CV (%)	M_a Mean (mm)	M_a CV (%)
Bvumbwe	1079	1.6	352	8.2
Chichiri	1106	1.5	406	17.5
Chileka	1170	2.1	646	8.2
Chitedze	1127	2.0	431	9.2
Chitipa	1170	1.1	599	2.8
Dedza	1075	1.8	397	5.7
Dwangwa	1259	2.8	359	13.4
Karonga	1291	0.9	544	6.8
Lilongwe	1117	2.4	461	9.4
Makhanga	1290	2.1	494	9.0
Makoka	1104	1.8	402	9.6
Mangochi	1250	2.0	556	6.7
Mimosa	1128	1.9	276	6.1
Mzimba	1157	2.3	356	6.1
Mzuzu	1109	2.3	208	7.5
Ngabu	1267	1.9	571	9.0
Nkhata Bay	1261	2.0	272	9.3
Nkhota Kota	1250	1.9	510	5.6
Salima	1268	2.6	546	9.2
Thyolo	1129	2.3	299	4.0
Mean	1180	2.0	434	8.2

Table 2.4 Mean average annual values of energy term M_e and aerodynamic term M_a for the two groups of climatological stations

Term	Rift valley stations Mean (mm)	Upland area stations Mean (mm)
Energy term (M_e)	1267	1123
Aerodynamic term (M_a)	482	403

of variation in Table 2.3 demonstrate that there is extremely little change from year to year in M_e at all stations, with the least variation being shown by Karonga and Chitipa.

Values of the aerodynamic term (M_a) are considerably smaller than those found for the energy term (M_e) varying from 19 to 55% of the corresponding value. Despite these lower absolute values they exhibit greater spatial variation, ranging from 208 to 646 mm. Although the mean value of M_a for the group of upland area stations is 16% less than that for the Rift Valley stations (Table 2.4), the distinction is not so clear-cut as was found for M_e previously; not all values of M_a in the rift valley exceed those on upland areas. Values of M_a appear to be depressed below 300 mm in the two areas centred respectively on Thyolo-Mimosa and Nkhata Bay-Mzuzu, with a least value of 208 mm estimated for Mzuzu; these areas exhibit for major part of the year a moist climate suitable for tea cultivation. On the other hand the highest values of M_a occur at Chitipa (599 mm) and Chileka (646 mm), both of which are located on the leeward side of high ground, so a possible explanation is warm dry air descending over the stations. Table 2.3 shows that the coefficients of variation for M_a are several times larger than those for M_e, although their mean values are much smaller, as noted previously; this implies that changes in M_e and M_a both contribute substantially to the year-to-year variation in E_{PN}. Chitipa station is again noteworthy for its extremely low coefficient of variation, whilst high values at Dwangwa and Chichiri led to further checks on the basic climatological data; that at Dwangwa arises from a genuine large change in vapour pressure deficit between the two years of data, whilst that at Chichiri cast doubts on the homogeneity of the wind records at this station.

2.6 CLASSIFICATION OF CLIMATOLOGICAL STATIONS

An alternative way of highlighting these variations in energy and aerodynamic terms, for each of the 20 climatological stations, is shown in Figure 2.3. The plotted points appear to lie in a number of distinct groups and these differences may be used to draw up a classification with stations within each class having similar values of M_e and also M_a (Table 2.5). The name 'regions' cannot be used, as points within a particular class are not necessarily contiguous. Whilst Classes 1 to 3 are distinct, the border between Classes 4 and 5 is blurred and a subjective decision was made to include Bvumbwe and Mzimba in Class 4 rather than Class 5, based on their values of M_a. This classification will be used later in the soil moisture recharge chapter to distinguish the climatic properties of different stations.

Table 2.5 Mean average annual values of energy term M_e and aerodynamic term M_a arising from classification of climatological stations

Class No	Climatological stations in class	M_e Mean (mm)	M_a Mean (mm)
	Karonga	1269	537
	Makhanga		
	Mangochi		
	Ngabu		
	Nkhota Kota		
	Salima		
	Dwangwa	1260	316
	Nkhata Bay		
	Chileka	1170	623
	Chitipa		
	Bvumbwe	1109	401
	Chichiri		
	Chitedze		
	Dedza		
	Lilongwe		
	Makoka		
	Mzimba		
	Mimosa	1122	261
	Mzuzu		
	Thyolo		

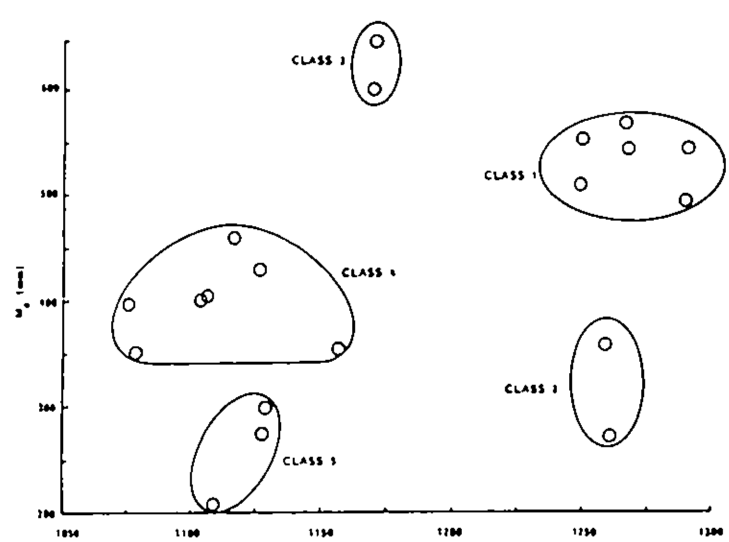

Figure 2.3 Plot of aerodynamic term M_a versus energy term M_e of Penman short grass potential evaporation for 20 climatological stations

3 Catchment waterbalance

3.1 SIMPLIFIED WATERBALANCE

The waterbalance of a catchment over given period may be expressed in terms of the main variables as:

$$\Sigma R = \Sigma Y + \Sigma E + \delta V + \delta W \qquad (3.1)$$

where R is rainfall
Y is yield i.e. surface runoff
E is actual evaporation
V is soil moisture storage
W is groundwater storage

and Σ and δ represent sum and difference respectively.

Although the changes in soil moisture and groundwater storage in Malaŵi during a typical year may be substantial, it is suggested that the changes from one year to the next are small. Regarding soil moisture storage, towards the end of the dry season after several months with little rainfall, the vegetation will have increasing difficulty in abstracting available water, and soil moisture deficits will tend asymptotically towards an upper limit. Regarding groundwater storage, Smith-Carington and Chilton (1983) found that, for boreholes with the longest and most frequent records, there was no evidence of declining water levels over the period 1971-1981 in either the weathered basement or alluvial aquifers. Therefore, provided the period for the waterbalance calculation is chosen to be the 12 months commencing at the start of the rainy season and finishing at the end of the long dry season, and provided that a minimum of five years' records are used, the terms involving soil moisture and groundwater storage may be safely neglected. In this case the waterbalance may be expressed in the following simplified form:

$$AAR = AAY + AAE \qquad (3.2)$$

Where AAR is average annual rainfall
AAY is average annual yield
AAE is average annual actual evaporation.

Average annual yield is the average annual runoff volume expressed as a depth in millimetres per year over the catchment.

3.2 ACTUAL EVAPORATION ESTIMATED FROM CATCHMENT RECORDS

As part of their regional analysis of river floods and low flows, Drayton *et al.* (1980) examined the relationship between annual yield and rainfall for 47 catchments distributed throughout Malaŵi. Annual values of catchment yield were calculated by summing the daily discharge data over the period 1 November to 31 October, which for Malaŵi runs from the start of the rainy season until the end of the following dry season. To estimate catchment annual rainfall a number of raingauges, normally two or three, were chosen on or near the selected catchment. Annual rainfall totals at these gauges for the same period as that above were weighted and combined using the Thiessen polygon method. Where either yield or rainfall data were missing for a particular year, this year was rejected, and some catchments were rejected entirely because there were no suitable raingauges. Further details of these analyses are given in Hill and Kidd (1980).

For the remaining 38 river gauging stations, catchment averages of annual rainfall and yield are listed in Table 3.1. Although for any given catchment the same years were used to determine the average values of rainfall and yield, it did not prove feasible to select a single period that was common to all the catchments. Therefore values listed in Table 3.1 should not be looked upon as forming long-term averages over a standardized period, for example three decades, that is often used as a common basis for rainfall records. Rather they should be regarded as preliminary estimates, which can be refined when longer records become available, of the magnitude of these hydrological variables in this part of Central Africa.

The values of rainfall and yield in Table 3.1 may be substituted into the simplified waterbalance, Equation 3.2, to provide, from their difference, estimates of catchment average annual actual evaporation, AAE. These values, also listed in Table 3.1, are superimposed on a map of Malaŵi in Figure 3.1, where they are located approximately at the centroid of the contributing catchment upstream of the river gauging station. Although there is a smooth progression between the majority of neighbouring estimates of actual evaporation, some anomalies are apparent where individual values differ substantially from those surrounding them. Values of 1077 and 1112 mm at station Nos 2.B.8 and 14.C.4. can be explained by the location of these catchments on the summit plateaux of inselbergs rising hundreds of metres above the surrounding plains. Variation of altitude between adjoining catchments may also explain the low estimate of 672 mm for station 2.B.22. However it is more difficult to provide a physical reason for the low value of 572 mm at station No. 15.A.8 and high values of 950 and 912 mm at station Nos. 7.E.2. and 7.F.2. respectively; a more likely reason is inaccuracies in the basic data, such as leakage of discharge past the river gauging station, paucity of raingauges leading to a poor estimate of catchment rainfall, or a wrong estimate of catchment area.

Inspection of Table 3.1 shows that in general values of actual evaporation vary between 572 and 1112 mm but the majority lie within the range 650 to 950 mm. The coefficient of variation of values from all the 38 catchments is 16%. In contrast values of rainfall lie approximately within the range 700 to 2100 mm, with a coefficient of variation of 28%, whilst values of yield lie approximately within the range 40 to 1000 mm, with a coefficient of variation of 80%. Consequently it may be deduced that, of the three hydrological variables under consideration, actual evaporation demonstrates the least variation throughout Malaŵi.

Table 3.1 ***Recorded catchment average annual rainfall AAR and yield AAY; with actual evaporation AAE estimated from their difference (After Drayton et al., 1980)***

River gauging station No	Name	AAR (mm)	AAY (mm)	AAE (mm)
14.B.2	Tuchila	1110	193	917
14.D.2	Ruo	1280	395	885
14.C.4	Chapaluka	2090	978	1112
14.A.2	Luchenza	1070	270	800
1.D.24	Kwakwazi	1240	332	908
1.F.2	Tangadzi East	1300	370	930
1.R.18	Mpamadzi	1080	199	881
2.B.8	Mulunguzi	2060	983	1077
2.B.21	Likangala	1430	499	931
2.B.22	Thondwe	880	208	672
2.C.3	Dombasi	1730	882	848
2.C.8	Naisi	1280	312	968
3.F.3	Nadzipulu	1000	337	663
4.B.1	Linthipe	880	133	747
4.B.3	Linthipe	910	192	718
4.D.4	Lilongwe	930	155	775
4.D.6	Lilongwe	940	182	758
4.E.1	Lingadzi	810	82	728
15.A.8	Lingadzi	870	298	572
5.D.1	Bua	900	83	817
5.D.2	Bua	900	73	827
5.D.3	Mtiti	710	53	657
5.E.1	Namitete	930	228	702
5.E.2	Bua	910	119	791
6.C.1	Dwangwa	740	37	703
16.F.1	Limphasa	1300	403	897
16.F.2	Luweya	1480	500	980
16.F.5	Luchelemu	1090	260	830
16.F.6	Luwawa	1240	340	900
7.D.3	Lunyangwa	1210	232	978
7.E.2	South Rukuru	990	40	550
7.F.1	Runyina	920	233	687
7.F.2	Chelinda	1260	348	912
7.H.1	North Rumphi	1320	661	659
7.G.11	Kambwiya	1370	625	745
7.G.14	South Rukuru	880	81	799
8.A.2	North Rukuru	910	227	683
17.C.6	Wovwe	1060	428	632
	Mean	1130	309	817
	Standard deviation	320	247	128

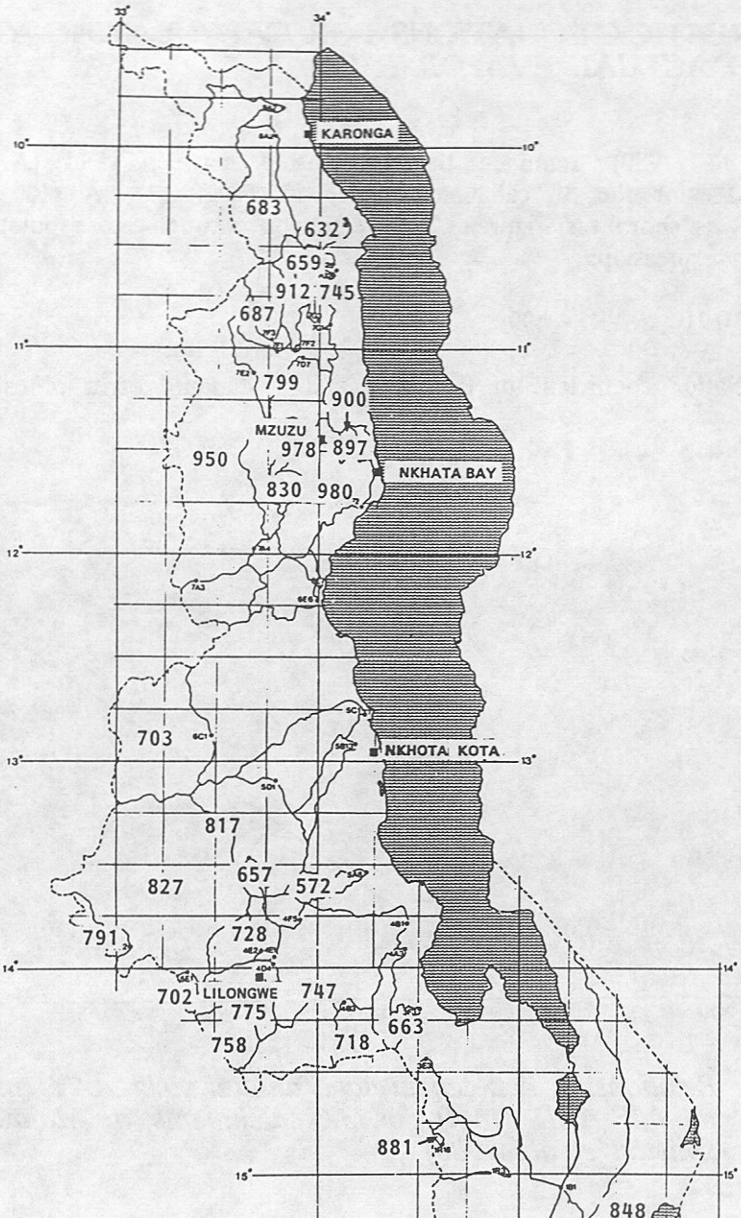

Figure 3.1 Estimated values of catchment average annual actual evaporation (mm)

3.3 YARDSTICK EQUATIONS FOR CALCULATING YIELD AND ACTUAL EVAPORATION

Drayton *et al.* (1980) examined the relationship between yield (AAY) and rainfall (AAR) for the 38 catchments listed in Table 3.1. A plot of AAY against AAR is shown in Figure 3.2; a regression through these points yielded the following expression:

$$AAY = 0.71 \quad AAR - 490 \tag{3.3}$$

with a correlation coefficient of R = 0.93 and a standard error of estimate of 90 mm.

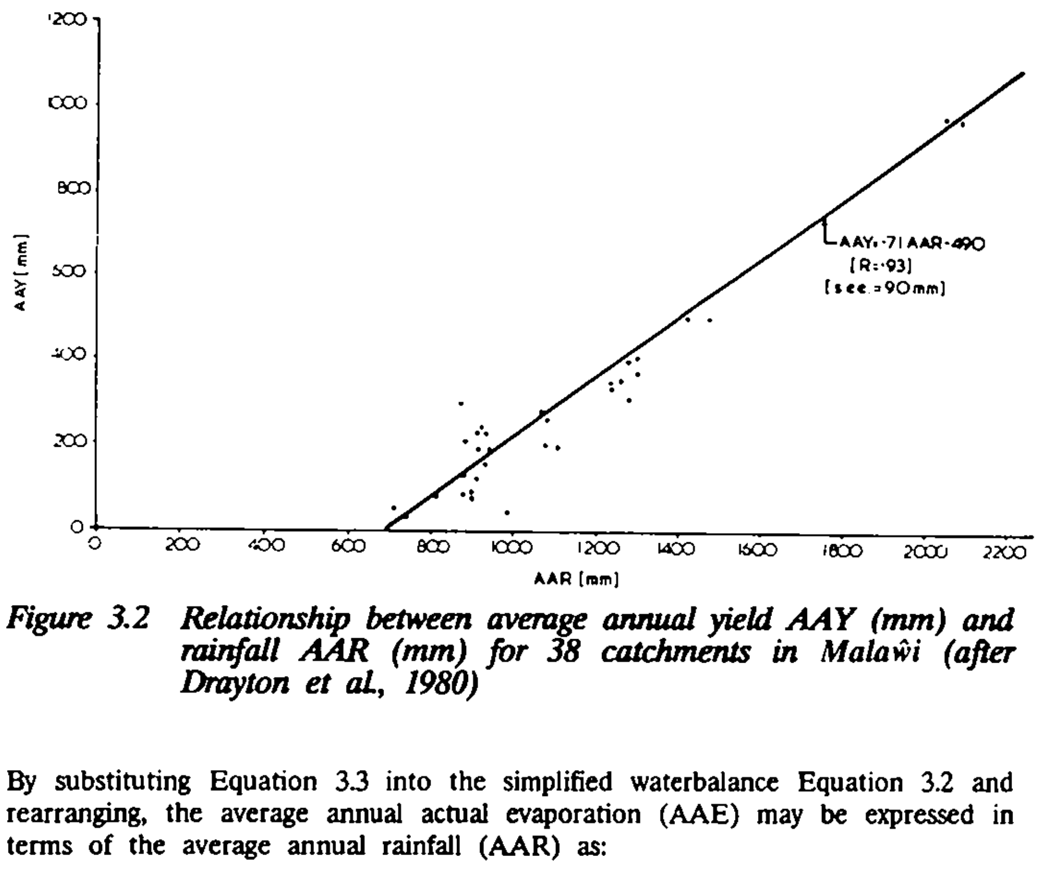

Figure 3.2 Relationship between average annual yield AAY (mm) and rainfall AAR (mm) for 38 catchments in Malaŵi (after Drayton et al., 1980)

By substituting Equation 3.3 into the simplified waterbalance Equation 3.2 and rearranging, the average annual actual evaporation (AAE) may be expressed in terms of the average annual rainfall (AAR) as:

$$AAE = 0.29 \quad AAR + 490 \tag{3.4}$$

Because the deviation of an AAY value from the regression line (3.3) is reflected in an equal, but opposite, deviation of the corresponding AAE value from the regression line (3.4), it can be demonstrated that Equation 3.4 retains the same standard error of estimate (90 mm) as Equation 3.3, but the correlation coefficient is reduced to 0.72. Equation 3.4 shows that actual evaporation increases slightly with increasing rainfall. The expression is valid only within the rainfall range to 2100 mm, but Drayton *et al.* (1980) point out that it should be used with caution for rainfall of below 800 mm. Equations 3.3 and 3.4 are used in Figure 3.3 to demonstrate how average annual actual evaporation, yield and rainfall vary with increasing average annual rainfall; this format emphasizes that, for any given rainfall, the sum of the yield and actual evaporation is equal to the rainfall.

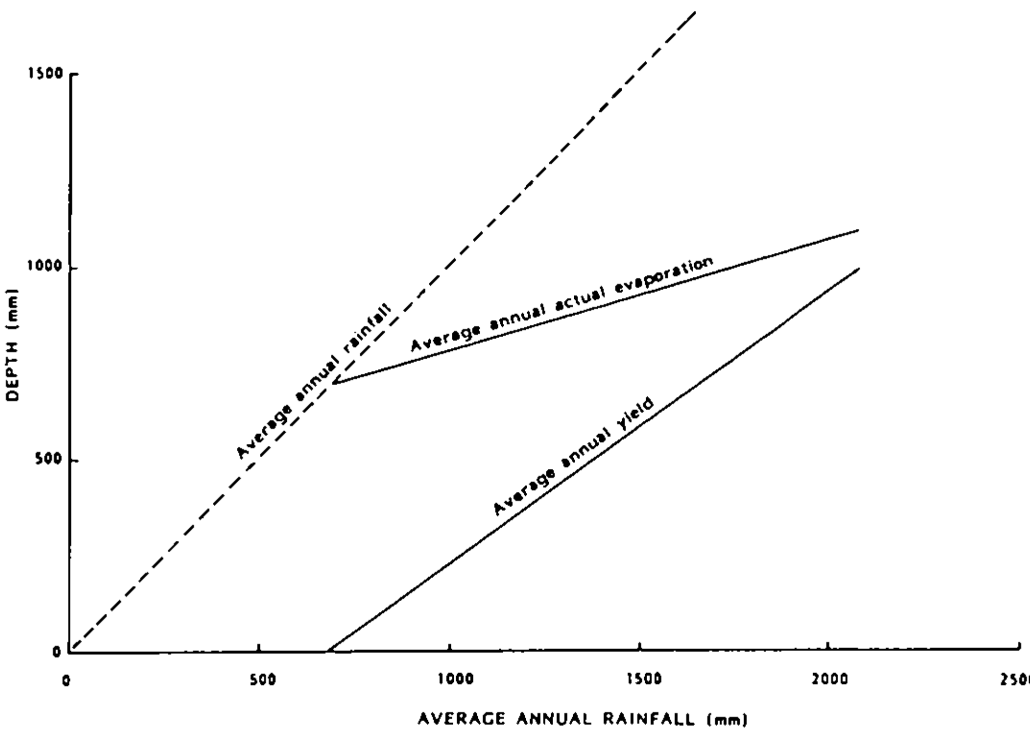

Figure 3.3 Relationship between actual evaporation, yield and rainfall from catchment waterbalance

Because of the high number of catchments examined and the wide range of average annual rainfall sampled, it is considered that the relationships shown in Fig. 3.3 provide, at present, the most reliable method, amongst those considered in this report, of estimating actual evaporation and yield given a knowledge of the rainfall at the location under consideration. They will be used as a yardstick against which other methods of estimating actual evaporation will be compared.

