Evaporation Modelling in Data Scarce Tropical Region of the Eastern Arc Mountain Catchments of Tanzania

Birhanu Zemadim [1*], Felix Mtalo[2], Simon Mkhandi[2], Raj Kachroo[2] and Matthew McCartney[1]

[1] International Water Management Institute (IWMI), East Africa and Nile Basin Office, Addis Ababa, Ethiopia
[2] Department of Water Resources Engineering, University of Dar es salaam, Tanzania
* E-Mail of corresponding author: b.zemadim@cgiar.org or birhanuzem@yahoo.com

Abstract
This paper focuses on developing methods for both potential and actual evapotranspiration (ET) models for the data scarce conditions of the Eastern Arc Mountains catchment of Tanzania. For reliable estimation of the components of the hydrological cycle and plant water uptake, potential ET estimates are required, and for catchment water balance actual ET estimates are needed. These potential and actual ET estimates, however, depend on reliable and good quality data records. The study catchments in this work are characterised by general lack of reliable meteorological (MET) data, though good records of rainfall, flow and pan evaporation data do exist in a few places. In the study reported here the Penman-Monteith (P-M) estimates were found to be closer to the pan evaporation model in areas where reliable records of pan data exist. By comparison, estimates derived solely from temperature (i.e. the Standard Thornthwaite method), were a lot lower. Assuming the P-M estimates to be reliable, new temperature based regional equations were developed using data obtained from six climate stations. The study also presents simpler methods for estimating actual ET from catchments.

Key words: Evaporation Modelling, Eastern Arc Mountains, Standard Thornthwaite Model, Penman Monteith Model, Turc and Pike's Model, Water Budget, Tanzania.

1. INTRODUCTION

Evapotranspiration (ET) from a catchment area, which is a combination of evaporation and transpiration, is one of the major factors in hydrological cycle and water resources research. Evaporation from a large water body or evaporation from any free water surface represent the total loss by evaporation equal to potential evaporation. But catchment ET means evaporation from all water, soil, ice and other surfaces plus transpiration from vegetation on the surface of the catchment. To avoid confusion of terminologies of evaporation, Jensen et al (1990) described that the terms "potential evaporation" or "potential evapotranspiration" have been replaced by the term reference ET and is defined as the rate at which water, if available, would be removed from the soil and plant surface of a specific crop, arbitrarily called a reference crop. Although any crop could be a reference crop, clipped grass (approximately 0.12m tall) or alfalfa (approximately 0.5m tall) has been the most widely used reference crop definitions (Jensen et al., 1990). Thus in this study the term Potential ET (PET) is synonymous to meant to be reference ET and potential evaporation.

Review of various PET estimating methods suggest that a PET method that holds good for a specific meteorological region, may or may not perform satisfactorily for other regions (Ali et al., 2008). Thus it is important to calibrate PET estimation methods so that they represent the regional hydrological processes reliably. In the present study the Penman-Monteith (Monteith, 1981) model and the Standard Thornthwaite models (Thornthwaite, 1948) were applied to estimate PET. The Penman-Monteith (P-M) model was applied because it is a well known method and has been recommended as a standard model for computing PET (Igbadun, 2006). In the present study the P-M estimate however was compared against pan potential estimates after applying pan corrections in networks where pan data were available. This is because pans have proved their practical value and have been used successfully to estimate evaporation, which is open water evaporation (Kirono et al., 2008; Xu and Singh, 2000). The Standard Thornthwaite model was used because temperature data can easily be available and the method is economical in the Eastern Arc Mountain (EAM) catchments. However temperature based models are not as accurate as models like the Penman-type (James, 1988). This is because temperature based models use only one data which is temperature and give only approximate results. In this study therefore this shortfall was overcome by developing a conversion relationship between the daily estimates of temperature based model and the P-M model.