3.4 EXTRAPOLATION OUTSIDE RANGE OF OBSERVED RAINFALL

Because the relationships shown in Fig. 3.3 are valid only for a limited range of average annual rainfall, it is worthwhile to speculate what form they might take outside this range (Figure 3.4). At rainfalls lower than 700 mm it is moist for much of the year. As the rainfall continues to increase the actual evaporation will approach the potential evaporation, which itself has an upper limit governed by the intensity of net radiation (R_n) occurring at the evaporating surface (de Bruin, 1983). Estimated average annual values of R_n are listed in Section 5.3; for upland area stations it will be noted that this limit is approximately 1600 mm, whilst for rift valley stations it is 120 mm

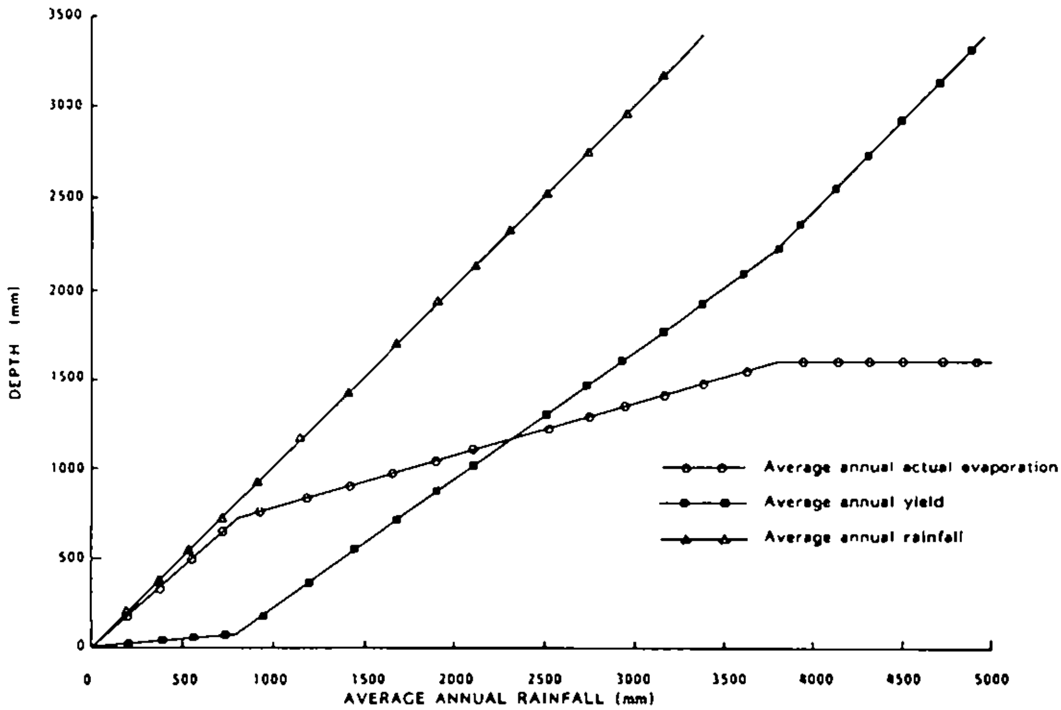

Figure 3.4 Possible variation in average annual actual evaporation and yield outside the range of observed rainfall values

higher. At higher rainfalls still it is thought that actual evaporation will not increase at the same rate as the increase of rainfall, and their relationships will thus run parallel at their upper ends, as shown in Fig. 3.4

3.5 ACTUAL EVAPORATION ESTIMATED FOR CLIMATOLOGICAL STATIONS

Equation 3.4 may be used to estimate actual evaporation for a catchment located anywhere in Malaŵi where the average annual rainfall is known. In the extreme case where the catchment area tends to zero it will be assumed that the expression may also be used for estimates at a point, though possibly with less reliability. In particular, Table 3.2 lists the values given by this expression in estimating average annual actual evaporation (AAE) at the 20 standard climatological stations. In this table the values listed of average annual rainfall (AAR) are taken equal to the corresponding values of R listed in Table 2.2. Table 3.2 also lists the values of average annual yield (AAY) obtained by using Equation 3.3. Values are AAE and AAY found for Makhanga station should be used with care since AAR is less than 800 mm for this station.

Table 3.2 Average annual yield AAY and actual evaporation AAE estimated from average annual rainfall AAR recorded at climatological stations

Climatological station	AAR (mm)	AAY (mm)	AAE (mm)
Bvumbwe	1122	307	815
Chichiri	1141	320	821
Chileka	912	158	754
Chitedze	983	208	775
Chitipa	953	187	766
Dedza	943	180	763
Dwangwa	1265	408	857
Karonga	1147	324	823
Lilongwe	898	148	750
Makhanga	722	23	699
Makoka	1060	263	797
Mangochi	856	118	738
Mimosa	1544	606	938
Mzimba	925	167	758
Mzuzu	1182	349	833
Ngabu	859	120	739
Nkhata Bay	1740	745	995
Nkhota Kota	1759	759	1000
Salima	1426	522	904
Thyolo	1229	383	846
Mean	1130	315	819

3.6 RATIO OF ACTUAL TO POTENTIAL EVAPOTRANSPIRATION

It is now feasible to make a preliminary survey of how much lower actual evapotranspiration is than potential evapotranspiration throughout the country. Values of actual evaporation (AAE) from Table 3.2 were expressed as a fraction of Penman short grass potential evaporation (E_{PN}) from Table 2.2. These fractions, listed in Table 3.3, range from a minimum of 39% at Makhanga to a maximum of 67% at Mimosa, with a countrywide mean value of 51.4%. The variation of this fraction throughout the country is shown in Figure 3.5.

Table 3.3 Actual evaporation, AAE, estimated from catchment waterbalance, expressed as a fraction of Penman short grass potential evaporation, E_{PN}

Climatological Station	$\frac{AAE}{E_{PN}}$ (%)	Climatological Station	$\frac{AAE}{E_{PN}}$ (%)
Bvumbwe	57.0	Makoka	52.9
Chichiri	54.3	Mangochi	40.9
Chileka	41.5	Mimosa	66.8
Chitedze	49.7	Mzimba	50.1
Chitipa	43.3	Mzuzu	63.3
Dedza	51.8	Ngabu	40.2
Dwangwa	53.0	Nkhata Bay	64.9
Karonga	44.9	Nkhota Kota	56.9
Lilongwe	47.5	Salima	49.8
Makhanga	39.2	Thyolo	59.3
		Countrywide mean	51.4

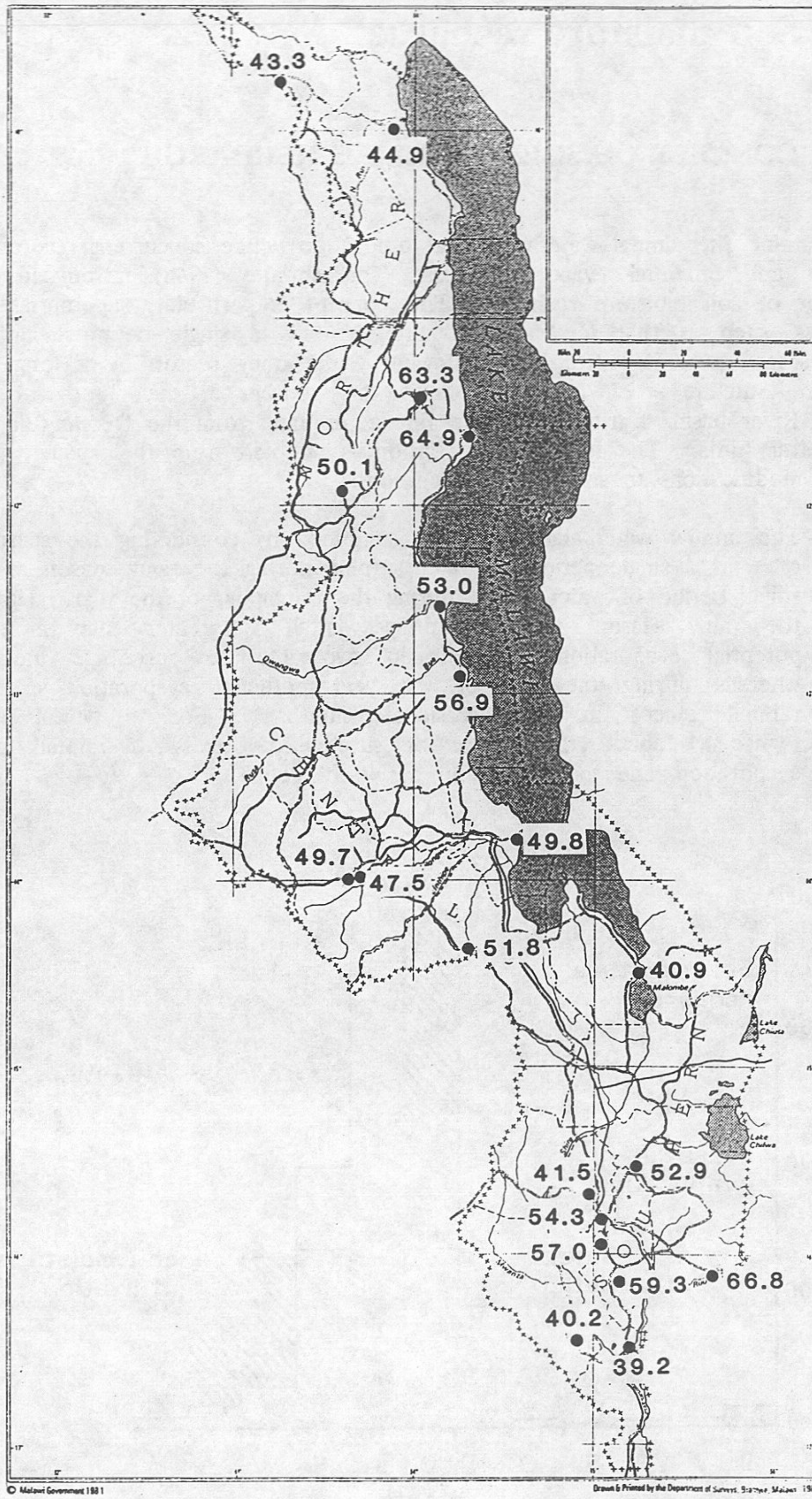

Figure 3.5 Actual evaporation AAE expressed as a fraction (%) of potential evaporation E_E

4. Soil moisture recharge

4.1 CONCEPT OF SOIL MOISTURE RECHARGE

To examine the annual waterbalance at a location where concurrent records of rainfall and potential evaporation exist, Thornthwaite (1948) introduced the concept of soil moisture recharge. This concept is particularly appropriate in climates, such as that in Malaŵi, where there is a single definitive annual rainy season separated from the following year's rainy season by a long dry season. Sutcliffe *et al.* (1981) employed this concept in their study of the Betwa River basin, a tributary of the Jamna, draining from the Deccan Plateau in central India. The following description is adopted from their paper, with minor modifications to suit Malaŵi conditions:

> The annual waterbalance may be simplified by considering the seasonal cycle as a single period of water surplus during the rainy season and a single period of water deficit during the remainder of the year. During the rainy season period, monthly rainfall is greater than monthly potential evaporation for between two and six successive months, whereas during the rest of the year potential evaporation exceeds rainfall except in the occasional month. For a typical year Figure 4.1 shows the period of surplus of excess of rainfall over evaporation, and the subsequent period of deficit.

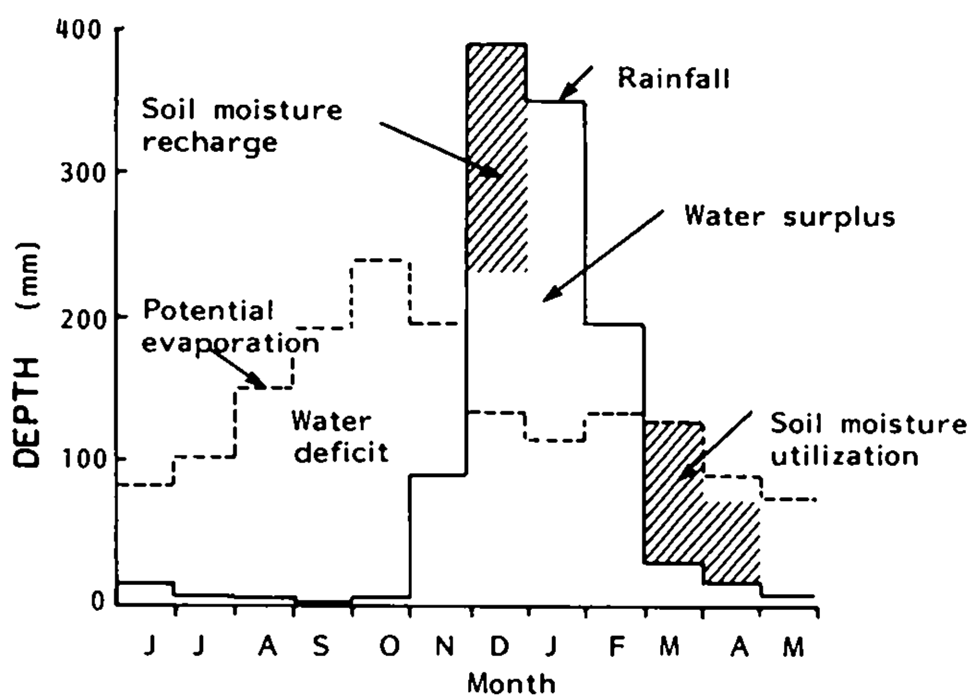

Figure 4.1 Schematic diagram of annual waterbalance cycle (after Sutcliffe et al., 1981)

The soil moisture recharge may be superimposed on this diagram, which then shows, to use the terminology of Thornthwaite (1948), a period of soil moisture recharge followed by a period of water surplus and then, after the end of the rainy season, a period of soil moisture utilization followed by a period of water deficit. This surplus supplies groundwater recharge as well as surface runoff. The soil moisture recharge clearly must equal the soil moisture utilization. Because the soil moisture storage is generally full at the end of the rainy season and always reaches wilting point during the dry season, the annual recharge will bring the storage from wilting point to field capacity throughout the rooting depth; this difference is defined as the 'root constant'. The soil moisture recharge should be reasonably constant from year to year in the absence of land-use change and may be considered as a first charge on the net rainfall, the surplus of rainfall over evaporation.

Furthermore, brief periods of drought during the rainy season and most periods of rain during the rest of the year, do not affect this cycle. The soil moisture deficit during dry periods in the rainy season will not approach wilting point, and the occasional rainfall surplus during April or May will not normally be sufficient to eliminate the soil moisture deficit. Thus, the net rainfall, or gross seasonal surplus, can be deduced by subtracting monthly potential evaporation from the monthly rainfall whenever the rainfall is the larger, and adding these monthly differences to give the net rainfall for the year.

Assuming that differences in groundwater storage between successive years are small in comparison with the annual groundwater recharge, the annual yield, which is the sum of surface and groundwater flows at the outlet of a catchment, is equal to the net rainfall less soil moisture recharge. Actual evaporation is assumed to equal potential evaporation during those months in which rainfall exceeds potential evaporation; during the remaining months actual evaporation is restricted by what moisture is available, and equals the sum of both the monthly values of rainfall together with the soil moisture utilization. The annual total of actual evaporation is thus estimated by subtracting the net from the gross rainfall and adding the total soil moisture utilization (which itself is equivalent to the soil moisture recharge).

4.2 ESTIMATION OF ACTUAL EVAPORATION AND YIELD

This verbal argument may be expressed algebraically by considering concurrent series of monthly rainfall and potential evaporation values spanning a period of K years. Let R_{ij} E_{ij} represent the monthly rainfall, and E_{ij} the monthly potential evaporation,

where i = 1, 2, 3, ..., 12 denotes months

and j = 1, 2, 3, ..., K denotes years.

Then, for any one particular month, the least of the two individual values of rainfall and potential evaporation will be represented by min (R_{ij}, E_{ij}) where:

$$\min(R_{ij}, E_{ij}) = R_{ij} \text{ if } R_{ij} < E_{ij} \tag{4.1}$$

or $$= E_{ij} \text{ if } R_{ij} > E_{ij}$$

The annual rainfall during year j is given by $\sum_{i=1}^{12} R_{ij}$, whilst the average annual rainfall over the complete period of record is given by $\frac{1}{K}\sum_{j=1}^{K}\sum_{i=1}^{12} R_{ij}$, which will be denoted in abbreviated form by $\overline{\Sigma R_{ij}}$. Similarly the abbreviated representation of the average annual values of potential evaporation E_{ij} and minimum $\min(R_{ij}, E_{ij})$ are given by $\overline{\Sigma E_{ij}}$ and $\overline{\Sigma\min(R_{ij}, E_{ij})}$ respectively.

Let S denote the annual value of the soil moisture recharge which will be assumed constant from year to year for any given location; this value will also be equivalent to the soil moisture utilization. The average annual actual evaporation determined by the soil moisture recharge method will be denoted by AAE' where:

$$AAE' = \overline{\Sigma \min(R_{ij}, E_{ij})} + S \tag{4.2}$$

and the average annual yield, denoted by AAY', as:

$$AAY' = \overline{\Sigma R_{ij}} - \overline{\Sigma \min(R_{ij}, E_{ij})} - S \tag{4.3}$$

4.3 COMPARISON WITH THE CATCHMENT WATERBALANCE METHOD

From general soil physical properties the value of soil moisture recharge (S) would be expected to lie within the range 50 to 250 mm for the soil and vegetation types encountered in Malaŵi (J.P. Bell, personal communication). Since there is, at present, no independent estimate of S available, two methods of estimating average annual actual evaporation, namely those of the catchment waterbalance and the soil moisture recharge, were compared to obtain an empirical estimate of S for locations in Malaŵi.

The comparison was made using records from the 20 climatological stations described in Section 2.1. At the majority of these stations monthly rainfall and potential evaporation data were available for 1970-1978; annual totals were obtained by summation over the period 1 January to 31 December. For individual years a more accurate estimate of the soil moisture recharge would be obtained by using the period 1 November to 31 October - the start of the rainy season to the end of the dry season. However, to estimate a mean value of S over the nine year-record, it was considered that this refinement could be safely neglected.

First, to initiate the soil moisture recharge method, monthly values of the

Penman estimate of short-grass potential evaporation (E_{PN}) were substituted for the E_{ij} values at each station. Average annual values of E_{PN} are listed in Table 2.2. Next, for each of the stations, $\Sigma\ R_{ij}$ and $\Sigma\ \min\ (R_{ij},\ E_{ij})$ were calculated. The former is exactly equivalent to the average annual rainfall (AAR) listed in Table 3.2; the latter is listed in Table 4.1 and differs,

Table 4.1 ***Individual station values of various variables arising from the soil moisture recharge method***

Column headings

A $\overline{\Sigma\min(R_{ij},\ E_{ij})}$

B AAE $-$ $\overline{\Sigma\min(R_{ij},\ E_{ij})}$

C $\overline{\Sigma R_{ij}}$ $\overline{\Sigma\min(R_{ij},\ E_{ij})}$

D $\overline{\Sigma\min(R_{ij},\ E_{ij})}$ + 120

E $\overline{\Sigma R_{ij}}$ $-$ $\overline{\Sigma\min(R_{ij},\ E_{ij})}$ 120

Climatological Station	A (mm)	B (mm)	C (mm)	D (mm)	E (mm)
Bvumbwe	699	116	423	819	303
Chichiri	706	115	435	826	315
Chileka	663	91	249	783	129
Chitedze	623	152	360	743	240
Chitipa	630	136	323	750	203
Dedza	557	206	386	677	266
Dwangwa	707	150	558	827	438
Karonga	737	86	410	857	290
Lilongwe	586	164	312	706	192
Makhanga	660	39	62	780	-58
Makoka	666	131	394	786	274
Mangochi	659	79	197	779	77
Mimosa	904	34	640	1024	520
Mzimba	579	179	346	699	226
Mzuzu	727	106	455	847	335
Ngabu	683	56	176	803	56
Nkhata Bay	880	115	860	1000	740
Nkhota Kota	793	207	966	913	846
Salima	695	209	731	815	611
Thyolo	802	44	427	922	307
Countrywide mean value	698	121	436	818	316

according to Equation 4.2, from the average actual evaporation (AAE') by the unknown value of S. Full details of a worked example of these calculations for a typical station are given in Appendix 4.

The second method of estimating AAE is the catchment waterbalance described previously in Section 3. Table 3.2 lists the values of AAE corresponding to the relevant values of AAR for each station. If it is assumed that the two estimates, AAE' and AAE, are equal, then it follows from Equation 4.2 that an estimate of the annual soil moisture recharge (S) is given for each station by:

$$S = AAE - \overline{\Sigma \min (R_{ij}, E_{ij})} \qquad (4.4)$$

Values of this difference are listed in Table 4.1. Exactly the same estimates of S may be obtained by assuming that the two estimates of average annual yield, AAY and AAY', calculated by the respective methods, are equal. In this case:

$$S = \overline{\Sigma R_{ij}} - \overline{\Sigma \min (R_{ij}, E_{ij})} \quad AAY \qquad (4.5)$$

with values of $\overline{\Sigma R_{ij}} - \overline{\Sigma \min (R_{ij}, E_{ij})}$ listed in Table 4.1 and AAY listed Table 3.2.

4.4 SOIL MOISTURE RECHARGE VARIATIONS

Estimates of soil moisture recharge obtained form Equation 4.4 vary between 34 and 209 mm with a mean value, rounded to the nearest 5 mm, of 120 mm. All values except three lie within the expected range suggested earlier. Comparison may also be made with the value of 175 mm deduced for the Betwa basin in India by Sutcliffe *et al.* (1981). Figure 4.2 illustrates the spatial variation of S throughout Malaŵi. Using the climatological classes defined in Section 2.6 this variation is summarized as:

Class No	Mean value of S for class (mm)
1	113
2	133
3	114
4	152
5	61

If the values of S for the rift valley stations (class Nos. 1 and 2) are plotted against average annual rainfall (AAR), as in Figure 4.3, a weak relation giving an increase in S for increasing AAR results, i.e.,

$$S = 0.129\ AAR - 40 \qquad (4.6)$$

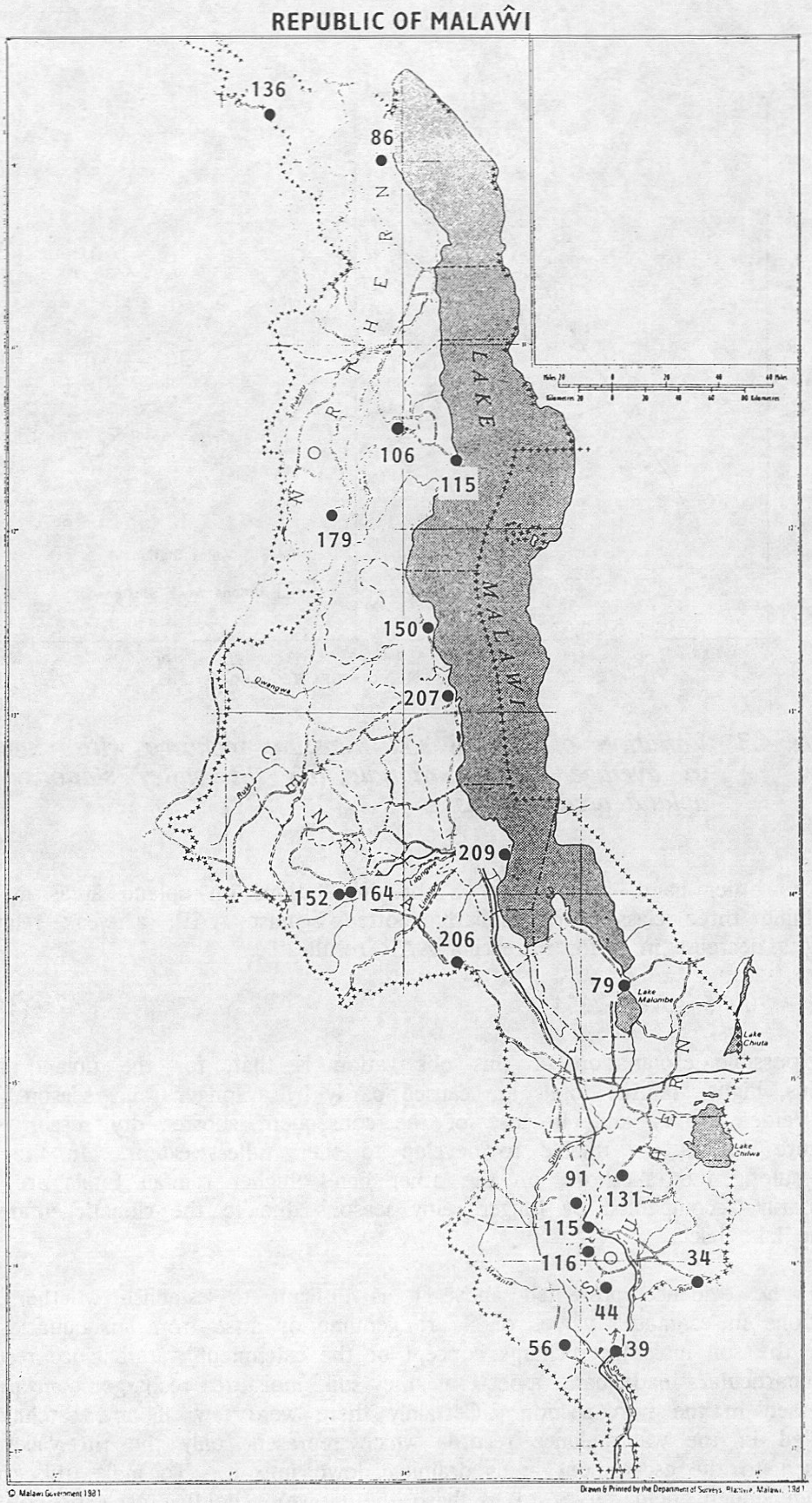

Figure 4.2 Values of soil moisture recharge S (mm) obtained from comparing two estimates of average annual actual evaporation

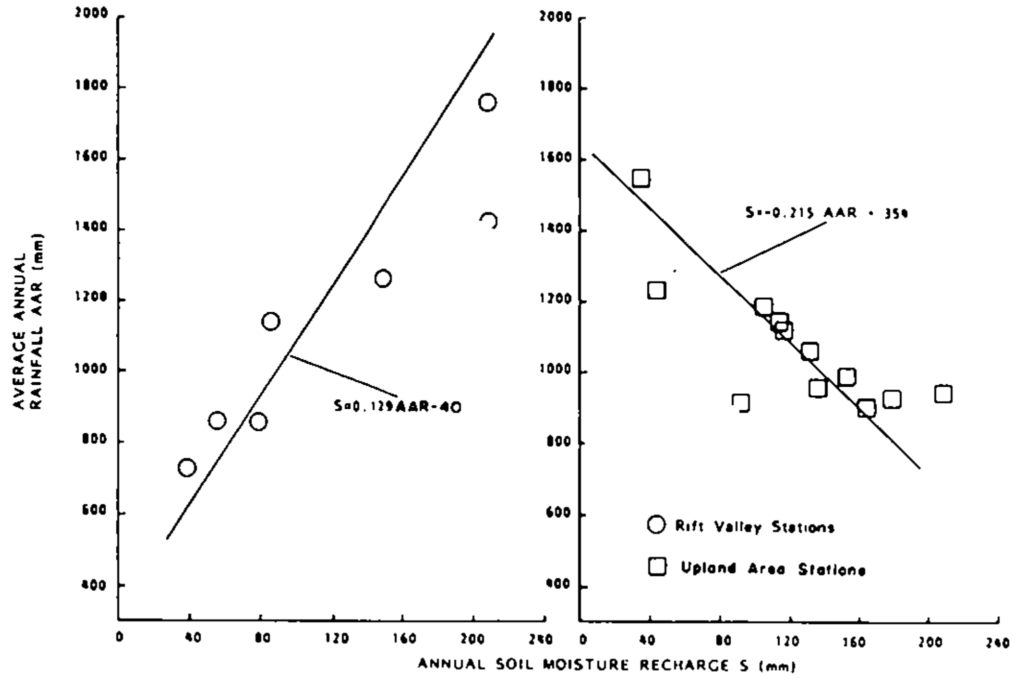

Figure 4.3 ***Variation of annual soil moisture recharge with changes in average annual rainfall (a) rift valley stations (b) upland area stations***

On the other hand, if values of S for the stations on upland areas in the remaining three classes are similarly plotted against AAR, a weak relation giving a decrease in S for increasing AAR results, i.e.,

$$S = -0.215\ AAR + 354 \qquad (4.7)$$

One possible explanation of this observation is that, for the upland area stations, higher rainfall totals are caused partly by a longer rainy season (van der Velden, 1979) and, because of the consequent shorter dry season, soil moisture deficits are unable to develop to their fullest extent. In the rift valley along the lakeshore, on the other hand, higher rainfall totals are not necessarily accompanied by longer rainy seasons due to the climatic influence of the lake itself.

From the evidence presented above it is difficult to establish whether the variations in estimated values of S are genuine or arise from inadequacies in either the soil moisture recharge concept or the catchment waterbalance results. One particular inadequate aspect of the soil moisture recharge concept is addressed in the next section. Certainly there were few, if any, catchments included in the waterbalance records which represent only the rift valley as opposed to the escarpment areas draining down into it. To make this clear, an independent field survey to establish the moisture holding capacities of the soils throughout Malaŵi under different vegetative covers is required.

4.5 CONCEPT MODIFICATION AT LOW RAINFALL LOCATIONS

Another explanation for some of the lowest values found for S is that the soil moisture recharge concept described above may break down for certain stations with low values of net rainfall. The formula:

$$AAE' = \overline{\Sigma \min\ (R_{ij},\ E_{ij})}\ +\ S \tag{4.8}$$

is valid only if the net rainfall, given by $\overline{\Sigma\ R_{ij}} - \overline{\Sigma \min\ (R_{ij},\ E_{ij})}$, exceeds the annual soil moisture recharge S. Where the net rainfall is less than S it is not normally possible to completely recharge the soil during the rainy season. In this case, the amount of moisture available in the soil at the end of the rainy season is equal to the net rainfall and not the value of soil moisture recharge proposed in the original concept. For such locations, therefore, AAE' is found from an alternative expression to Equation 4.8, namely:

$$AAE' = [\overline{\Sigma \min\ (R_{ij},\ E_{ij})}] + [\overline{\Sigma R_{ij}} - \overline{\Sigma \min\ (R_{ij},\ E_{ij})}] \tag{4.9}$$

$$= \overline{\Sigma\ R_{ij}} \tag{4.10}$$

i.e. equal to the average annual rainfall itself although, in practice, this value would be slightly reduced due to minor losses to surface runoff and groundwater recharge.

The three lowest values of net rainfall from the 20 stations listed in Table 4.1 are 62 mm (Makhanga), 176 mm (Ngabu) and 197 mm (Mangochi). Since the value for Makhanga is well below the mean value of 113 mm found for S in climatological class No. 1 (see Section 4.4), it is likely that the the original recharge concept is not valid for this station and in most years the soil moisture will remain in deficit throughout the rainy season. Consequently the average annual actual evaporation should be estimated as the same value, 722 mm, as the average annual rainfall (Table 3.2).

4.6 COUNTRYWIDE MEAN VALUE OF SOIL MOISTURE RECHARGE

If the most appropriate value of S is chosen for any particular location in Malaŵi where monthly records of rainfall and potential evaporation exist, annual values of actual evaporation (AE_j') and yield (AY_j') during year j may be found from the formulae:

$$AE_j' = \sum_{i=1}^{12} \min\ (R_{ij},\ E_{ij}) + S \tag{4.11}$$

$$AY_j' = \sum_{i=1}^{12} R_{ij} - \sum_{i=1}^{12} \min (R_{ij}, E_{ij}) - S \tag{4.12}$$

As pointed out in Section 4.3, for individual years it is preferable to take the summations shown over the 12 months commencing 1 November.

Bearing in mind the variation of S throughout Malaŵi, described previously, the remainder of this section will examine the estimates of average annual actual evaporation and yield obtained when S is constrained to take the countrywide mean value of 120 mm. Substitution of this value in the appropriate Equations 4.2 and 4.3 yields the values listed in the final two columns of Table 4.1. To compare these values with the corresponding estimates deduced from the catchment waterbalance, Figure 4.4 employs background relationships that are drawn directly from Figure 3.3 which was established when discussing the catchment waterbalance in Section 3.

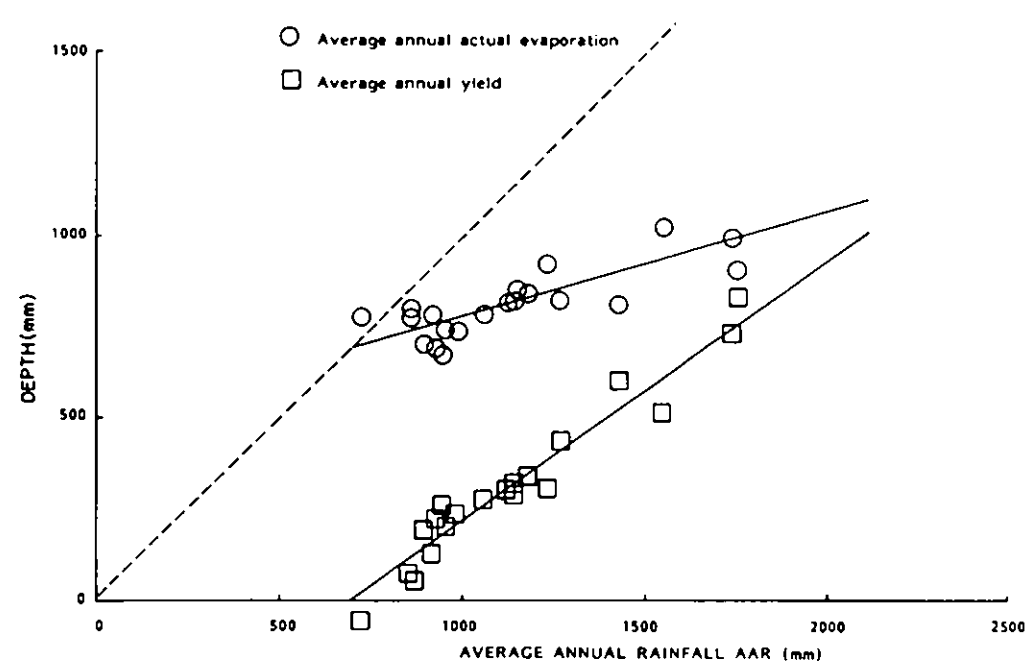

Figure 4.4 Average annual actual evaporation and yield deduced from the soil moisture recharge method assuming S takes countrywide mean value of 120 mm, compared with background relationships for the same variables deduced from catchment waterbalance

In Fig. 4.4 there is nothing remarkable about the close agreement between the location of the centroid of each set of points and the line of the corresponding background relationship, because the mean value of S was adjusted automatically to 120 mm to provide just this when the individual values of S were being deduced. What is interesting is that, firstly, there are no extreme outliers amongst the calculated values falling far away from the background relationships. This suggests that the soil moisture recharge concept is a reliable method of estimating actual evaporation and, hence, yield. The second point to note is that the broad rates of increase of average annual actual evaporation and yield against increasing average annual rainfall found for the catchment waterbalance are replicated by the values obtained from the soil moisture recharge method. This latter feature is independent of the value of S chosen, because a change in S in Equation 4.2 and 4.3 will only move all plotted points by the same distance parallel to the ordinate axis, though points representing AAE' will move in the opposite direction to those representing AAY'. Indeed, even if an approximate value, e.g. of 200 mm, were chosen for S based on a rudimentary knowledge of the soils and vegetation in Malaŵi, there would still be a reasonable agreement between the values deduced from each of the two methods.

5. Complementary evaporation

5.1 PREVIEW OF METHODS

The remaining four methods of estimating actual evapotranspiration require only climatological data as input; no soil moisture data or stomatal resistance properties of the vegetation, nor any other additional aridity parameters are needed. One of these methods is that of equilibrium evaporation; the other three are based on the concept of complementary evaporation which is described in the following section.

For ease of comparison all the four methods may be rearranged in a form involving M_e and M_a, the energy and aerodynamic terms of the Penman estimate of short-grass potential evaporation. Neglecting G, the heat flux into the ground, the methods may be written as follows:

Brutsaert-Stricker

$$E_{BS} = 1.52\ M_e - M_a \tag{5.1}$$

Equilibrium evaporation

$$E_E = M_e \tag{5.2}$$

Difference

$$E_D = M_e - M_a \tag{5.3}$$

Bouchet

$$E_{BO} = \frac{\gamma}{\Delta}\ M_e + R_L - M_a \tag{5.4}$$

where R_L is the outgoing long-wave radiation, γ the psychrometric constant and Δ the slope of the saturation vapour pressure curve at mean air temperature.

Estimates of actual evapotranspiration obtained from these methods above were compared with AAE, the estimate obtained from the catchment waterbalance described in Section 3. For the convenience of the reader the three most important variables (AAR, E_{PN} and AAE) referred to in this comparison are repeated in Table 5.1

5.2 CONCEPT OF COMPLEMENTARY EVAPORATION

Bouchet (1963) introduced the concept of complementary evaporation, in which a symmetry is assumed between actual and potential evapotranspiration with respect to the evaporative power of the air in the absence of advection. The following description is taken from Brutsaert and Stricker (1979) who provided

Table 5.1 Average annual values of rainfall AAR, Penman short grass potential evaporation E_{PN} and actual evaporation estimated from catchment waterbalance AAE

Climatological station	AAR (mm)	E_{PN} (mm)	AAE (mm)
Bvumbwe	1122	1430	815
Chichiri	1141	1512	821
Chileka	912	1816	754
Chitedze	983	1558	775
Chitipa	953	1769	766
Dedza	943	1472	763
Dwangwa	1265	1618	857
Karonga	1147	1835	823
Lilongwe	898	1578	750
Makhanga	722	1784	699
Makoka	1060	1506	797
Mangochi	856	1806	738
Mimosa	1544	1404	938
Mzimba	925	1513	758
Mzuzu	1182	1316	833
Ngabu	859	1840	739
Nkhata Bay	1740	1534	995
Nkhota Kota	1759	1759	1000
Salima	1426	1816	904
Thyolo	1229	1427	846
Mean	1130	1610	819

a useful summary of the concept:

> Bouchet considered a large uniform surface of regional size, involving characteristic scale lengths of the order of 1 to 10 km, in which the actual evapotranspiration is E. The potential evapotranspiration (E_p) is the evapotranspiration which would take place if the available energy were the only limiting factor; under conditions when E equals E_p, it is denoted by E_{po}. If for one or another reason, independent from the available energy, E decreases below E_{po}, a certain amount of energy becomes available, that is:
>
> $$E_{po} - E = q \tag{5.5}$$
>
> At the scale of the region this decrease of E with respect to E_{po} has only a small impact on the net radiation, and it affects primarily the temperature, the humidity and the turbulence of the air near the ground. As a result, this available energy flux increases E_p. Bouchet assumed that if the energy balance remains otherwise unaffected, in the

absence of local oasis effects, this increase equals q or:

$$E_{po} = E_{po} + q \tag{5.6}$$

The combination of the symmetrical relationships (5.5) and (5.6) yields:

$$E_p + E = 2E_{po} \tag{5.7}$$

Equation (5.7) is known as the complementary relationship between actual and potential evapotranspiration.

5.3 BRUTSAERT-STRICKER METHOD

Prior to examining the first of the methods it is necessary to define the Priestley-Taylor (1972) estimate of potential evaporation (E_{PT}) as:

$$E_{PT} = \alpha\ M_e \tag{5.8}$$

where M_e, the energy term of the Penman estimate of short grass potential evaporation, has been previously defined in Equation 2.5 as:

$$M_e = \frac{\Delta}{\Delta + \gamma}\ R_n \tag{5.9}$$

and α is an empirical constant. The value of α was found to be 1.26 by Priestley and Taylor but Brutsaert and Stricker (1979) used this as well as the alternative value of 1.28.

Average annual values of E_{PT}, together with the net radiation (R_n) and dimensions less factor $\Delta/(\Delta+\gamma)$ are listed in Table 5.2 for each station. Average monthly values of these three variables are also listed in Appendix 2. As explained in that appendix, because the calculations for Equation 5.9 were undertaken on an individual monthly basis, it is not possible to relate directly the three columns of values listed in Table 5.2.

The version of complementary evaporation proposed by Brutsaert and Stricker (1979) is found by substituting E_{PT} and E_{PN} for E_{Po} and E_P in Equation 5.7 and rearranging to give an estimate (E_{BS}) of actual evapotranspiration:

$$E_{BS} = 2E_{PT} - E_{PN} \tag{5.10}$$

where E_{PN} is the Penman estimate of short grass potential evaporation defined in Equations 2.1 - 2.3; average annual values are listed in Table 5.1. Substituting in Equation 5.10 these values of E_{PN}, together with those of E_{PT} from Table 5.2, provide the average annual values of E_{BS} listed in Table 5.3.

Equation 5.10 may also be recast in a different format to obtain the expression for estimating E_{BS} mentioned in Section 5.1. Following Equation 2.4, E_{PN} can be expressed in terms of its constituent components:

$$E_{PN} = M_e + M_a \tag{5.11}$$

Table 5.2 Average annual values of net radiation (water equivalent) R_n, dimensionless factor $\Delta/(\Delta+\gamma)$, Priestley-Taylor potential evaporation E_{PT} and incoming short-wave radiation at the surface (water equivalent) R_s

Climatological Station	R_n Mean (mm)	R_n CV (%)	$\Delta/(\Delta+\gamma)$ Mean (mm)	$\Delta/(\Delta+\gamma)$ CV (%)	E_{PT} Mean (mm)	E_{PT} CV (%)	R_s Mean (mm)	R_s CV (%)
Bvumbwe	1518	1.6	0.705	0.4	1358	1.6	2753	2.1
Chichiri	1544	1.6	0.711	0.4	1393	1.6	2820	2.2
Chileka	1594	1.9	0.730	0.4	1475	2.0	2926	2.7
Chitedze	1567	2.0	0.715	0.4	1420	2.1	2915	2.8
Chitipa	1606	1.3	0.727	0.4	1475	1.1	2966	1.6
Dedza	1528	1.6	0.700	0.4	1356	1.8	2862	2.2
Dwangwa	1716	2.1	0.731	0.7	1586	2.8	3058	2.9
Karonga	1722	1.0	0.747	0.4	1626	0.9	3084	1.8
Lilongwe	1554	2.4	0.714	0.6	14.08	2.4	2888	2.9
Makhanga	1717	2.2	0.745	0.4	1626	2.1	3037	2.7
Makoka	1530	1.7	0.717	0.4	1391	1.8	2785	2.3
Mangochi	1678	1.9	0.741	0.4	1577	2.1	3056	2.4
Mimosa	1562	1.8	0.717	0.3	1422	1.9	2774	2.3
Mzimba	1608	2.1	0.717	0.6	1457	2.2	2966	2.5
Mzuzu	1597	2.5	0.691	0.4	1397	2.3	2842	2.8
Ngabu	1673	1.7	0.752	0.5	1597	1.9	2976	2.1
Nkhata Bay	1718	2.0	0.732	0.4	1590	2.0	2970	2.3
Nkhota Kota	1693	1.9	0.735	0.3	1576	2.0	3040	2.4
Salima	1704	2.4	0.741	0.4	1598	2.6	3104	3.1
Thyolo	1568	2.3	0.714	0.6	1422	2.3	2810	2.9
Mean	1620	1.9	0.724	0.4	1490	2.0	2930	2.5

where M_a represents the aerodynamic term defined in Equation 2.6. Assuming α takes the value 1.26, then from Equation 5.8 it follows:

$$E_{PT} = 1.26\ M_e \tag{5.12}$$

Substituting (5.11) and (5.12) into (5.10) gives

$$E_{BS} = 1.52\ M_e - M_a \tag{5.13}$$

Using in this equation the values of M_e and M_a listed in Table 2.3 provides an alternative way of obtaining the estimates of E_{BS} listed in Table 5.3.

Figure 5.1 illustrates the comparison of actual evapotranspiration estimated by the Brutsaert-Stricker and catchment waterbalance methods. The background waterbalance relationships are copied directly from Fig. 3.3. It was found that

Table 5.3 Average annual values of actual evapotranspiration by four methods

Climatological Station	Brutsaert-Stricker E_{BS} (mm)	Equilibrium evaporation E_E (mm)	Difference E_D (mm)	Bouchet E_{BO} (mm)
Bvumbwe	1286	1079	727	635
Chichiri	1274	1106	700	603
Chileka	1134	1170	524	379
Chitedze	1282	1127	696	628
Chitipa	1181	1170	571	456
Dedza	1240	1075	678	675
Dwangwa	1554	1259	900	676
Karonga	1417	1291	747	478
Lilongwe	1238	1117	656	588
Makhanga	1468	1290	796	494
Makoka	1276	1104	702	583
Mangochi	1348	1250	694	486
Mimosa	1440	1128	852	677
Mzimba	1401	1157	801	712
Mzuzu	1478	1109	901	816
Ngabu	1354	1267	696	392
Nkhata Bay	1646	1261	989	694
Nkhota Kota	1393	1250	740	521
Salima	1380	1268	722	512
Thyolo	1417	1129	830	681
Mean	1360	1180	746	584

the majority of E_{BS} values exceeded the average annual rainfall (AAR) observed at the same location; this is possible only if there is a net flow of water into the area which is available to the vegetation for evaporation - a situation which rarely occurs. Even the four E_{BS} values which were less than the average annual rainfall exceeded the catchment waterbalance estimate AAE by at least 39%. At three locations (Mimosa, Mzuzu and Nkhata Bay) the actual evapotranspiration estimate (E_{BS}) exceeded the potential evaporation estimate (E_{PN}). However, on the positive side, the slopes of the two relationships being compared were similar.

It must be concluded that in its present form the Brutsaert-Stricker method does not provide a reliable estimate of actual evapotranspiration for locations in Malaŵi. This is in harmony with the more general conclusion drawn by de Bruin and Stewart (1983) that for inland tropical stations the Brutsaert-Stricker method yields actual evaporation values greater than rainfall for the majority of stations with rainfall less than 1600 mm.