In water balance studies, actual ET (AET) is one of the main components (Yin, 1988) of the water balance. In the EAM catchments of Tanzania where this work is based it was not possible to get AET directly (Yin, 1988; Igbadun, 2006; Brutsaert, 1982). This is because AET measurements require special and expensive instruments and these instruments are not available. Thus AET were estimated using water balance approach (Guitjens, 1982; Yawson, 2002) and using empirical models (Pike, 1964).

Therefore this paper seeks to address methods to develop both PET and AET which are useful components for hydrological cycle and water balance studies in areas of EAM based on data availability. This is important because the EAM catchments are sources of water supply and irrigation for major urban cities in Tanzania (Dar es Salaam, Morogoro, and Tanga). Besides, some of the rivers like Pangani river and Kihansi river draining from the EAM catchments are important sources of water for generating hydro-electric power. All the hydroelectric power facilities deriving their waters from the EAM contribute about 50% of the electricity supply to the Tanzania National grid. Hence reliable estimation of catchment ET, i.e. PET and AET, means increasing the reliability of other components of the hydrological cycle and water balance components respectively. Moreover with limited data how to arrive at a reasonable estimate of ET rate is another important requirement for water resources planning and management and further research in the region.

2. MATERIALS AND METHODS

2.1. Description of the Study Area

The EAM catchments start from a chain of isolated mountain ranges, from the Taita Hills, close to the Kenyan border through eastern Tanzania to the gap between the Udzungwa Mountains and Mt. Rungwe (Lovett and Wasser, 1993) (Figure 1). Based on the distribution of flow gauging stations, the EAM catchments were discretised into four: Sigi (705 km^2) located in the northern part, Wami (36,450 km^2) and Ruvu (19,190 km^2) located in the central part and Kilombero (33,062 km^2) located in the southern part (Figure 1). The Kihansi catchment is located in the southern EAM as part of Kilombero catchment. The catchment areas for the study range from 75 km^2 to 36,450 km^2.

The land cover of the EAM catchments varies significantly over short distances, partly reflecting altitudinal variation and partly human influence. However, the most common land cover is natural forests, artificial forests, natural vegetation, including bush lands and wooded grasslands, and agricultural fields. The most important human activities in the areas are extensive grazing, clearing of woody vegetation for fire wood, timber and charcoal burning (Msanya et al., 2001). The factors most limiting land utilization in the EAM catchments are: moisture availability, biological hazards (tsetse and ticks infestation), and availability of drinking water (Msanya et al., 2001).

Places like the central part of the EAM i.e the Wami plains, require high levels of management in order to increase their productivity and minimize degradation. In the south western EAM catchments, which include the Ruvu area, smallholder rainfed and irrigated farming are common. Ridge and bench terrace cultivation of maize, millet and beans (i.e. staple foods) is a common practice (Kimaro et al., 2001). The vegetation in the southern part of the EAM areas like the Kilombero basin is characterised by miombo woodland on upper and middle slopes, grassland in the seasonally inundated valley bottoms, and wooded grassland on foot slopes and hilltops. Patches of evergreen forest are found throughout the area (Chase, 1993). Similarly part of the protected Udzungwa forest is located in this area.

The soils of the EAMs catchments are widely varied, for example, the soils of Wami catchment are a complex of: deep, well drained, dark greyish brown clays, and moderately well to imperfectly drained, dark greyish brown, sandy clays and very shallow, well drained, dark reddish brown, sandy clays to clays (Msanya et al., 2001).

The soils in the Ruvu area are a complex of moderate, well to somewhat excessively drained, dark yellowish brown to dark red, sandy clays to clays; and shallow, well to somewhat excessively drained dark reddish brown, sandy clays to clays (Kimaro et al., 2001). In the Kilombero catchment, distinctly red deep, freely drained, stone-free weakly acid clays, with moderate levels of soil fertility are found on the gentle slopes and broad hilltops (Chase, 1992).

2.2. Data

Eighteen weather stations with different lengths of data record were available for the study. Three stations are located in Kihansi river catchment (south central Tanzania in Kilombero catchment); these are Udzungwa (983506), Mapanda (983508), and Uhafiwa (983509). Two weather stations, Morogoro (9637060) and Iringa (9735013), are located in central EAM. The rest are located in the North eastern part of the catchment (Figure 1). Data sets of daily maximum and minimum temperature, sunshine hours, solar radiation, relative humidity and wind speed were available at these stations (Table 1).

In the central and southern parts of the EAM catchments, climatic data records are scarce and cover short periods (Table 1). Relatively better data (spatially and temporally) are available in the north eastern part of the EAM catchments (Figure 1). However, overall the climatic data are characterised as poor quality with huge chunks of missing data and lack concurrent records (IUCN, 2003). The wide range of missing data, ranging from few days in a month to several years, makes the computation of PET difficult using methods that require lots of determinants. With the exception of the Kihansi River catchment, long time series of rainfall, flow and pan evaporation were most commonly available (Table 2). In the Kihansi river catchment recorded pan evaporation data were deemed unreliable as a consequence of poor data recording (Birhanu, 2008).

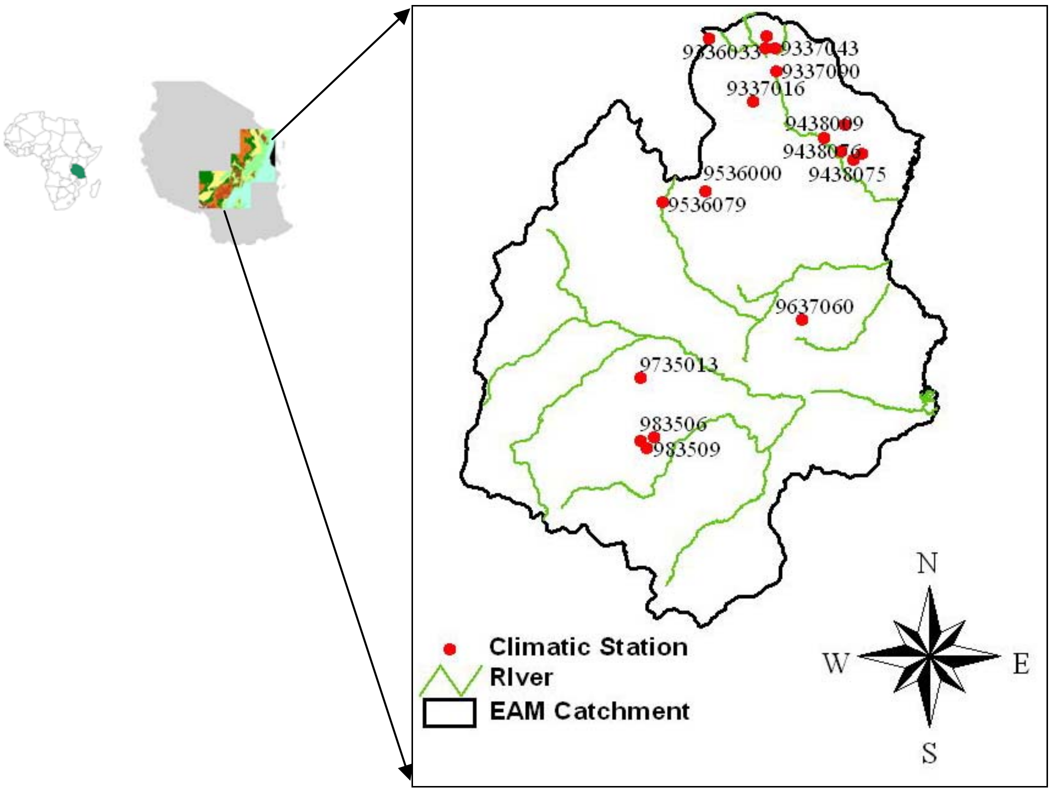

Figure 1: Eastern Arc Mountains catchment and locations of climatic stations

Table 1: Available weather data in the EAM catchments

Station Code	Station Name	Latitude	Longitude	Elevation (m)	From	To	Years	Percentage Missing (%)
983506	Udzungwa	-8.38	35.93	1860	2/3/2000	2/28/2002	3	0.00
983508	Mapanda	-8.42	35.76	1871	2/29/2000	12/31/2001	2	0.00
983509	Uhafiwa	-8.52	35.85	1410	2/3/2000	5/31/2002	3	5.17
9637076	Morogoro	-6.88	37.65	526	1/1/1995	12/31/2005	11	7.61
9735013	Iringa	-7.63	35.77	1428	1/1/1995	12/31/2005	11	47.86
9336033	Arusha	-3.37	36.63	1387	1/1/1972	12/31/1990	19	0.00
9337004	Moshi	-3.35	37.33	813	1/1/1972	12/31/1990	19	12.30
9337016	Naururu	-4.17	37.17		1/1/1976	12/31/1989	14	43.66
9337028	Langasani	-3.50	37.32	701	1/1/1978	12/31/1982	5	26.89
9337043	Kahe	-3.50	37.43	700	1/1/1975	12/31/1991	17	78.32
9337090	NYM	-3.78	37.45	999	1/1/1976	12/31/1994	19	80.00
9438009	Buiko	-4.65	38.05	534	1/1/1976	12/31/2000	25	73.50
9438023	Mazumbai	-4.82	38.52	1524	1/1/1987	12/31/1995	9	83.00