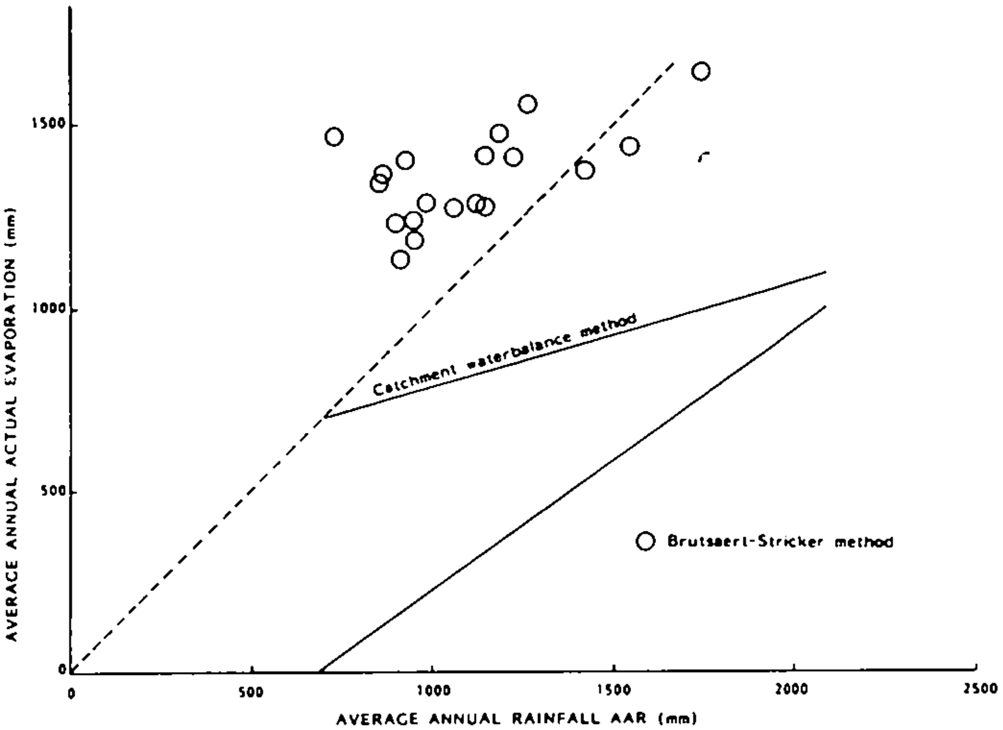

Figure 5.1 Comparison of Brutsaert-Stricker method E_{BS} and catchment waterbalance AAE estimates of actual evapotranspiration

5.4 EQUILIBRIUM EVAPORATION METHOD

In this second method an estimate of actual evapotranspiration (E_E) is given simply by:

$$E_E = M_e \tag{5.14}$$

where M_e is the energy term of the Penman estimate of short grass potential evaporation mentioned in Equation 5.9. Although this method is not based on the complementary evaporation concept, it bears certain features in common with the other three methods which make it useful for consideration alongside. This estimate was referred to as the equilibrium evaporation by Slatyer and McIloy (1961) who considered it represents a lower limit to evaporation surfaces.

Brutsaert and Stricker (1979) mention Denmead and McIlroy's (1970) theory that equilibrium evaporation (E_E), could perhaps serve as a simple index for actual evapotranspiration (E) and their tests with hourly data above a wheat crop indicated approximate agreement up to a value of about 25 mW cm^{-2}, but E was overestimated by E_E at higher rates. Brutsaert and Stricker themselves undertook a comparison between their own method (E_{BS}) and the equilibrium evaporation (E_E) by determining how closely these expressions matched a separate estimate of actual evapotranspiration found from using the energy budget approach for small catchment in The Netherlands during the drought of 1976. They concluded that their method was superior over periods of one to three days but both methods produced similar results with these data over longer periods of the order of a month.

Figure 5.2 illustrates the comparison between the methods of equilibrium evaporation (E_E) and catchment waterbalance (AAE) for Malaŵi. Values of E_E equal to the M_e values shown in Table 2.3 are listed in Table 5.3. Values of E_E for the six lakeshore stations have been omitted from the figure for the sake of clarity; their values are approximately equal to the two highest E_E values shown.

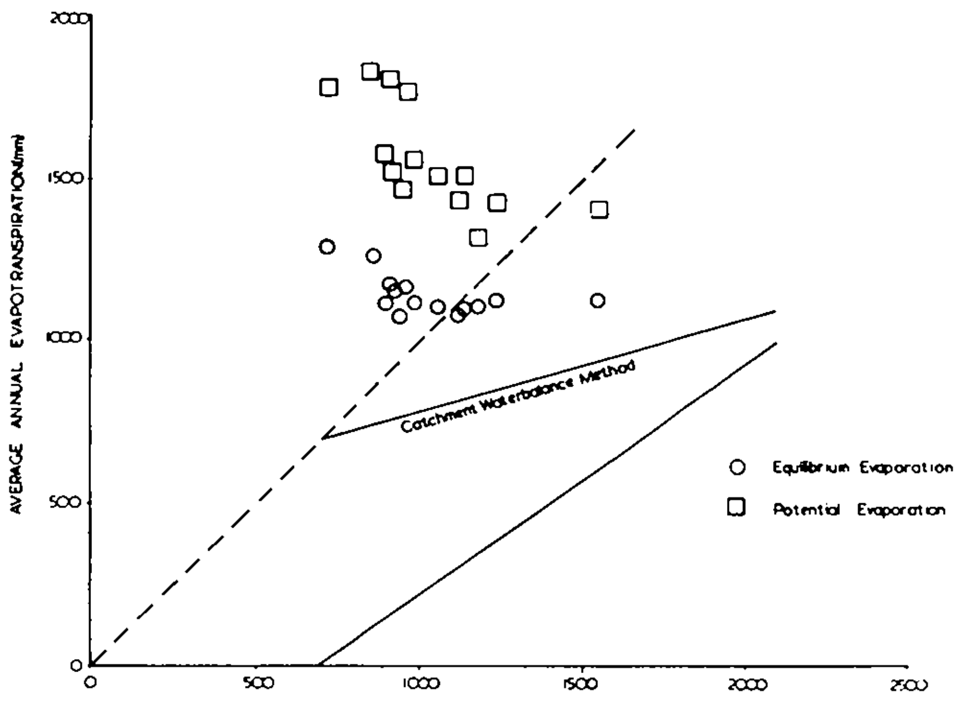

Figure 5.2 Comparison of equilibrium evaporation method E_E and catchment waterbalance AAE estimates of actual evapotranspiration, together with Penman estimates of short grass potential evapotranspiration E_{PN} for upland area stations

It was found that although all E_E values, except Chileka, were less than the corresponding E_{BS} values, they were all more than the AAE values by at least 20%. Over 50% of the E_E values still exceeded the average annual rainfall (AAR). Because M_e is less than $M_e + M_a$ it follows from Equations 5.14 and 5.11 that estimates of actual evapotranspiration (E_E) will always be less than Penman short grass potential evaporation (E_{PN}) as in Fig. 5.2. This figure also shows a further negative feature of the method, namely that E_E does not exhibit any increasing trend with AAR, unlike AAE or even E_{BS} (cf. Fig. 5.1.).

The conclusion drawn is that equilibrium evaporation provides an improved estimate of actual evapotranspiration over the method of Brutsaert-Stricker but sill overestimates in comparison with the corresponding values deduced from the catchment waterbalance.

5.4.1 Choice of E_{po} in the complementary evaporation equation

Some evidence in support of the complementary evaporation concept is provided by the average annual values shown in Fig. 5.2. As actual evapotranspiration (AAE) increases, it will be noted that:

(a) the potential evapotranspiration (E_{PN}) decreases
(b) the energy term (M_e), and hence net radiation (R_n) to which it is closely connected, remains relatively unchanged.

No derivation of the concept from physical principles is offered here. Even if the physical basis of the complementary method is weak, it may prove a unique empirical method for solving many practical problems (de Bruin and Stewart, 1983).

Inspection of Fig. 5.2 reveals some suggestions regarding the choice of variable to represent E_{po}, the evaporative power of the air in the absence of advection, in the complementary evaporation equation (5.7). From the form of this equation the value of E_{po} should ideally lie half way between the estimates of AAE and E_{PN}. Comparison of Tables 5.2 and 5.1 reveals that E_{PT}, the Priestley-Taylor estimate of potential evaporation, lies much closer to E_{PN} than AAE for Malaŵi locations and for three stations (Mimosa, Mzuzu and Nkhata Bay E_{PT} actually exceeds E_{PN}. This explains why the choice of E_{PT} for E_{po} in the Brutsaert-Stricker method leads to the overestimates of actual evapotranspiration (E_{BS}) mentioned previously.

The 20 climatological stations were divided into two groups, upland area and rift valley; for each station values of (E_{PN} + AAE)/2 were calculated from Table 5.1 and the mean for each group determined as 1163 and 1297 mm. It would be preferable if E_{po} possessed values equal or close to these. A suitable contender is proposed by assuming $E_{po} = E_E$, the equilibrium evaporation which, from Equation 5.14 is simply equal to M_e, the energy term of the Penman estimate of shortgrass potential evaporation. Table 2.4 shows that the mean values of M_e are 1123 and 1267 mm for the upland area and rift valley stations respectively, which differ by only 3.4% and 2.3% from the mean values of (E_{PN} + AAE)/2 given above.

5.5 DIFFERENCE METHOD

Substitution of E_{PO} = M_e into the complementary evaporation Equation 5.7 and taking E_{PN} as the potential evapotranspiration gives, after rearrangement, the third estimate of actual evapotranspiration (E_D) where:

$$E_D = 2M_e - E_{PN} \tag{5.15}$$

By expressing E_{PN} in terms of its two components (Equation 5.11) this expression can be recast in an even simpler form:

$$E_D = M_e - M_a \tag{5.16}$$

Because this estimate of actual evapotranspiration is similar to the expression for the Penman estimate of short grass potential evaporation, but with the sign changed form positive to negative, it will be referred to as the Difference method. Average annual values of E_D are listed in Table 5.3; these may be obtained by substituting either values of E_{PN} from Table 5.1 and E_E (=M_e) from Table 5.3 into Equation 5.15 or values of M_e and M_a from Table 2.3 into Equation 5.16.

Figure 5.3 illustrates the comparison between the Difference (E_D) and catchment waterbance (AAE) methods. It was found that all the E_D actual evapotranspiration estimates, except that for Makhanga station, were less than the average annual rainfall (AAR). There was also a slight trend for E_D to increase with increase in AAR. From the inequality:

$$M_e - M_a < M_e < M_e + M_a \tag{5.17}$$

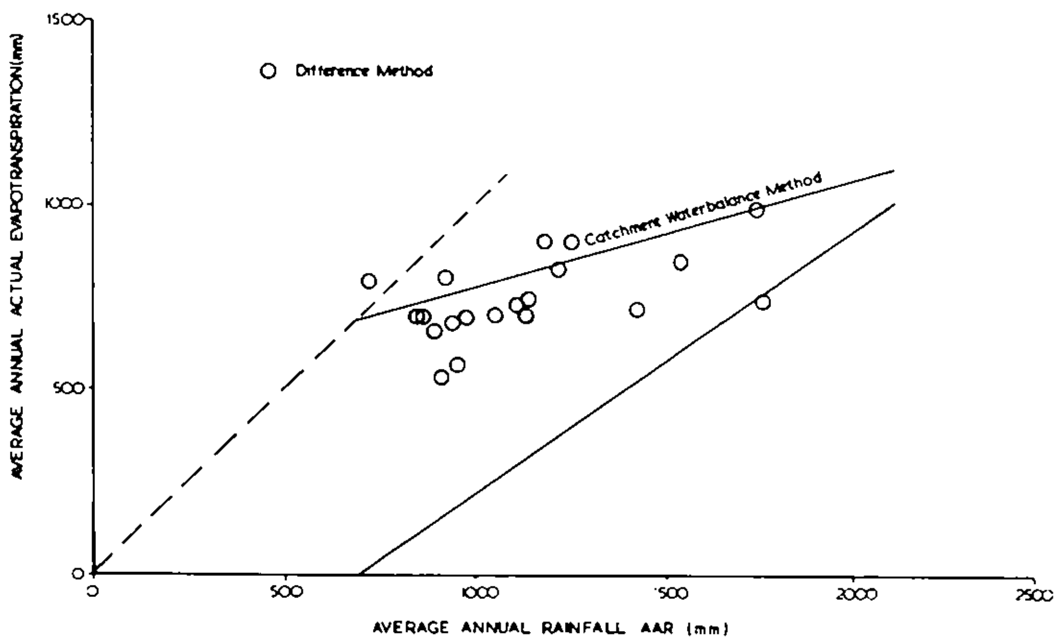

***Figure 5.3** Comparison of Difference method E_D and catchment waterbalance AAE estimates of actual evapotranspiration in lakeshore and upland stations*

it follows that E_D must be less than all values of not only potential evaporation (E_{PN}) but also equilibrium evaporation (E_E).

Figure 5.4 shows a more direct comparison between the values of E_D from Table 5.3 and AAE from Table 5.1. Fifteen of the 20 values of E_D differ by less than 100 mm from the corresponding value of AAE. It should be recalled here that the standard error of estimate of AAE from Equation 3.4 is, by comparison, 90 mm. The mean of all 20 points using the Difference method underestimates by 73 mm, or 8.9%, the corresponding mean from the catchment waterbalnce method. The five poorly-fitting points are from the stations at Chichiri, Chileka, Chitipa, Nkhota Kota and Salima; a possible explanation for the discrepancies of the last two may lie in the large differences between average annual rainfall for the period 1970-1978 examined and for the longer period 1951-1978 given in van der Velden (1979).

The conclusion drawn in this section is that the Difference method provides a promising technique for estimating actual evapotranspiration at the majority of locations in Malaŵi, but slightly underestimates in comparison with the catchment waterbalance method.

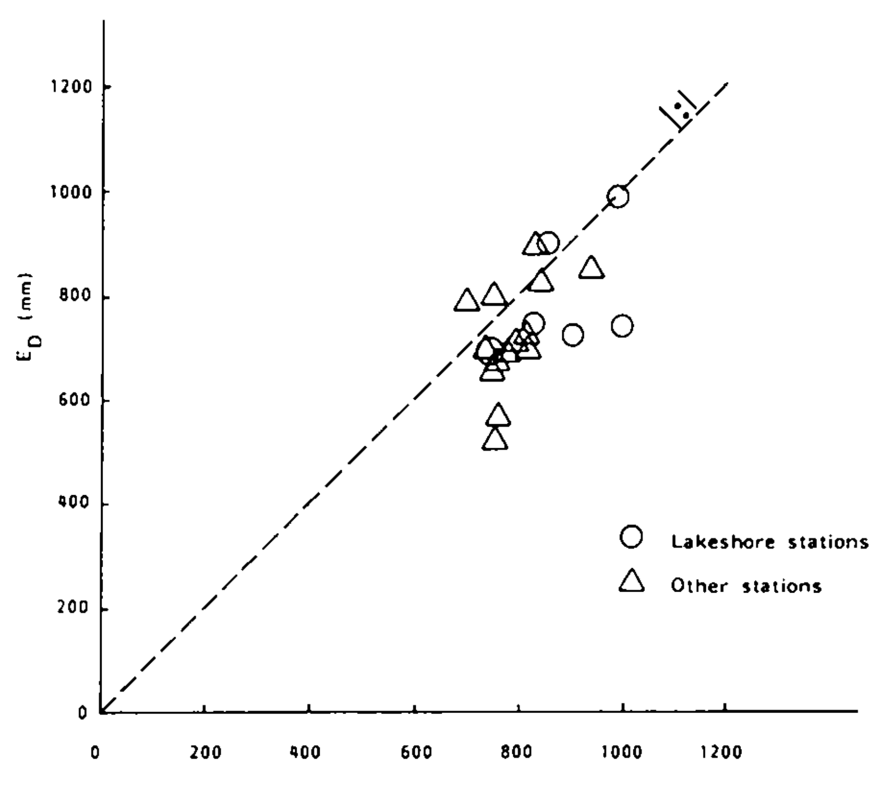

Figure 5.4 ***Comparison of Difference method E_D and catchment waterbalance AAE estimates of actual evapotranspiration in lakeshore upland stations***

5.5.1 Connection between Difference and Brutsaert-Stricker methods

The Brutsaert-Stricker method of estimating actual evapotranspiration is one of the better-known recent versions of the complementary evaporation concept. To understand the relationship between this and the new Difference method, described above it is necessary to refer to Equation 14 of Brutsaert and Stricker's 1979 paper, namely:

$$E = (2\alpha - 1)\frac{\Delta}{\Delta + \gamma}(R_n - G) - \frac{\gamma}{\Delta + \gamma}E_a \tag{5.18}$$

where G represents the ground heat flux, E_a the drying power of the air $[f(U_2)(e_s - e)]$ as in Equation 2.1, and α the Priestley-Taylor empirical constant as in Equation 5.8. In their application of this expression Brutsaert and Stricker neglected G and adopted values of either 1.26 or 1.28 for α.

In the Difference method G is similarly neglected in Equation 5.18, but instead of the previous values adopted α is taken equal to 1. To convert estimates of actual evapotranspiration which originally used the Brutsaert-Stricker method to those using the Difference method it is necessary to subtract either 0.52 M_e or 0.56 M_e, depending on the value of α adopted, where:

$$M_e = \frac{\Delta}{\Delta + \gamma}R_n \tag{5.19}$$

Consequently the new estimates are always less than those of Brutsaert-Stricker, which may alleviate some of the widespread overestimation noted in Section 5.3. Another expression for determining the Brutsaert-Stricker estimate (E_{BS}) is Equation 5.10 involving the Priestley-Taylor (E_{PT}) and Penman (E_{PN}) potential evaporation estimates:

$$E_{BS} = 2E_{PT} - E_{PN} \tag{5.20}$$

To convert this to the Difference method it is necessary first to divide the Priestley-Taylor estimate by either 1.26 or 1.28, as the case may be; for example:

$$\frac{2E_{PT}}{1.26} - E_{PN} \tag{5.21}$$

5.6 BOUCHET METHOD

The last of the complementary evaporation methods entails returning to the expression given in the original paper by Bouchet (1963) which introduced the concept. After establishing the complementary evaporation equation (5.7), Bouchet then derived a second equation, on the basis of additional energy budget considerations, expressing E_{po} in terms of the absorbed short-wave radiation $(1 - r)R_s$. Substituting this into Equation 5.7 gave:

$$E_p + E \leqslant (1 - r)R_s = Q \tag{5.22}$$

where r is the albedo, R_s the incoming short-wave radiation at the surface and Q is a large-scale (i.e. larger than regional) advection term. In subsequent applications Equation 5.22 has usually been simplified to the following equality:

$$E_p + E = (1 - r) R_s \tag{5.23}$$

The approximate validity of this latter expression has been verified with experimental data for annual periods by Bouchet.

In this present study an estimate (E_{BO}) of actual evapotranspiration (E) was obtained by substituting E_{PN}, the Penman estimate of short grass potential evaporation, for E_p in Equation 5.23 and rearranging:

$$E_{BO} = (1 - r) R_s - E_{PN} \tag{5.24}$$

Taking the albedo r = 0.25 and using the average annual values of R_s and E_{PN} listed in Tables 5.2 and 5.1 respectively gives the average annual values of E_{BO} listed in Table 5.3. Average monthly values of R_s are also listed in Appendix 2.

Equation 5.24 may also be recast in a different format to obtain the expression for estimating E_{BO} mentioned in Section 5.1. Equation 2.2 for net radiation (R_n) may be summarized as:

$$R_n = (1 - r) R_s - R_L \tag{5.25}$$

where R_L is the outgoing long-wave radiation. Following Equation 5.11 E_{PN} may be expressed in terms of its constituent energy and aerodynamic terms:

$$E_{PN} = M_e + M_a \tag{5.26}$$

Substituting (5.25) and (5.26) into (5.24) gives:

$$E_{BO} = R_n + R_L - M_e - M_a \tag{5.27}$$

Making use of the inverse form of Equation 5.9:

$$R_n = \frac{\Delta + \gamma}{\Delta} M_e \tag{5.28}$$

Equation 5.27 reduces to:

$$E_{BO} = \frac{\gamma}{\Delta} M_e + R_L - M_a \tag{5.29}$$

For the group of 12 upland area climatological stations the mean average annual values of γ/Δ, M_e and R_L are 0.403, 1123 mm and 580 mm respectively. Bearing in mind that all the original basic calculations were done strictly on a monthly data period, an approximate estimate of the mean value for the sum of the first two terms in Equation 5.29 using the three values given above is 1033 mm; this is only 90 mm lower than the mean value 1123 mm of M_e used in Equation 5.16 as discussed in Section 5.5. This means that for locations in Malaŵi there will be a certain measure of agreement between the Difference (E_D) and Bouchet (E_{BO}) methods. However it must be emphasized that estimates of actual evapotranspiration obtained from any of the methods founded on the complementary evaporation concept are very sensitive to the exact choice of E_{po} values, since the form of Equation 5.7 dictates that any change in E_{po} results in a change twice that size in E, if E_p remains unchanged.

Figure 5.5 illustrates the comparison between the Bouchet (E_{BO}) and catchment waterbalance (AAE) methods. It was found that all the E_{BO} actual evapotranspiration values were less than both the average annual rainfall (AAR) and potential evaporation (E_{PN}). For every station E_{BO} was lower than the corresponding value (E_D) obtained from the Difference method; six values were even lower than 500 mm, which would give unreasonably high values for average annual yield at these locations. There was little, if any, trend for E_{BO} to increase with increase in AAR.

In Section 5.5 it was demonstrated that the Difference method slightly underestimated actual evapotranspiration in comparison with the catchment waterbalance method. The conclusion drawn in this present section is that the Bouchet method underestimates actual evapotranspiration by an even greater degree; however it does not suffer from the disadvantages shown by the Brutsaert-Stricker and equilibrium evaporation methods, namely exceeding the average annual rainfall at the majority of stations.

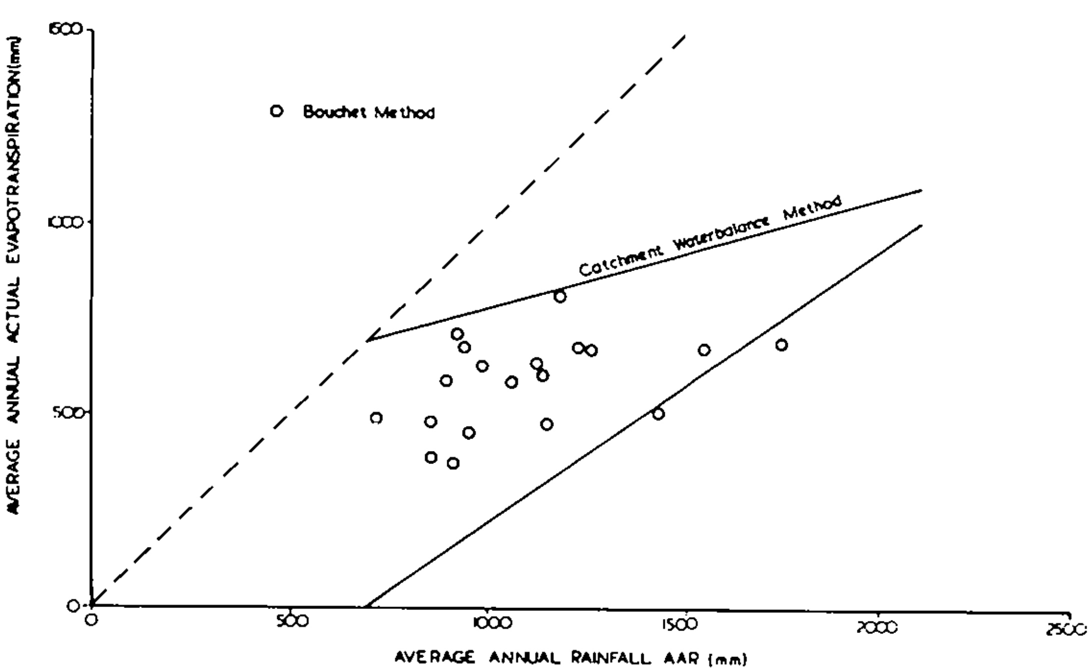

Figure 5.5 Comparison of Bouchet method E_{BO} and catchment waterbalance AAE estimates of actual evapotranspiration

6. Discussion and conclusions

6.1 RAINFALL AND POTENTIAL EVAPORATION

An initial review of rainfall and potential evaporation in Malaŵi provided the following conclusions. In this region of Central Africa there is, generally, one distinct annual rainy season followed by a long dry season. The spatial variation of average annual rainfall is consistent both in the upland areas and in the rift valley south of Lake Malaŵi, but is erratic along the western lakeshore. Stations in all areas demonstrate considerable variation from year to year in annual rainfall totals.

In general higher values of Penman short grass potential evaporation (E_{PN}) are estimated along the rift valley floor with lower values on the upland areas. Average annual values of E_{PN} range from 1316 to 1840 mm with a mean of 1610 mm. The Penman open water evaporation (E_0) is approximately 25% larger than E_{PN} and exhibits similar spatial variation. Both E_{PN} and E_0 demonstrate little variation from year to year at all stations.

The term E_{PN} may be usefully expressed as the sum of its components, the energy term (M_e) and the aerodynamic term (M_a). As one factor influencing higher values of E_{PN}, it is particularly noticeable that all the higher values of M_e occur at rift valley stations; the mean value of M_e for upland area stations is 11% less than the corresponding value for the rift valley. Annual values of M_e show very little variation from year to year.

Values of M_a are considerably smaller than M_e, but show both greater spatial variation and greater year-to-year variation than M_e. The mean value of M_a for upland area stations is 16% less than the corresponding value for the rift valley but, unlike the value for M_e, not all individual rift valley station values are greater than the individual upland area values. Values of M_a appear to be depressed in the tea cultivation areas but enhanced on the leeward side of high ground.

To highlight these variations a plot of M_a against M_e allowed the 20 climatological stations to be divided into five classes to distinguish their climatic properties.

6.2 ACTUAL EVAPOTRANSPIRATION

The six methods (listed in Table 6.1) used in this study to estimate actual evapotranspiration were applied to data from 20 climatological stations, eight of which were located down in the rift valley and 12 on upland areas. Catchment waterbalance (AAE) was considered the most reliable method, with which the other five were compared.

Three of the methods did not prove reliable for locations in Malaŵi: Brutsaert-Stricker (E_{BS}), equilibrium evaporation (E_E) and Bouchet (E_{BO}).

Table 6.1 The countrywide mean value of average annual actual evapotranspiration estimated by the six different methods

Method	Formula	Actual evapotranspiration Mean (mm)
Catchment waterbalance	$AAE = 0.29\ AAR + 490$	819
Soil moisture recharge	$AAE' = \overline{\Sigma \min (R_{ij}, E_{ij})} + S$	818
Brutsaert-Stricker	$E_{BS} = 1.52\ M_e - M_a$	1360
Equilibrium evaporation	$E_E = M_e$	1180
Difference	$E_D = M_e - M_a$	746
Bouchet	$E_{BO} = \frac{\gamma}{\Delta} M_e + R_L - M_a$	584

The main drawbacks were that firstly the majority of E_{BS} and E_E values exceeded the rainfall (AAR), secondly E_E and E_{BO} did not increase with increasing rainfall, and thirdly, as demonstrated in Table 6.1, E_{BS} substantially overestimated AAE, whilst E_E and E_{BO}, though closer to AAE, over- and underestimated respectively.

The remaining three methods are all considered suitable for practical use in Malaŵi; Catchment waterbalance (AAE), Soil moisture recharge (AAE') and Difference (E_D). Greatest reliance can be placed on the catchment waterbalance method for two reasons: first, it is based on data drawn from a large number of catchments (38) spread throughout the country; and second, it is valid for the widest range of rainfall, 700 to 2100 mm. The formula in Table 6.1 shows that actual evapotranspiration (AAE) increases slightly with increasing rainfall (AAR). If AAE is expressed as a fraction of E_{PN} (the Penman estimate of short grass potential evaporation) it is found to vary from 39 to 67% with a mean of 51%.

The concept underlying the soil moisture recharge method is particularly appropriate for climates, such as that in Malaŵi, which have a single rainy season. When fitted to the data, the formula in Table 6.1 exhibits several encouraging features: all values of AAE' are less than or equal to the rainfall; there are no extreme outliers; the trend of increasing actual evapotranspiration with increasing rainfall is replicated. The main disadvantage concerns the estimation of soil moisture recharge (S). By comparing this method with that of the catchment waterbalance, S was found empirically to vary between 34 and 209 mm for individual stations, with a countrywide mean of 120 mm. It would be preferable if S could be determined from an independent field soil survey. The close agreement between the mean values of AAE' and AAE in Table 6.1 is not significant because, in the absence of such a field survey, the empirically derived mean value 120 mm was assumed for S. However it does indicate that if an approximate value, say of 200 mm, was chosen for S based on a rudimentary knowledge of soils and vegetation in Malawi, there would still be a reasonable agreement between the values deduced from each of the two methods AAE' and AAE.

The well-known formula for estimating Penman short grass potential evaporation is:

$$E_{PN} = \frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} f\ (U_2)\ (e_s - e) \tag{6.1}$$

where the albedo r is set equal to 0.25 in the net radiation term R_n. In the difference method an hypothesis for estimating actual evapotranspiration (E_D) is proposed which employs the same two major terms as in the formula for E_{PN} above but, instead of their sum, it takes their difference:

$$E_D = \frac{\Delta}{\Delta + \gamma} R_n - \frac{\gamma}{\Delta + \gamma} f\ (U_2)\ (e_s - e) \tag{6.2}$$

When fitted to the data, E_D gives values which show a slight trend to increase with increasing rainfall, and for which all but one are less than the rainfall. From Table 6.1 it is seen that the countrywide mean value of E_D slightly underestimates the corresponding value of AAE by 9%. However the individual station values of the Difference method demonstrate greater scatter than those of the soil moisture recharge method AAE'.

Before concluding it should, however, be recalled that these methods for estimating actual evapotranspiration are applicable only under the following restraints (see also Section 1.4):

a) the evaporating surface is mixed vegetation
b) the estimate is of annual, rather than monthly, values of actual evapotranspiration and
c) the estimate is primarily a regional rather than a site-specific value of actual evapotranspiration.

Although some of the methods can be adapted to estimate monthly values, further research is required to see whether this can be justified.

6.3 COMPLEMENTARY EVAPORATION

The difference method (E_D) and the methods of Brutsaert-Stricker (E_{BS}) and Bouchet (E_{BO}) are founded on the concept of complementary evaporation (Bouchet, 1963):

$$E_p + E = 2E_{PO} \tag{6.3}$$

in which a symmetry is assumed between actual E and potential evapotranspiration (E_p) with respect to the evaporative power of the air in the absence of advection (E_{po}).

Some evidence in support of the concept, at least for annual periods, is provided by analysis of the Malaŵi data: as the actual evapotranspiration (AAE) increases, firstly the potential evapotranspiration (E_{PN}) decreases and secondly the net radiation (R_n) remains relatively unchanged; however this evidence is not firm enough to be conclusive.

Regarding the choice of a suitable variable to represent E_{po}, ideally it needs to lie halfway between E_{PN} and AAE to maintain the symmetry inherent in Equation 6.3. In the Brutsaert-Stricker method the Priestley-Taylor estimate of potential evaporation (E_{PT}) is chosen for E_{po}. For stations in Malaŵi it is found that E_{PT} lies much closer to E_{PN} than AAE; this leads to the substantial overestimates by E_{BS} values and makes the method unsuitable for use in this country. In contrast, in the Difference method the equilibrium evaporation (E_E) is chosen to represent E_{po}. The reason for this choice is that mean values of E_E for the two groups of upland area and rift valley stations were only 3% less than the corresponding ideal values of (E_{PN} + AAE)/2. This method gives estimates (E_D) of actual evapotranspiration that are always less than E_{BS} values. From the form of the formula (Table 6.1) it can also be demonstrated that E_D is always less than both the equilibrium evaporation (E_E) and the potential evapotranspiration (E_{PN}). Therefore it may be concluded that the choice of E_E for E_{po} leads to a method more suitable for use in Malaŵi. However it must be emphasized that estimates of actual evapotranspiration obtained from any of the methods founded on the complementary evaporation concept are very sensitive to the exact choice of variable for E_{po}, since the form of Equation 6.3 dictates that any change in E_{po}, results in a change twice that size in E, if E_p remains unchanged.

No derivation of the new Difference method from physical principles is offered in this report. Even if the physical basis is weak it may prove a useful empirical method for solving practical problems. Further work on the theoretical aspects together with practical testing under different climates in other countries are required to establish whether this hypothesis has any validity other than as an empirical method for estimating actual evapotranspiration in Malaŵi.

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References

Agnew, S. and Stubbs, M., 1972. *Malaŵi in Maps*, Univ. of London Press, London, UK.

Bouchet, R.J., 1963. Evaporation réele et potentielle, signification climatique. *Proc. IASH* 62, 134-142.

Brutsaert, W.H. and Stricker, H., 1979. An advection-aridity approach to estimate actual regional evapotranspiration. *Wat. Resour. Res.* 15, 443-450.

Dandaula, H.E., 1979. Mean annual potential evapotranspiration and evaporation in Malaŵi. Malaŵi Met. Office Internal Report. Malaŵi Met. Office, Blantyre, Malaŵi.

de Bruin, H.A.R., 1983. Evapotranspiration in humid tropical regions. In: *Hydrology of humid tropical regions with particular reference to the hydrological effects of agriculture and forestry practice*, (Proc. Hamburg Symp., August 1983), IAHS Publ. no. 140, 299-311.

de Bruin, H.A.R. and Stewart, J.B., 1983. Estimation of actual evapotranspiration in the tropics using the concept of complementary evaporation. Report no. OD 61/8. Institute of Hydrology, Wallingford, UK.

Denmead, O.T. and McIlroy, I.C., 1970. Measurements of non-potential evaporation from wheat. *Agric. Meteorol.* 7, 285-302.

Doorenbos, T. and Pruitt, W.O., 1977. Crop water requirements. Irrig. & Drain. Paper no. 24, FAO, Rome, Italy.

Drayton, R.S., Kidd, C.H.R., Mandeville, A.N. and Miller, J.B., 1980. A regional analysis of river floods and low flows in Malaŵi. Institute of Hydrology Report no 72, Wallingford, UK.

Hill, J.L. and Kidd, C.H.R., 1980. Rainfall-runoff relationships for 47 Malaŵi catchments. Report no. T.P.7, Water Resources Division, Dept. of Lands, Valuation and Water, Lilongwe, Malaŵi.

Malaŵi Meteorological Service, 1970-1978. Monthly Summaries, Malaŵi. Met. Office, Blantyre, Malaŵi.

Pike, J.G., 1962. Evaporation and evapotranspiration in Nyasaland. Water Resources Department, Ministry of Works, Zomba, Nyasaland.

Priestley, C.H.B. and Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Mon. Weath. Rev. 100,* 81-92.

Slatyer, R.O. and McIlroy, I.C., 1961. *Practical Microclimatology*, CSIRO, Melbourne, Australia.

Smith-Carington, A.K., 1983. Hydrogeological bulletin for the Bua catchment: water resources unit 5. Dept. of Lands, Valuation and Water, Lilongwe, Malaŵi.

Smith-Carington, A.K. and Chilton, P.J., 1983. Groundwater resources of Malaŵi. Dept. of Lands, Valuation and Water, Lilongwe, Malaŵi.

Sutcliffe, J.V., Agrawal, R.P. and Tucker, J.M., 1981. The water balance of the Betwa basin, India. *Hydrol. Sci. Bull.* 26, 2. 149-158.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. *Geogr. Rev.* 38, 55-94.

van der Velden, J., 1979. A summary of rainfall, pan evaporation and temperature data at pan evaporation stations in Malaŵi. Report no. T.P.3, Water Resources Department, Ministry of Agriculture and Natural Resources, Lilongwe, Malaŵi.

van der Velden, J., 1980. A summary and review of monthly temperature data in Malaŵi. Report no. T.P.4, Water Resources Division, Dept. of Lands, Valuation and Water, Lilongwe, Malaŵi.

World Meteorological Organization, 1976. A water resources assessment of Lake Malaŵi. UNDP/WMO/Malaŵi Government Project Report no. 71/518, Geneva, Switzerland.

Appendix 1 Practical calculation of potential evaporation

This appendix contains in greater detail the practical background to the calculation of potential evaporation for Malaŵi.

CORRECTIONS UNDERTAKEN TO THE OBSERVATIONS BEFORE PROCESSING

- New climatological stations were opened at Ngabu on 17 October 1971 and at Dwangwa on 3 December 1971.
- The previous name of the station at Thyolo was Cholo. The previous name of the station at Mangochi was Mangoche, and prior to that Fort Johnson.
- The instruments at Mangochi station were moved on 2 September 1971 to a new site 500 yards to the south-east.
- At Lilongwe the observations from the 6 ft. high anemometer were missing for all months of the 1970-1978 record. Readings were taken instead form the Munro cup anemograph, which was assumed to be mounted at the standard height of 10 m. A factor of 0.78, as recommended in the British Meteorological Office observer's handbook, was applied to all windspeeds to reduce them to the equivalent speeds found at 2 m height.
- Observations of windspeed, dew point temperature, mean air temperature, sunshine hours and rainfall were missing for occasional months for all stations, as listed in Table A1.1. The average of the observations for the same month in all the remaining years was used to fill in these missing values for each variable.

CALCULATION OF MINOR VARIABLES

The explanation and source of the variables used in the calculation of potential evaporation, described in Equations 2.1-2.3, are given in Table A1.2.

ANOMALIES IN THE PROCESSED DATA

Inspection of the computer listings of processed potential evaporation data revealed a number of anomalies which are listed in Table A1.3. The remaining seven stations, Bvumbwe, Chitedze, Chitipa, Karonga, Mzimba, Nkhota Kota and Thyolo did not reveal any easily recognisable anomalies.

Table: A1.1 Months in which observations of certain variables were missing at the climatological stations

Climatological Station	Windspeed	Missing months observations Dew point temperature	Mean air temperature	Sunshine hours	Rainfall
Bvumbwe	0374	0171	0572	0374	0374
		0374	0374		
Chichiri		0171	0572		
Chileka		0171	0572		0670
					0770
					0870
Chitedze	0273	0171	0572	0273	0273
		0273	0273		
		0774			
Chitipa	0375	0171	0572		0570
					0870
					0671
Dedza		0171	0572		
Dwangwa					
Karonga		0171	0572		
Lilongwe		0171	0572		0770
					0870
					0671
Makhanga	1272	0171	0572	1272	0970
	0376	1272	1272	0376	1272
	0476	0376	0376	0476	0376
		0476	0476		0476
Mangochi	0276	0171	0572		0570
					0770
					0870
Mimosa		0171	0572		
Mzimba		0171	0572		
Mzuzu		0171	0572		
Ngabu	0678				
Nkhata Bay		0171	0572	0976	0777
Nkhota Kota	0170	0171	0572		
Salima		0171	0572		
Thyolo		0171	0572		
Makoka		0171	0572		

Table: A1.2 Source of variables used in calculation of potential evaporation

Variable	Source
R	Rainfall measured in a Snowdon pattern raingauge with rim at 2ft 6ins above ground level
U_2	Windspeed measured in a 6ft high cup anemometer, which was assumed equal to the speed at 2m height
T_a	Mean air temperature taken as the mean of observations from the maximum and minimum thermometers
	Stefan-Boltzman constant: 5.67×10^{-8} W m^{-2} K^{-4}
$\frac{n}{N}$	n is hours of bright sunshine observed on a Campbell-Stokes recorder, with WMO type reductions; N is maximum possible hours of bright sunshine calculated from values of latitude and day of year.
R_a	Incoming short-wave radiation at the top of the earth's atmosphere calculated from values of latitude, day of year and solar constant
	Saturation vapour pressure at mean air temperature; e_s is a function of temperature T_a
	Vapour pressure is a function of the mean dewpoint temperature, which is taken as the mean of the dewpoint temperatures of 0800 and 1400 hours
	Slope of saturation vapour pressure curve at mean air temperature. Δ is a function of temperature T_a
	Psychrometric constant is taken as a function of altitude and temperature T_a

Table: A1.3 Anomalies discovered in the processed potential evaporation data

Climatological Station	Anomalies
Chichiri	Windspeed decreasing over period 1972-1974
	Mean air temperature error in August 1973
Chileka	Vapour pressure error February 1971
Dedza	March rainfall much higher in 1974-1978 than in 1970-1973
	Low potential evaporation estimates in 1974 and 1978
Dwangwa	Rainfall in May 1974, but not in May 1973, affects radiation term
Lilongwe	Vapour pressure errors in August 1970 and July 1971
	March rainfall much higher in 1974-1978 than in 1970-1973
	Low potential evaporation estimates in 1974 and 1978
Makhanga	Rainfall does not have same pattern as Ngabu
Makoka	Rainfall error in January 1976
	Doubtful rainfall value in January 1970, since it differs greatly from values at Chileka and Chichiri
Mangochi	In general processed variables, except rainfall, very similar to same variables recorded at Salima; however 1970-1978 rainfall recorded at Salima is not representative of long-term average there
	In general processed variables very similar to same variables recorded at Ngabu
	Very high rainfall recorded in 1978, as it was also for other stations on the lakeshore
Mimosa	Mean air temperature error in February 1978
	Vapour pressure error in May 1970
	Rainfall agrees quite closely with that recorded at Thyolo station
Mzuzu	Mean air temperature error in November 1974
	Windspeed error in August 1977
	Some doubtful values in vapour pressure deficits
	Good correlation between values of M_e and n/N
Ngabu	Extremely high value of M_a recorded in October 1977
Nkhata Bay	Windspeed gradually decreasing over 1970-1978
	Thom-Oliver wind function RA gradually increasing over 1970-1978
Salima	Rainfall recorded during 1970-1978 is not representative of long-term average

Appendix 2 Average monthly values of rainfall and selected evaporation variables

This appendix lists the average monthly values of the most useful nine variables at each of the 20 climatological stations. For each variable separate tables give the mean and coefficient of variation over the period of record, which is nine years for all but two of the stations. All values of the mean expressed in units of mm were rounded to the nearest mm; consequently some average annual values may not exactly equal the sum of the average monthly values shown. The coefficient of variation is a measure of the year-to-year change in a variable; a star in a column indicates that its values is indeterminate, for example if, for a certain month, all annual values of rainfall are zero.

The 18 tables in this appendix are arranged as shown below:

Variable	Mean Table No.	Coefficient of variation Table No.
R	A2.1A	A2.1B
E_{PN}	A2.2A	A2.2B
E_0	A2.3A	A2.3B
M_e	A2.4A	A2.4B
M_a	A2.5A	A2.5B
E_{PT}	A2.6A	A2.6B
R_n	A2.7A	A2.7B
$\Delta/(\Delta+\gamma)$	A2.8A	A2.8B
R_s	A2.9A	A2.9B

From these listings of nine variables it is possible to calculate average monthly values for any of the other major variables mentioned in the main text, for example:

Brutsaert and Stricker actual evaporation estimates

$$E_{BS} = 2E_{PT} - E_{PN} \quad \text{(A2.1)}$$

$$\text{or } E_{BS} = 1.52M_e - M_a \quad \text{(A2.2)}$$

Actual evaporation estimated from the Difference method

$$E_D = 2M_e - E_{PN} \quad \text{(A2.3)}$$

$$\text{or } E_D = M_e - M_a \quad \text{(A2.4)}$$

$$E_D = \frac{2E_{PT}}{1.26} - E_{PN} \tag{A2.5}$$

Outgoing long-wave radiation

$$R_L = (1 - r)\ R_s - R_n \tag{A2.6}$$

with $r = 0.25$

Bouchet actual evaporation estimate

$$E_{BO} = (1 - r)\ R_s - E_{PN} \tag{A2.7}$$

with $r = 0.25$

$$\text{or } E_{BO} = \frac{\gamma}{\Delta} M_e + R_L - M_a \tag{A2.8}$$

Dimensionless factors

$$\frac{\gamma}{\Delta + \gamma} = \qquad \frac{\Delta}{\Delta + \gamma} \tag{A2.9}$$

$$\frac{\gamma}{\Delta} \qquad \left[\frac{\Delta}{\Delta + \gamma}\right]^{-1} \tag{A2.10}$$

It should be noted that expression:

$$M_e = \frac{\Delta}{\Delta + \gamma} R_n \tag{A2.11}$$

was evaluated using the individual monthly values of $\Delta/(\Delta+\gamma)$ and R_n for each station. Since this is a product of two variables it follows that:

$$\overline{M_e} \neq \overline{\frac{\Delta}{\Delta + \gamma}}\ \overline{R_n} \tag{A2.12}$$

where the bars denote average monthly values or average annual values. Therefore the values of M_e, $\Delta/(\Delta+\gamma)$ and R_n in Tables A2.4A, A2.8A and A2.7A cannot be directly related; in practice, although the inequality (A2.12) is true for average annual values, the two sides of the expression show close agreement for average monthly values.

Table A2.1 Average monthly values of rainfall R for 1970-1978

a) Mean (mm)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	284	204	153	88	21	17	15	4	1	20	102	213	1122
Chichiri	271	195	193	68	18	13	13	3	1	25	113	228	1141
Chileka	197	167	149	44	18	3	1	0	1	21	108	200	912
Chitedze	248	209	142	67	15	1	1	0	1	7	81	211	983
Chitipa	206	201	208	56	14	1	1	0	0	4	82	180	953
Dedza	268	216	127	52	14	6	3	0	0	11	38	208	943
Dwangwa*	280	167	379	138	84	1	6	5	0	1	19	188	1265
Karonga	202	163	314	204	42	2	2	1	0	2	35	179	1147
Lilongwe	243	196	134	58	13	1	4	0	1	9	56	184	898
Makhanga	167	93	91	40	17	20	14	8	4	20	70	178	722
Makoka	267	197	195	67	18	6	3	1	2	21	92	207	1076
Mangochi	202	191	164	49	8	2	7	1	1	16	55	160	856
Mimosa	275	205	271	159	60	69	43	11	13	49	134	256	1544
Mzimba	245	190	155	44	17	1	1	0	0	6	63	201	925
Mzuzu	220	139	221	219	52	38	19	6	5	30	61	172	1182
Ngabu†	149	139	187	54	21	19	11	5	1	19	56	199	859
Nkhata Bay	258	193	380	291	129	68	42	6	3	7	125	237	1740
Nkhota Kota	366	274	438	246	46	13	5	1	1	8	81	280	1759
Salima	404	287	299	108	21	0	1	0	1	4	38	261	1426
Thyolo	215	190	218	93	27	33	30	11	7	42	127	234	1229

b) Coefficient of variation %

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	33.2	61.0	70.1	70.4	76.2	50.7	74.7	123.1	68.2	116.6	36.0	34.8	23.6
Chichiri	32.7	43.6	61.8	43.0	53.0	46.3	94.7	120.8	138.3	59.8	56.8	47.1	21.2
Chileka	38.3	52.2	83.0	51.4	154.7	123.6	145.4	163.5	234.5	96.1	39.8	49.1	30.0
Chitedze	28.6	34.2	59.7	42.4	202.1	172.9	221.1	*	260.5	102.8	69.1	40.3	8.5
Chitipa	20.6	30.9	46.0	58.3	175.9	190.3	240.0	*	198.4	202.9	62.3	41.7	17.3
Dedza	37.7	25.1	66.5	71.9	155.2	93.4	151.1	212.1	198.4	114.8	78.4	35.4	16.7
Dwangwa*	38.4	31.0	45.0	1.5	141.4	12.9	141.4	*	*	141.4	118.5	36.1	33.6
Karonga	41.1	22.5	46.4	47.0	206.7	121.9	236.2	260.5	*	153.5	85.9	32.7	32.9
Lilongwe	37.4	40.0	54.3	48.3	194.5	193.6	219.7	163.5	198.4	136.7	79.1	40.3	22.2
Makhanga	50.5	61.1	47.8	69.7	104.1	51.0	69.1	114.9	210.5	128.9	92.4	16.1	15.4
Makoka	52.2	28.2	68.6	60.2	130.7	181.8	149.3	105.0	279.5	95.5	47.7	20.2	15.6
Mangochi	29.7	49.4	54.3	87.0	193.0	83.0	159.0	182.5	194.9	92.1	67.3	41.1	28.3
Mimosa	45.7	40.5	66.8	64.0	62.8	49.2	35.6	100.7	129.0	96.1	36.9	47.7	25.3
Mzimba	39.3	25.5	31.4	55.1	261.1	264.4	157.3	*	*	180.6	83.6	32.3	19.2
Mzuzu	34.5	25.0	36.7	33.4	107.5	74.7	61.3	84.3	171.1	92.0	96.7	31.8	16.0
Ngabu†	53.7	62.2	46.0	68.1	91.3	70.1	68.3	95.9	200.0	115.3	72.7	52.9	19.0
Nkhata Bay	36.0	35.3	32.6	41.1	94.9	78.8	112.3	125.0	127.5	119.4	81.0	34.1	18.8
Nkhota Kota	31.1	50.2	48.0	43.3	174.6	105.1	258.8	300.0	300.0	112.9	74.1	30.4	16.2
Salima	41.0	39.5	64.4	79.9	170.5	212.1	198.4	*	260.5	123.7	111.5	54.8	31.0
Thyolo	37.9	71.2	58.0	59.2	86.8	49.0	67.7	87.7	123.0	83.1	39.6	38.3	24.4

* 1973 - 1974

† 1973 - 1978   Computer printout nomenclature : RAIN

Table A2.2 Average monthly values of Penman short grass potential evaporation E_{PN} for 1970-1978

a) Mean (mm)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	126	112	120	99	94	77	86	116	148	175	150	128	1430
Chichiri	127	115	123	105	99	85	96	123	159	183	164	131	1512
Chileka	153	138	144	127	123	105	118	150	189	218	192	159	1816
Chitedze	125	113	125	112	107	95	103	127	159	188	169	134	1558
Chitipa	118	112	122	123	127	120	135	166	201	229	184	133	1769
Dedza	119	107	119	103	102	86	95	120	156	180	160	126	1472
Dwangwa*	125	115	121	121	109	106	112	132	156	182	189	151	1618
Karonga	138	130	138	130	134	128	136	156	181	214	193	159	1835
Lilongwe	125	115	126	114	109	97	105	128	162	191	172	134	1578
Makhanga	166	147	153	129	110	87	97	133	175	215	202	169	1784
Makoka	130	115	123	103	98	86	94	123	158	181	163	133	1506
Mangochi	152	137	151	135	124	107	116	141	175	211	197	161	1806
Mimosa	135	117	123	100	90	73	80	107	137	161	150	133	1404
Mzimba	113	106	116	112	110	98	106	130	157	184	158	125	1513
Mzuzu	115	106	110	96	84	69	75	98	127	160	151	126	1316
Ngabu†	175	150	147	122	111	90	99	140	184	227	220	175	1840
Nkhata Bay	128	117	122	111	108	96	103	127	148	175	162	137	1534
Nkhota Kota	130	121	134	130	127	119	128	146	171	210	196	149	1759
Salima	138	129	147	141	131	118	129	148	171	208	198	157	1816
Thyolo	136	119	121	100	91	71	78	110	139	170	155	136	1427

b) Coefficient of variation (%)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	6.6	9.7	9.8	8.6	12.1	5.7	8.3	6.7	4.7	4.8	6.0	10.0	3.0
Chichiri	7.1	10.4	13.3	11.0	13.6	7.5	10.2	16.9	8.8	4.2	9.2	10.1	5.3
Chileka	6.0	13.3	14.4	7.8	11.1	6.5	7.7	5.6	5.8	3.3	6.5	10.6	4.2
Chitedze	7.4	8.1	10.6	5.6	11.1	4.3	5.2	5.0	5.6	2.7	4.8	9.4	3.9
Chitipa	5.6	5.2	6.4	5.7	8.7	5.9	4.2	3.5	2.6	4.0	8.0	9.6	1.2
Dedza	6.1	7.9	10.1	8.4	10.2	5.7	3.5	6.6	3.1	2.7	6.9	9.4	2.8
Dwangwa*	9.3	9.4	10.8	2.4	16.6	5.3	7.3	2.2	2.8	3.8	8.8	2.5	5.1
Karonga	5.3	6.3	8.4	6.1	7.5	5.5	5.0	3.3	3.1	4.5	6.5	7.8	2.4
Lilongwe	7.7	8.9	10.9	6.2	9.9	6.4	7.1	6.8	4.6	3.3	5.0	10.0	3.8
Makhanga	6.7	7.5	6.3	8.6	12.0	6.7	8.2	5.0	5.8	5.7	9.8	4.9	3.0
Makoka	8.9	9.7	13.7	9.6	12.0	5.9	7.1	6.5	4.6	3.3	6.7	9.3	3.7
Mangochi	6.2	10.0	10.9	6.1	7.8	5.8	4.1	3.1	1.4	3.7	7.0	9.2	3.3
Mimosa	5.5	11.3	7.0	9.9	10.5	5.1	6.2	7.9	3.6	4.8	8.7	9.2	2.5
Mzimba	7.4	7.3	7.8	7.1	9.1	6.1	5.2	3.0	2.9	2.6	6.1	8.4	2.8
Mzuzu	4.5	7.6	8.4	4.6	6.6	6.3	3.7	4.7	1.9	2.1	6.2	8.5	1.9
Ngabu†	5.1	8.9	9.4	8.7	13.2	5.8	9.3	7.7	4.7	8.9	6.3	3.8	3.7
Nkhata Bay	7.3	6.9	8.6	8.3	7.4	5.1	5.3	5.0	3.2	2.6	6.9	10.8	2.7
Nkhota Kota	8.2	8.7	10.3	4.7	7.1	3.7	4.2	2.4	3.6	2.9	6.3	13.1	2.8
Salima	8.8	11.1	12.0	7.1	8.0	4.8	3.0	4.2	1.3	3.1	7.3	11.4	4.2
Thyolo	7.1	9.2	8.6	9.5	10.1	6.3	6.7	9.3	4.0	4.7	7.2	10.3	2.4

* 1973 1974

† 1973 - 1978 Computer printout nomenclature : PN

Table A2.3 Average monthly values of Penman open water evaporation E_o for 1970-1978

a) Mean (mm)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	161	143	154	128	122	100	111	147	186	217	189	162	1820
Chichiri	163	148	158	136	129	110	222	155	198	227	203	166	1914
Chileka	191	173	181	160	155	131	146	184	229	263	234	197	2244
Chitedze	159	145	161	145	139	122	132	161	200	234	210	169	1975
Chitipa	149	142	155	157	161	152	170	206	244	275	225	167	2201
Dedza	151	137	153	133	133	112	123	153	195	225	200	160	1874
Dwangwa*	160	147	156	155	142	138	144	169	198	230	236	191	2065
Karonga	174	164	175	164	169	160	170	196	226	264	238	198	2297
Lilongwe	159	146	161	146	141	124	133	162	202	237	213	169	1992
Makhanga	209	186	194	165	142	112	125	168	216	263	248	212	2239
Makoka	166	147	157	132	126	110	121	155	197	225	203	168	1907
Mangochi	191	172	191	171	158	136	147	176	218	260	242	200	2261
Mimosa	172	150	157	129	119	96	104	139	175	204	190	170	1804
Mzimba	145	136	149	144	144	128	137	167	200	232	199	159	1939
Mzuzu	146	135	141	125	113	94	102	130	166	205	192	160	1710
Ngabu†	218	188	185	156	143	115	126	175	225	275	267	216	2288
Nkhata Bay	163	150	157	144	141	125	134	164	190	223	206	175	1968
Nkhota Kota	164	153	170	165	162	150	160	184	214	258	242	187	2208
Salima	175	164	186	178	167	149	161	186	214	258	244	196	2276
Thyolo	173	152	156	131	121	94	104	143	177	214	195	172	1830

b) Coefficient of variation (%)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	6.6	9.9	9.8	8.5	11.7	5.4	7.8	6.9	4.4	4.5	6.3	10.0	2.8
Chichiri	7.2	10.2	12.8	10.3	12.6	6.3	8.9	15.0	7.7	3.5	8.6	10.0	4.6
Chileka	5.9	12.7	13.9	7.7	10.6	6.1	7.1	5.8	5.6	3.2	6.5	10.2	3.9
Chitedze	7.5	8.3	10.8	5.6	10.9	3.5	5.5	5.2	4.9	2.4	4.8	9.4	3.7
Chitipa	5.8	5.3	6.4	5.9	8.6	5.4	3.7	3.4	2.2	3.6	8.0	9.5	1.2
Dedza	6.3	8.1	10.2	8.2	10.0	5.7	6.5	7.0	2.9	2.6	6.9	9.3	2.6
Dwangwa*	9.6	9.3	10.7	2.1	17.8	3.5	6.7	1.3	2.5	3.9	7.5	2.6	4.8
Karonga	5.7	6.3	8.2	6.1	7.3	5.2	4.7	3.2	3.0	4.1	6.6	7.9	2.1
Lilongwe	7.9	8.8	11.0	6.3	9.8	5.6	6.5	6.6	4.0	3.0	4.8	10.2	3.6
Makhanga	6.4	7.6	8.4	11.5	6.2	7.6	4.9	5.1	5.1	9.4	5.1	9.4	2.8
Makoka	9.0	9.9	13.4	9.7	11.8	5.7	6.8	6.7	4.4	3.2	6.8	9.2	3.5
Mangochi	6.2	10.0	10.8	6.4	7.9	5.3	3.8	3.0	1.4	3.6	6.9	9.1	3.1
Mimosa	5.4	11.1	7.4	10.1	10.6	5.4	6.5	8.0	3.5	4.6	8.7	9.2	2.5
Mzimba	7.7	7.3	8.1	6.9	9.1	5.5	4.9	2.9	2.5	2.5	6.1	8.6	2.7
Mzuzu	5.1	7.6	8.9	5.1	6.7	5.8	3.8	4.8	1.8	1.9	8.1	8.7	2.0
Ngabu†	4.9	8.7	9.2	8.6	12.7	5.8	8.7	7.4	3.9	7.7	6.1	4.2	3.4
Nkhata Bay	7.4	7.1	8.8	8.1	7.4	4.9	5.0	5.0	2.9	2.4	6.9	10.8	2.6
Nkhota Kota	8.2	8.5	10.2	4.7	7.1	3.2	4.1	2.4	3.3	2.5	6.0	12.7	2.7
Salima	8.9	11.0	12.0	6.9	7.7	4.2	2.6	3.0	1.3	2.7	6.9	11.2	4.0
Thyolo	7.1	9.4	9.1	9.6	10.1	6.2	7.1	8.9	3.5	4.5	7.2	10.3	2.5

* 1973 - 1974

† 1973 - 1978 Computer printout nomenclature : EO

Table A2.4 Average monthly values of energy term of Penman short grass potential evaporation M_e for 1970 - 1978

a) Mean (mm)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	109	96	101	81	70	55	59	77	97	116	112	107	1079
Chichiri	110	99	102	84	73	57	61	78	99	119	115	108	1106
Chileka	119	105	110	92	78	60	64	81	103	122	121	117	1170
Chitedze	105	96	105	91	78	61	64	81	102	122	116	106	1127
Chitipa	96	91	98	94	89	78	82	97	109	123	113	101	1170
Dedza	99	90	98	83	74	58	62	78	100	120	112	101	1075
Dwangwa*	110	100	107	100	87	76	77	95	113	136	136	123	1259
Karonga	111	105	113	100	94	79	84	102	117	136	129	120	1291
Lilongwe	104	95	103	89	78	61	65	80	101	121	115	105	1117
Makhanga	136	122	125	102	81	62	67	87	108	133	135	132	1290
Makoka	111	98	101	82	72	57	61	78	101	120	116	108	1104
Mangochi	122	110	119	100	86	67	71	87	109	131	129	122	1250
Mimosa	117	102	105	84	73	56	60	79	100	120	119	114	1128
Mzimba	98	91	99	91	85	70	73	91	109	129	117	104	1157
Mzuzu	98	91	95	84	77	65	68	85	103	123	117	105	1109
Ngabu†	136	119	118	96	81	62	66	87	108	132	138	127	1267
Nkhata Bay	111	103	107	97	89	74	78	98	117	139	131	119	1261
Nkhota Kota	109	101	110	101	91	73	76	93	112	135	132	118	1250
Salima	114	106	116	103	90	71	75	92	112	135	134	121	1268
Thyolo	116	102	105	86	74	56	62	80	99	120	118	111	1129

b) Coefficient of variation (%)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	5.2	8.6	7.4	6.7	7.1	2.6	4.3	6.1	2.8	3.6	5.9	8.7	1.6
Chichiri	6.3	8.1	8.3	6.5	7.3	1.7	4.2	6.6	2.2	4.0	5.9	8.3	1.5
Chileka	4.7	8.9	9.5	6.1	6.2	2.0	3.2	5.7	2.9	2.6	4.9	7.5	2.1
Chitedze	6.5	7.5	9.1	4.7	6.4	2.1	4.2	5.2	1.8	3.1	3.8	8.0	2.0
Chitipa	5.3	5.4	5.2	5.0	5.8	2.7	1.7	2.4	1.3	2.4	6.2	7.2	1.1
Dedza	5.6	7.7	7.9	5.5	6.3	2.8	5.0	6.5	2.1	2.5	5.2	7.4	1.8
Dwangwa*	9.9	8.3	9.3	1.4	15.5	3.1	1.3	2.8	0.7	3.1	1.4	3.1	2.8
Karonga	6.2	6.8	6.3	5.3	5.0	3.5	2.6	2.6	1.7	2.2	5.4	7.1	0.9
Lilongwe	6.9	7.5	9.0	5.8	6.4	1.9	4.4	5.3	2.5	3.1	3.9	9.2	2.4
Makhanga	5.2	7.8	5.8	6.7	7.7	3.2	4.3	5.0	2.2	2.9	6.7	6.7	2.1
Makoka	8.0	8.5	9.6	7.8	7.7	2.8	3.5	6.3	2.8	2.3	6.0	7.6	1.8
Mangochi	5.1	9.1	8.1	6.2	5.6	2.6	3.4	4.3	1.6	2.7	5.1	8.0	2.0
Mimosa	4.4	9.6	7.0	8.8	7.6	3.1	4.7	6.4	2.1	3.0	7.3	8.2	1.9
Mzimba	7.3	6.3	7.8	4.9	6.1	2.3	2.9	3.1	1.2	2.3	4.9	7.5	2.3
Mzuzu	6.1	7.0	9.0	6.1	6.3	3.9	3.1	4.3	1.5	1.8	5.7	7.8	2.3
Ngabu†	3.2	7.0	6.7	6.4	8.0	4.0	3.9	5.4	2.2	1.8	6.8	6.3	1.9
Nkhata Bay	6.8	7.5	8.2	6.7	5.8	4.4	3.7	4.5	1.9	2.0	5.8	9.7	2.0
Nkhota Kota	6.8	6.9	7.7	4.0	5.4	2.0	3.3	2.9	1.5	2.0	3.0	9.5	1.9
Salima	7.8	9.0	9.7	5.0	4.5	2.6	4.0	3.2	1.4	1.8	3.6	8.6	2.6
Thyolo	5.9	9.0	8.5	8.4	7.6	3.0	5.9	6.1	2.7	3.0	6.0	8.9	2.3

* 1973 - 1974

† 1973 - 1978 Computer printout nomenclature : ETRM

Table A2.5 Average monthly values of aerodynamic term of Penman short grass potential evaporation M_a for 1970 - 1978

a) Mean (mm)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	17	16	20	18	23	23	27	39	52	59	39	21	353
Chichiri	17	16	21	21	26	28	35	45	60	65	48	23	406
Chileka	34	33	34	36	45	46	54	69	86	97	71	42	646
Chitedze	20	17	21	21	29	34	39	47	57	66	53	28	431
Chitipa	23	21	24	30	38	42	54	68	92	105	71	32	599
Dedza	20	17	21	21	28	28	33	42	56	60	48	25	397
Dwangwa*	15	15	14	21	22	30	35	37	44	46	53	28	359
Karonga	28	25	25	30	39	49	52	54	64	77	64	39	544
Lilongwe	22	20	23	24	31	36	40	48	61	70	57	29	461
Makhanga	30	25	28	27	29	25	30	46	67	83	67	37	494
Makoka	19	17	22	21	26	29	33	44	57	62	47	25	402
Mangochi	29	27	32	35	39	40	46	54	67	80	68	39	556
Mimosa	18	14	17	15	17	17	20	28	38	42	31	20	276
Mzimba	16	15	17	20	26	28	33	39	48	55	41	21	356
Mzuzu	17	16	14	13	7	4	7	12	24	38	35	21	208
Ngabu†	39	32	29	27	30	27	33	53	76	96	83	47	571
Nkhata Bay	17	15	15	14	20	22	25	30	31	35	31	18	272
Nkhota Kota	21	20	24	29	36	46	51	54	60	75	65	31	510
Salima	24	23	31	38	41	47	54	57	59	73	64	35	546
Thyolo	19	17	16	15	17	15	17	30	41	50	37	25	199

b) Coefficient of variation (%)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	17.4	19.1	26.2	22.6	30.5	17.3	19.8	12.5	10.2	11.2	10.5	21.8	8.2
Chichiri	18.0	28.8	43.0	33.9	38.6	23.1	26.1	38.9	20.9	14.2	21.9	23.6	17.5
Chileka	14.5	39.5	32.2	16.7	22.1	14.0	15.2	8.6	9.6	7.0	10.7	22.0	8.2
Chitedze	14.1	14.5	25.2	19.5	26.9	13.7	7.7	10.7	13.8	9.4	9.1	17.3	9.2
Chitipa	9.4	13.2	12.5	10.5	16.4	13.9	9.1	6.2	5.3	6.7	11.6	20.2	2.8
Dedza	10.2	15.6	21.5	21.1	23.7	13.6	12.9	9.0	7.1	4.8	11.8	18.9	5.7
Dwangwa*	4.5	17.4	22.9	6.9	20.9	26.5	20.5	14.9	8.1	5.9	27.6	0.4	13.4
Karonga	9.3	23.6	21.9	12.0	16.3	14.1	10.7	7.6	7.7	11.0	9.7	15.9	6.8
Lilongwe	12.8	21.5	24.5	17.6	22.4	16.3	18.0	17.3	10.1	9.1	11.5	17.8	9.4
Makhanga	22.8	19.0	14.7	20.3	26.9	19.6	19.7	11.4	12.6	11.6	17.6	17.0	9.0
Makoka	19.4	18.0	37.4	23.4	29.0	14.3	16.0	12.3	9.6	7.3	12.2	18.5	9.6
Mangochi	12.4	20.8	24.3	12.1	15.7	12.2	10.5	9.4	3.8	6.7	12.2	18.5	6.7
Mimosa	15.6	49.9	14.6	18.6	27.5	15.2	14.0	15.3	10.0	12.1	15.0	21.1	6.1
Mzimba	11.3	15.2	12.8	21.0	21.8	17.0	11.7	8.5	8.1	6.2	11.1	17.0	6.1
Mzuzu	11.4	26.1	15.7	20.2	56.2	65.0	22.7	20.9	7.2	7.8	20.7	16.4	7.5
Ngabu†	16.9	18.3	20.7	17.8	29.7	14.1	21.9	14.2	11.1	19.2	13.1	10.5	9.0
Nkhata Bay	15.2	14.6	14.7	25.8	22.5	16.4	15.6	12.8	12.2	8.8	13.0	23.4	9.3
Nkhota Kota	17.1	21.3	24.9	13.2	16.7	10.9	9.9	6.5	7.8	7.5	13.7	28.7	5.6
Salima	15.2	23.6	25.2	18.1	19.5	10.1	9.9	15.3	4.8	8.9	17.0	24.4	9.2
Thyolo	16.3	23.3	12.2	18.1	24.6	22.0	15.9	21.4	13.3	9.9	14.5	21.1	4.0

* 1973 1974

† 1973 1978 Computer printout nomenclature : AETM

Table A2.6 Average monthly values of Priestley-Taylor potential evaporation E_{PT} for 1970 - 1978

a) Mean (mm)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	137	121	127	102	89	69	74	97	122	146	141	134	1358
Chichiri	139	125	129	106	92	72	77	98	125	150	145	136	1393
Chileka	149	133	138	115	99	75	81	103	129	153	153	147	1475
Chitedze	132	121	132	114	98	77	81	102	128	153	146	134	1420
Chitipa	121	115	123	118	112	98	103	123	137	155	143	128	1475
Dedza	125	114	124	104	94	73	78	98	126	151	141	128	1356
Dwangwa*	136	126	135	126	110	96	98	120	142	172	171	155	1586
Karonga	140	132	142	127	119	100	106	129	148	172	162	151	1626
Lilongwe	131	120	130	112	98	77	81	101	127	153	145	132	1408
Makhanga	171	154	158	128	103	78	84	110	137	167	170	166	1626
Makoka	140	123	127	103	91	72	77	99	127	151	146	136	1391
Mangochi	154	138	150	126	108	84	89	109	137	165	163	153	1577
Mimosa	147	129	132	106	92	71	76	100	126	151	150	143	1422
Mzimba	123	115	124	115	107	88	92	114	137	162	148	131	1457
Mzuzu	123	113	120	105	98	81	86	107	130	155	147	132	1397
Ngabu†	171	149	148	120	102	78	83	109	136	166	173	160	1597
Nkhata Bay	140	129	135	122	112	94	38	123	147	176	165	150	1590
Nkhota Kota	138	127	139	127	114	92	96	117	131	170	166	148	1576
Salima	143	134	147	130	113	89	94	115	141	171	169	153	1598
Thyolo	146	129	132	108	94	71	78	101	124	151	148	140	1422

b) Coefficient of variation (%)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	5.2	8.6	7.4	6.7	7.1	2.6	4.3	6.1	2.8	3.6	5.9	8.7	1.6
Chichiri	6.3	8.1	8.3	6.5	7.3	1.7	4.2	6.6	2.2	4.0	5.9	8.3	1.6
Chileka	4.7	8.9	9.5	6.1	6.2	2.0	3.2	5.7	2.9	2.6	4.9	7.5	2.0
Chitedze	6.5	7.5	9.1	4.7	6.4	2.1	4.2	5.2	1.8	3.1	3.8	8.0	2.1
Chitipa	5.3	5.4	5.2	5.0	5.8	2.7	1.7	2.4	1.3	2.4	6.2	7.2	1.1
Dedza	5.6	7.7	7.9	5.5	6.3	2.8	5.0	6.5	2.1	2.5	5.2	7.4	1.8
Dwangwa*	9.9	8.3	9.3	1.4	15.5	3.1	1.3	2.8	0.7	3.1	1.4	3.1	2.8
Karonga	6.2	6.8	6.3	5.3	5.0	3.5	2.6	2.6	1.7	2.2	5.4	7.1	0.9
Lilongwe	6.9	7.5	9.0	5.8	6.4	1.9	4.4	5.3	2.5	3.1	3.9	9.2	2.4
Makhanga	5.2	7.8	5.8	6.7	7.7	3.2	4.3	5.0	2.2	2.9	6.7	6.7	2.1
Makoka	8.0	8.5	9.6	7.8	7.7	2.8	3.5	6.3	2.8	2.3	6.0	7.6	1.8
Mangochi	5.1	9.1	8.1	6.2	5.6	2.6	3.4	4.3	1.6	2.7	5.1	8.0	2.1
Mimosa	4.4	9.6	7.0	8.8	7.6	3.1	4.7	6.4	2.1	3.0	7.3	8.2	1.9
Mzimba	7.3	6.3	7.8	4.9	6.1	2.3	2.9	3.1	1.2	2.3	4.9	7.5	2.2
Mzuzu	6.1	7.0	9.0	6.1	6.3	3.9	3.1	4.3	1.5	1.8	5.7	7.8	2.3
Ngabu†	3.2	7.0	6.7	6.4	8.0	4.0	3.9	5.4	2.2	1.8	6.8	6.3	1.9
Nkhata Bay	6.8	7.5	8.2	6.7	5.8	4.4	3.7	4.5	1.9	2.0	5.8	9.7	2.0
Nkhota Kota	6.8	6.9	7.7	4.0	5.4	2.0	3.3	2.9	1.5	2.0	3.0	9.5	2.0
Salima	7.8	9.0	9.7	5.0	4.5	2.6	4.0	3.2	1.4	1.8	3.6	8.6	2.6
Thyolo	5.9	9.0	8.5	8.4	7.6	3.0	5.9	6.1	2.7	3.0	6.0	8.9	2.3

* 1973 1974

† 1973 - 1978 Computer printout nomenclature : PT

Table A2.7 Average monthly values of net radiation R_n (water equivalent) for 1970-1978

a) Mean (mm)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	150	133	139	115	103	83	90	113	136	158	152	146	1518
Chichiri	151	136	141	118	105	86	92	114	138	161	156	148	1544
Chileka	159	141	148	125	110	87	94	115	139	160	160	155	1594
Chitedze	143	132	143	127	112	91	96	117	143	165	155	143	1567
Chitipa	130	123	134	129	124	112	118	138	148	163	150	137	1606
Dedza	138	126	137	117	108	89	95	116	141	166	153	141	1528
Dwangwa*	147	134	144	136	121	110	112	135	156	182	176	163	1716
Karonga	147	139	151	134	128	109	117	140	157	177	166	157	1722
Lilongwe	142	129	142	124	112	91	97	117	142	164	154	142	1554
Makhanga	178	159	165	136	113	89	96	121	144	171	174	172	1717
Makoka	151	133	138	114	103	85	91	113	139	161	155	146	1530
Mangochi	162	145	158	135	119	95	101	121	145	171	167	159	1678
Mimosa	158	139	143	117	105	84	90	115	139	162	159	153	1562
Mzimba	135	125	136	126	120	103	108	131	151	173	157	142	1608
Mzuzu	136	124	133	118	115	101	108	132	153	174	161	144	1597
Ngabu†	176	154	154	128	111	89	94	119	142	169	174	164	1673
Nkhata Bay	149	137	144	131	123	106	112	138	161	187	174	158	1718
Nkhota Kota	147	135	148	137	126	105	109	130	152	177	172	156	1693
Salima	152	142	155	138	124	100	106	127	150	177	173	160	1704
Thyolo	157	139	143	120	107	85	93	117	138	162	158	150	1568

b) Coefficient of variation (%)

Bvumbwe	5.1	8.7	7.6	6.3	6.1	2.7	4.3	4.8	1.8	3.0	5.2	8.0	1.6
Chichiri	5.9	8.2	8.3	5.9	6.3	2.0	4.4	4.3	1.6	3.2	5.1	7.6	1.6
Chileka	4.5	8.8	9.2	5.8	5.4	2.3	3.6	5.0	2.1	2.4	4.4	6.8	1.9
Chitedze	6.3	7.3	9.0	4.8	6.0	2.8	4.1	4.9	1.4	3.0	3.7	7.7	2.0
Chitipa	5.4	4.9	5.3	5.0	5.6	2.3	1.3	2.0	1.3	2.2	5.7	6.7	1.3
Dedza	5.6	7.2	7.6	5.0	5.7	2.3	4.7	5.6	1.6	2.1	4.6	6.9	1.6
Dwangwa*	9.3	7.1	7.5	0.6	15.8	3.5	1.1	2.7	0.1	3.0	0.5	3.1	2.1
Karonga	6.6	6.5	6.2	5.0	4.8	3.4	2.1	2.2	1.6	1.7	4.9	6.6	1.0
Lilongwe	6.7	7.4	9.1	5.9	6.2	2.2	4.6	5.1	2.2	3.0	3.9	8.8	2.4
Makhanga	5.0	7.6	5.9	6.2	6.8	3.1	4.0	4.4	1.5	2.4	6.0	6.7	2.2
Makoka	7.9	8.4	9.5	7.3	6.7	3.2	3.7	5.4	2.0	1.7	5.6	6.9	1.7
Mangochi	4.9	8.6	7.8	5.8	5.2	2.2	3.9	4.3	1.2	2.2	4.7	7.4	1.9
Mimosa	4.2	9.4	7.3	8.2	7.0	3.4	4.9	5.5	1.4	2.4	6.7	7.6	1.8
Mzimba	7.1	5.5	7.6	4.5	6.0	1.4	2.4	2.7	0.9	2.0	4.4	6.9	2.1
Mzuzu	6.3	6.7	9.2	6.3	7.0	4.0	3.7	4.4	1.3	1.7	5.4	7.7	2.5
Ngabu†	3.1	6.4	6.3	5.9	6.9	3.8	3.8	4.7	2.2	1.4	6.2	6.1	1.7
Nkhata Bay	6.7	7.1	8.1	6.2	5.8	4.2	3.6	4.2	1.5	1.3	5.3	9.2	2.0
Nkhota Kota	6.6	6.3	7.6	3.7	5.5	1.9	3.7	2.8	1.3	1.5	2.5	8.6	1.9
Salima	7.6	8.4	9.4	4.7	4.2	2.1	4.2	3.5	1.1	1.3	3.0	7.9	2.4
Thyolo	5.6	8.9	8.7	7.8	6.8	3.3	5.9	5.4	3.0	2.4	5.5	8.0	2.3

* 1973 1974

† 1973 - 1978 Computer printout nomenclature : QN

Table A2.8 Average monthly values of dimensionless factor Δ/Δ + γ employed in the Penman evaporation formula for 1970-1978

a) Mean (mm)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	0.726	0.726	0.722	0.704	0.685	0.659	0.655	0.679	0.712	0.734	0.734	0.729	0.705
Chichiri	0.729	0.729	0.726	0.713	0.695	0.667	0.666	0.680	0.720	0.737	0.739	0.733	0.711
Chileka	0.746	0.745	0.741	0.729	0.710	0.686	0.685	0.707	0.740	0.758	0.760	0.751	0.730
Chitedze	0.733	0.732	0.729	0.719	0.696	0.673	0.668	0.686	0.715	0.739	0.749	0.739	0.715
Chitipa	0.734	0.736	0.733	0.729	0.715	0.695	0.693	0.708	0.735	0.756	0.757	0.739	0.727
Dedza	0.715	0.715	0.714	0.702	0.687	0.658	0.655	0.675	0.706	0.724	0.731	0.720	0.700
Dwangwa*	0.745	0.748	0.743	0.736	0.718	0.695	0.689	0.702	0.723	0.747	0.769	0.752	0.731
Karonga	0.754	0.754	0.750	0.748	0.738	0.725	0.719	0.727	0.749	0.769	0.774	0.761	0.747
Lilongwe	0.734	0.736	0.730	0.718	0.694	0.668	0.665	0.683	0.683	0.715	0.739	0.749	0.741
Makhanga	0.766	0.765	0.761	0.746	0.721	0.696	0.694	0.719	0.752	0.773	0.779	0.769	0.745
Makoka	0.734	0.734	0.731	0.717	0.697	0.674	0.671	0.692	0.723	0.742	0.746	0.738	0.717
Mangochi	0.756	0.756	0.754	0.745	0.721	0.700	0.698	0.717	0.746	0.768	0.774	0.762	0.741
Mimosa	0.742	0.737	0.736	0.721	0.695	0.671	0.667	0.686	0.718	0.737	0.745	0.744	0.717
Mzimba	0.725	0.727	0.726	0.772	0.704	0.680	0.676	0.693	0.721	0.744	0.747	0.734	0.717
Mzuzu	0.722	0.724	0.717	0.709	0.674	0.641	0.633	0.644	0.675	0.708	0.725	0.725	0.691
Ngabu†	0.774	0.772	0.764	0.748	0.728	0.704	0.700	0.727	0.760	0.780	0.789	0.775	0.752
Nkhata Bay	0.746	0.748	0.744	0.738	0.723	0.701	0.696	0.707	0.726	0.747	0.755	0.749	0.732
Nkhota Kota	0.746	0.748	0.744	0.739	0.721	0.701	0.699	0.711	0.736	0.760	0.676	0.752	0.735
Salima	0.750	0.751	0.750	0.746	0.725	0.705	0.705	0.721	0.744	0.766	0.772	0.759	0.741
Thyolo	0.738	0.736	0.732	0.716	0.692	0.665	0.662	0.686	0.716	0.740	0.744	0.741	0.714

b) Coefficient of variation (%)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	0.7	0.9	0.7	1.2	1.3	1.2	1.5	1.8	1.4	1.3	1.3	0.9	0.4
Chichiri	0.7	0.8	0.8	1.1	1.3	1.0	1.1	4.4	1.1	1.1	1.3	0.9	0.4
Chileka	0.6	0.7	0.7	0.9	1.1	0.6	1.2	1.3	1.3	1.0	0.9	1.0	0.4
Chitedze	0.6	0.5	0.8	0.6	0.8	1.2	1.0	1.0	1.1	1.0	0.7	0.5	0.4
Chitipa	0.5	0.8	0.5	0.3	0.7	0.7	0.9	0.9	1.0	0.9	0.6	0.8	0.4
Dedza	0.6	0.8	0.7	0.8	1.3	0.9	1.2	1.3	1.1	1.1	0.9	0.8	0.4
Dwangwa*	0.6	1.2	1.8	0.8	0.3	0.5	0.2	0.1	0.8	0.1	2.0	0.0	0.7
Karonga	0.6	0.8	0.5	0.4	0.4	0.4	0.8	0.7	0.6	0.9	0.5	0.8	0.4
Lilongwe	0.6	0.6	0.7	0.5	0.9	0.8	0.9	0.8	1.0	1.0	0.8	0.8	0.6
Makhanga	0.8	0.9	0.8	1.0	1.4	1.2	1.3	1.3	1.2	1.0	1.1	0.7	0.4
Makoka	0.5	0.7	0.8	1.2	1.3	1.0	1.3	1.6	1.2	1.2	0.9	0.8	0.4
Mangochi	0.5	0.9	0.7	0.6	0.8	1.2	1.3	1.0	0.8	1.2	0.7	0.9	0.4
Mimosa	0.5	1.5	0.8	0.8	0.8	0.8	1.0	1.5	1.1	1.2	0.9	0.8	0.3
Mzimba	0.6	0.9	0.8	0.6	0.8	1.1	1.1	1.0	1.2	1.0	0.6	0.9	0.6
Mzuzu	0.5	0.6	0.8	0.7	1.1	1.3	1.1	1.3	1.0	1.3	1.1	0.6	0.4
Ngabu†	0.3	0.8	0.6	0.8	1.5	1.1	1.4	1.3	.13	1.2	1.1	0.7	0.5
Nkhata Bay	0.5	0.8	0.5	1.0	0.5	0.6	0.9	0.8	0.8	0.9	0.5	0.7	0.4
Nkhota Kota	0.5	0.8	0.5	0.4	0.6	0.6	0.8	0.8	0.7	0.9	0.8	1.0	0.3
Salima	0.5	0.8	0.6	0.5	0.9	1.2	1.1	0.7	0.6	0.9	1.0	0.8	0.4
Thyolo	0.7	1.0	0.8	1.1	1.2	1.3	1.3	1.8	1.3	0.9	1.1	1.0	0.6

* 1973 1974

† 1973 - 1978 Computer printout nomenclature : DDG

Table A2.9 Average monthly values of incoming short-wave radiation R_s at the surface (water equivalent) for 1970-1978

a) Mean (mm)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	243	217	235	205	205	175	191	233	264	289	260	236	2753
Chichiri	244	223	237	211	212	185	197	237	271	296	268	239	2830
Chileka	258	234	250	226	225	189	205	241	273	297	276	253	2926
Chitedze	232	216	243	228	230	202	212	248	284	311	273	235	2915
Chitipa	212	203	222	227	239	234	249	282	293	310	269	228	2966
Dedza	227	209	237	213	224	197	211	245	283	313	272	233	2862
Dwangwa*	233	212	233	234	227	227	232	267	294	326	307	266	3058
Karonga	236	226	247	229	238	222	238	277	297	325	290	260	3084
Lilongwe	229	211	240	224	229	201	213	246	282	309	271	232	2888
Makhanga	283	256	271	239	219	183	199	243	270	306	294	274	3037
Makoka	245	217	232	202	205	181	196	234	274	296	267	236	2785
Mangochi	261	235	266	240	237	205	217	247	283	316	291	259	3056
Mimosa	243	225	237	203	204	172	185	231	263	290	268	244	2774
Mzimba	218	205	228	225	238	220	232	269	297	324	277	233	2966
Mzuzu	219	202	220	201	213	197	211	256	287	316	281	238	2842
Ngabu†	282	248	253	223	217	184	196	241	267	304	297	264	2976
Nkhata Bay	235	218	231	219	223	205	219	263	290	323	290	253	2970
Nkhota Kota	232	216	243	237	243	221	230	261	286	320	297	253	3040
Salima	242	228	259	246	247	218	230	261	290	324	302	260	3104
Thyolo	254	226	238	211	211	175	193	238	262	293	268	241	2810

b) Coefficient of variation (%)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bvumbwe	6.4	10.7	10.0	8.3	9.5	5.2	7.4	7.2	2.8	3.9	6.7	9.5	2.1
Chichiri	7.2	10.1	11.1	8.0	9.7	4.6	7.4	6.9	3.2	3.8	6.5	9.1	2.2
Chileka	5.4	11.4	12.2	7.5	8.4	5.4	6.4	7.2	3.8	3.2	6.0	8.3	2.7
Chitedze	7.8	8.9	11.7	6.6	10.0	4.4	7.0	7.2	2.1	3.6	5.2	9.6	2.8
Chitipa	6.8	5.7	6.8	6.5	8.5	3.5	2.2	3.1	1.9	2.5	8.1	8.8	1.6
Dedza	7.1	8.8	10.2	7.1	9.0	5.4	7.2	8.2	2.3	2.7	6.3	8.7	2.2
Dwangwa*	10.3	7.9	8.4	0.6	21.8	2.7	4.3	1.8	0.5	4.2	0.2	3.1	2.9
Karonga	8.0	7.1	7.8	6.3	7.0	5.3	3.3	3.5	2.5	2.2	6.6	8.3	1.8
Lilongwe	8.4	9.0	11.8	7.8	10.0	4.6	6.9	7.8	2.3	3.6	5.1	10.8	2.9
Makhanga	5.8	8.4	7.5	7.7	9.3	5.7	6.5	6.1	2.8	3.4	7.2	6.9	2.7
Makoka	9.7	10.3	12.7	10.0	10.4	6.4	6.7	7.8	2.9	2.7	7.2	8.4	2.3
Mangochi	6.0	10.0	10.3	7.7	7.8	4.1	6.0	5.8	1.3	2.9	6.4	8.7	2.4
Mimosa	5.3	11.0	9.1	10.6	10.5	6.9	8.2	7.9	2.6	3.4	8.3	8.9	2.3
Mzimba	8.8	6.6	9.1	6.1	9.0	3.1	4.1	3.7	1.2	2.8	6.0	8.6	2.5
Mzuzu	7.5	8.1	11.2	7.6	9.2	5.6	5.3	5.9	1.5	2.2	7.4	9.5	2.8
Ngabu†	4.2	7.7	8.2	8.1	10.3	6.8	7.3	6.7	2.1	2.4	6.8	6.5	-2.1
Nkhata Bay	7.9	8.0	9.4	7.3	7.6	5.3	5.1	5.2	1.9	1.4	6.6	10.6	2.3
Nkhota Kota	8.0	7.3	9.6	4.7	7.7	2.5	5.4	3.7	2.2	1.1	4.0	10.5	2.4
Salima	9.2	10.0	11.9	6.5	6.6	2.4	5.6	4.2	1.5	1.8	4.7	9.9	3.1
Thyolo	6.9	10.6	10.9	9.9	9.6	6.4	8.7	7.8	3.7	3.5	6.9	9.6	2.9

* 1973 1974

† 1973 - 1978 Computer printout nomenclature : QS

Appendix 3 Geographical variations in components of potential evaporation

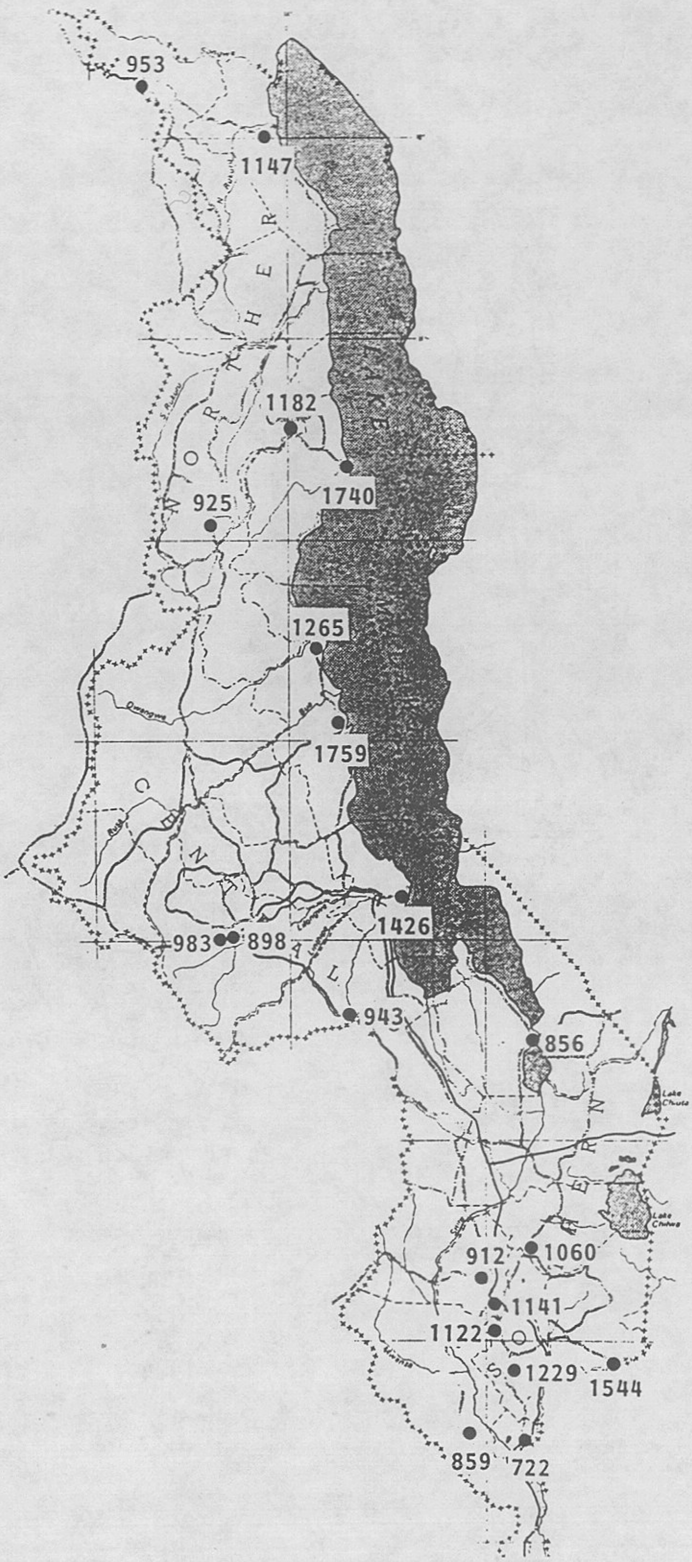

Figure A3.1 Average annual values of rainfall R (mm)

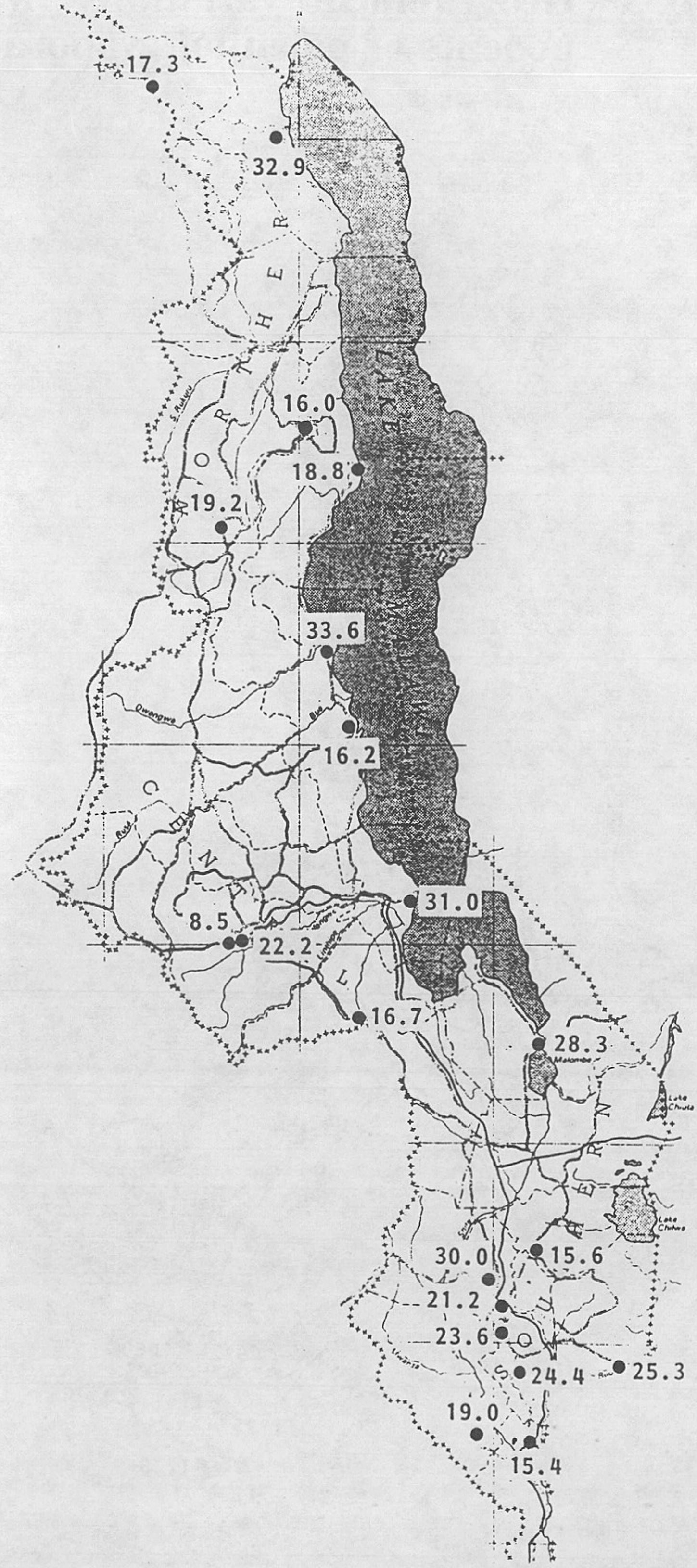

Figure A3.2 *Coefficient of variation (%) of annual values of rainfall R*

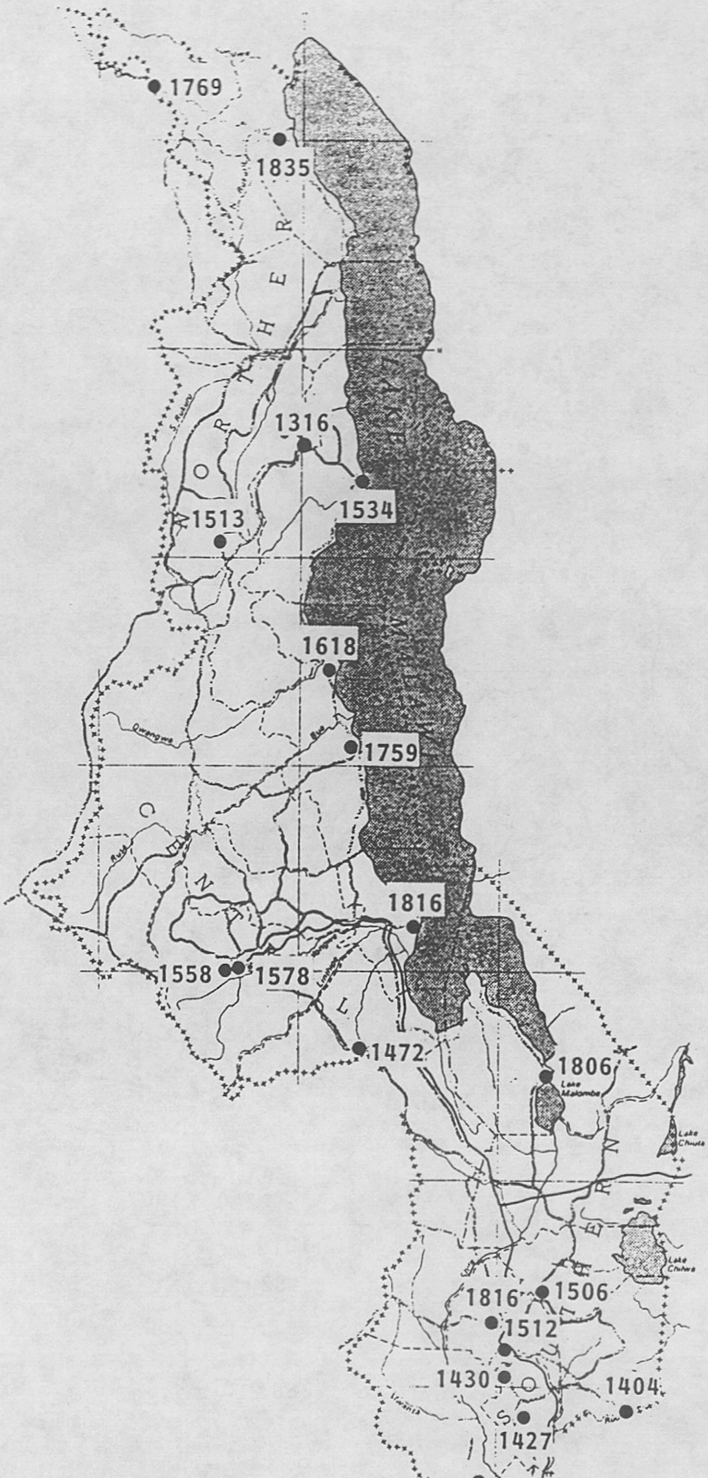

Figure A.3.3 *Average annual values of Penman short grass potential evaporation E_{PN} (mm)*

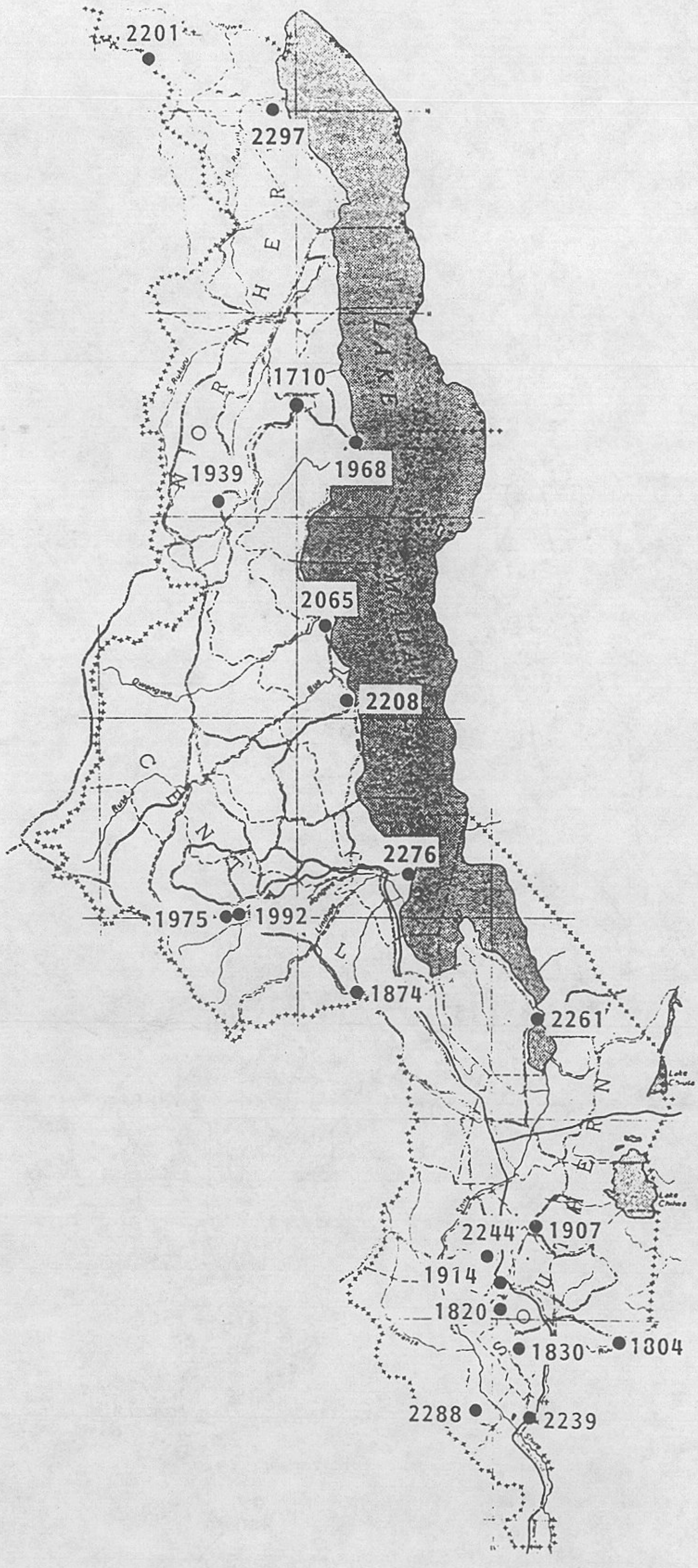

Figure A3.4 Average annual values of Penman open water evaporation E_o (mm)

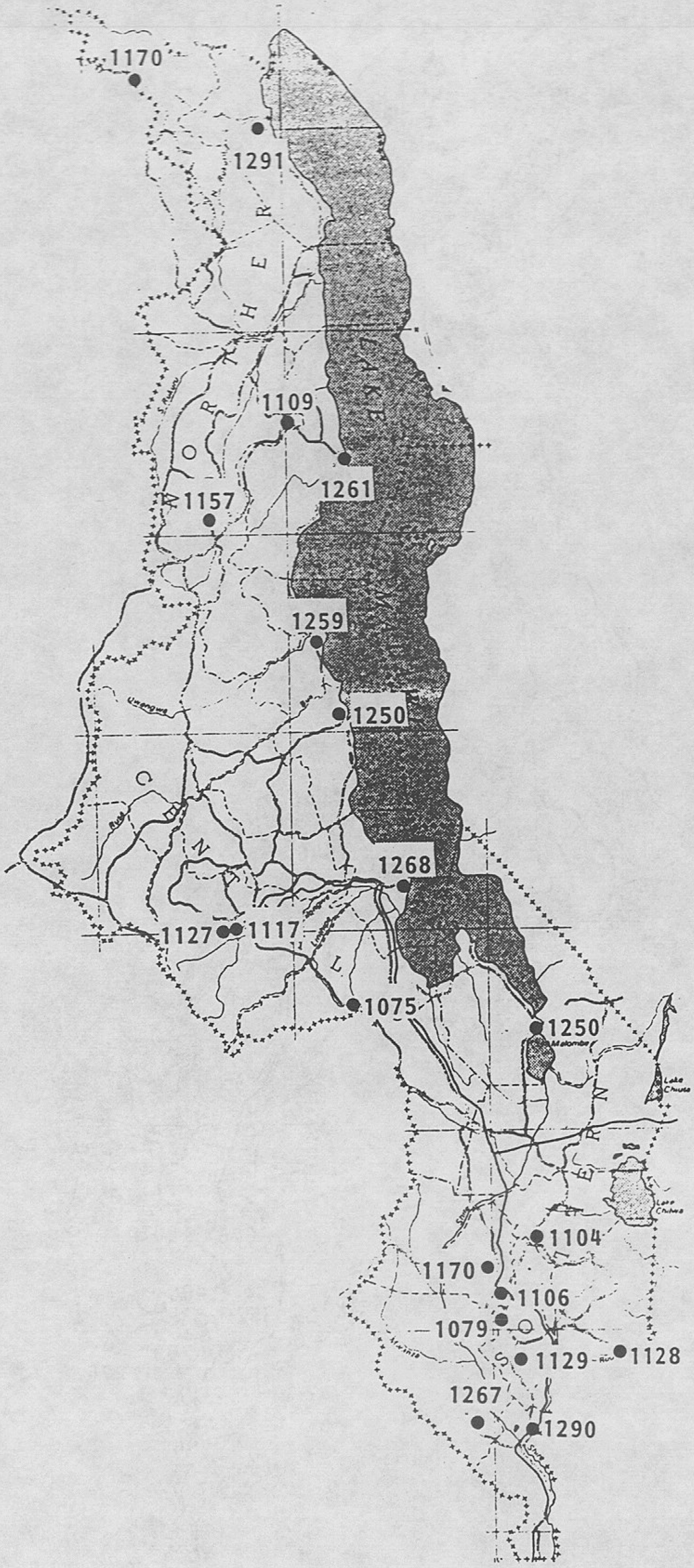

Figure A3.5 *Average annual values (mm) of the energy term M_e of Penman short grass potential evaporation*

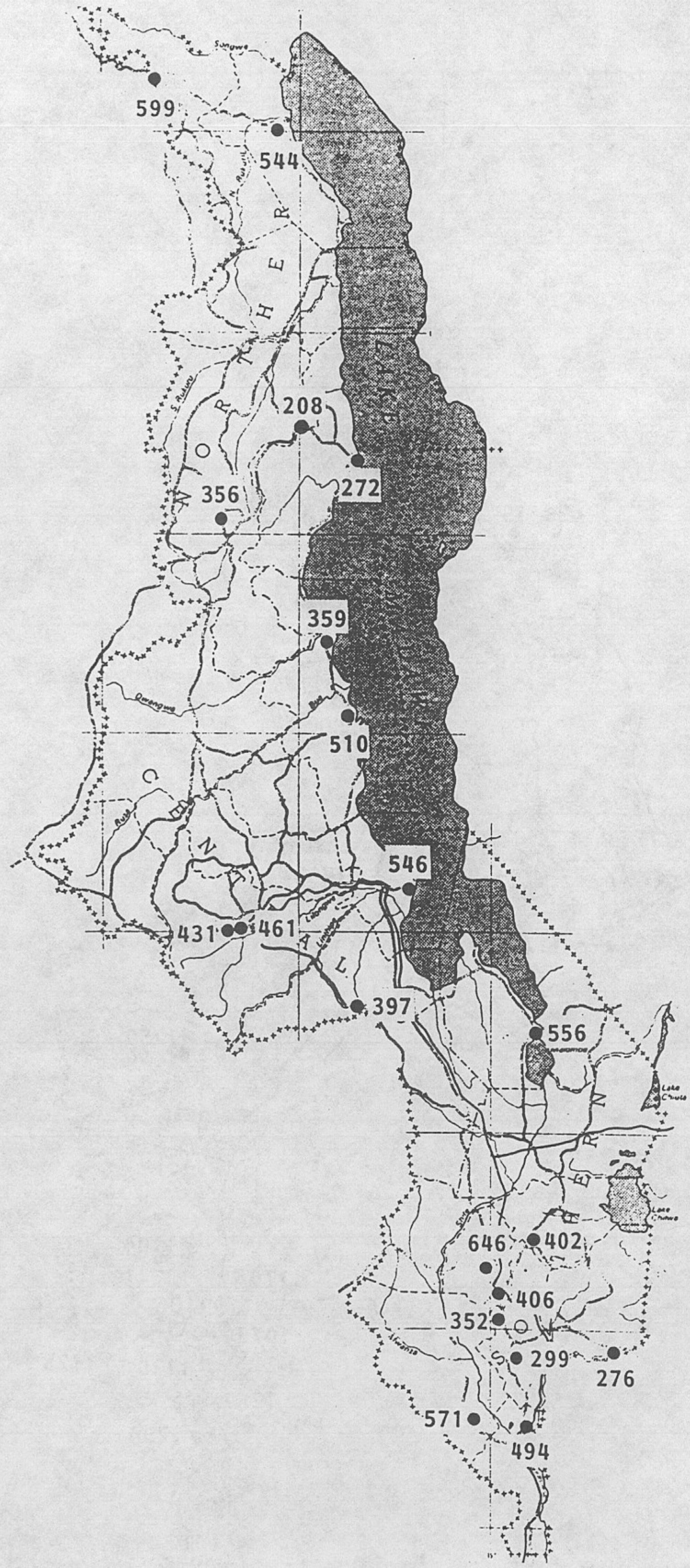

Figure A3.6 *Average annual values (mm) of the aerodynamic term M_a of Penman short grass potential evaporation*

Appendix 4 Soil moisture recharge method

This appendix illustrates the practical application of the soil moisture recharge method to calculate actual evaporation and yield from nine years of records at Chitedze climatological station.

Tables A4.1 and A4.2 display the monthly values of rainfall (R_{ij}) and potential evaporation (E_{ij}). An earlier version of Penman short grass potential evaporation (E_{PN}) is substituted for E_{ij} in this calculation, but it differs from the final version displayed in Table A2.2A in Appendix 2 by less than 1%.

The least value of either R_{ij} or E_{ij} for each month is displayed as min (R_{ij}, E_{ij}) in Table A4.3. This latter value is subtracted from the R_{ij} values to give the values of R_{ij} - min (R_{ij}, E_{ij}) displayed in Table A1.4.

Over each year the monthly values are totalled to give the values displayed in the right hand column of each table. The mean of these latter values is calculated over nine years and tabulated on the bottom line.

From Equation 4.2 in Section 4 of the report and Table A4.3, the average annual actual evaporation AAE' is found from :

$$AAE' = 623 + S \qquad (A4.1)$$

where S is the estimate of soil moisture recharge. From Equation 4.3 and Table A4.4 the average annual yield (AAY') is found from:

$$AAY' = 360 - S$$

If S is assumed to take the value 120 mm, that is the countrywide mean found for Malawi by comparison with the catchment waterbalance, then it follows that AAE' = 743 mm and AAY' = 240 mm.

Table: A4.1 Monthly values of rainfall R_{ij} (mm) at Chitedze climatological station

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual total ΣR_{ij}
1970	257	219	30	30	0	3	0	0	0	2	76	363	980
1971	215	293	101	44	23	1	0	0	0	5	211	84	977
1972	235	146	99	129	17	0	1	0	0	16	81	163	887
1973	206	209	105	75	2	0	0	0	0	9	49	188	843
1974	293	216	121	62	91	0	6	0	0	0	42	230	1061
1975	101	250	297	68	0	0	0	0	0	0	121	146	983
1976	270	306	87	85	0	0	1	0	7	11	20	211	998
1977	315	164	207	52	0	0	0	0	1	17	58	315	1129
1978	340	80	235	58	0	4	0	0	0	0	75	195	987
Mean $\overline{R_{ij}}$	248	209	142	67	15			0		[illegible]	81	211	983 $\overline{\Sigma R_{ij}}$

Table: A4.2 Monthly values of Penman short grass potential evaporation E_{ij} (mm) at Chitedze climatological station

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual total ΣE_{ij}
1970	137	128	143	120	118	99	112	128	177	195	163	124	1644
1971	116	115	134	122	114	101	105	133	161	190	169	144	1604
1972	125	123	133	107	98	98	104	137	167	187	179	149	1607
1973	135	114	139	107	113	97	104	123	161	184	166	142	1585
1974	115	95	123	108	79	86	93	117	145	182	166	129	1438
1975	129	112	128	114	117	94	105	123	154	192	171	141	1580
1976	134	111	112	102	106	95	107	130	156	184	184	143	1564
1977	122	120	109	115	109	93	98	123	153	196	169	127	1534
1978	112	110	108	112	110	95	105	134	163	186	157	109	1501
Mean $\overline{E_{ij}}$	125	114	125	112	107	95	104	128	160	188	169	134	1562 $\overline{\Sigma E_{ij}}$

Table: A4.3 Monthly values of variable min R_{ij}, E_{ij} (mm) at Chitedze climatological station

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual total $\Sigma min(R_{ij},E_{ij})$
1970	137	128	30	30	0	3	0	0	0	2	76	124	530
1971	116	115	101	44	23	1	0	0	0	5	169	84	658
1972	125	123	99	107	17	0	1	0	0	16	81	149	718
1973	135	114	105	75	2	0	0	0	0	9	49	142	631
1974	115	95	121	62	79	0	6	0	0	0	42	129	649
1975	101	112	128	68	0	0	0	0	0	0	121	141	671
1976	134	111	87	85	0	0	1	0	7	11	20	143	599
1977	122	120	109	52	0	0	0	0	1	17	58	127	606
1978	112	80	108	58	0	4	0	0	0	0	75	109	546
Mean $\overline{min(R_{ij},E_{ij})}$	122	111	99	65	13			0		[illegible]	77	128	623 $\overline{\Sigma min(R_{ij},E_{ij})}$

Table: A4.4 Monthly values of variable R_{ij} - min R_{ij}, E_{ij} (mm) at Chitedze climatological station

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual total ΣR_{ij} - $\Sigma min(R_{ij},E_{ij})$
1970	120	91	0	0	0	0	0	0	0	0	0	239	450
1971	99	178	0	0	0	0	0	0	0	0	42	0	319
1972	110	23	0	22	0	0	0	0	0	0	0	14	169
1973	71	95	0	0	0	0	0	0	0	0	0	46	212
1974	178	121	0	0	12	0	0	0	0	0	0	101	412
1975	0	138	169	0	0	0	0	0	0	0	0	5	312
1976	136	195	0	0	0	0	0	0	0	0	0	68	399
1977	193	44	98	0	0	0	0	0	0	0	0	188	523
1978	228	127	127	0	0	0	0	0	0	0	0	86	441
Mean $\overline{R_{ij}} - \overline{min(R_{ij},E_{ij})}$	126	98	44	[illegible]		0	0	0	0	0	5	83	360 $\overline{\Sigma R_{ij}} - \overline{\Sigma min(R_{ij},E_{ij})}$

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