9438074	Magoma	-4.90	38.57	350	1/1/1987	12/31/1989	4	72.90
9438075	Mnazi	-4.40	38.30	510	1/1/1992	12/31/1997	7	39.00
9438076	Lushoto	-4.78	38.27	1400	1/1/1989	12/31/1994	6	32.80
9536000	Kibaya	-5.28	36.57	1457	1/1/1973	12/31/1982	10	77.00
9536079	Handeni	-5.43	36.03	690	1/1/1976	12/31/1999	24	53.67

Table 2: EAMs available hydro climatic data (Rainfall, Flow and Pan)

Catchment Name	Gauging	From	To	Years	Percentage
Sigi	1C1	01/01/1973	31/12/1989	17	6.51
	1G5	01/01/1974	31/12/1982	9	24
	1GD29	01/01/1974	31/12/1981	8	15.57
	1GB1A	01/01/1979	31/12/1989	11	14.09
	1G1	01/01/1973	31/12/1982	10	10.3
Wami	1G2	01/01/1973	31/10/1981	9	11.56
	1HB2	01/01/1973	31/12/2001	29	5.84
	1H5	01/01/1973	31/12/2001	29	12.43
	1H10	01/01/1966	31/12/1987	22	17.18
Ruvu	1H8	01/01/1958	31/01/1999	42	26.16
	FSU1	01/01/1997	31/12/2004	8	0
	FSU2	01/01/1997	31/12/2004	8	0
	FSU3	01/01/1997	31/12/2004	8	0
	FSU4	01/01/1997	31/12/2004	8	0
	FSU5	01/01/1997	31/12/2004	8	0
	FSU7	01/01/1997	31/12/2004	8	0
	NC1	01/01/1997	31/12/2004	8	0
Kihansi	NC3	01/01/1997	31/12/2004	8	0
	1KB9	01/01/1958	31/12/1989	32	23.56
	1KB4	01/01/1958	31/12/1982	25	43.35
	1KB10	01/01/1960	31/12/1987	28	21.05
	1KB8	01/01/1958	31/12/1985	28	11.82
Kilombero	1KB17	01/01/1958	31/12/1975	18	12.29

2.3. Estimation of Potential Evapotranspiration (PET)

In this section PET estimation methods adopted in the study are discussed as follows:

2.3.1. Pan evaporation measurement

The most common method of measuring open water evaporation is by means of an evaporation pan. Because of its apparent simplicity, the evaporation pan is probably the instrument used most widely to estimate open water evaporation (Abtew et al., 2010; Shuttleworth, 1993). In the present work the US. Class A pans installed at Morogoro (96370760), Iringa (99735013) and Arusha (9336033) were used. The pan is 25.4 cm deep and 120.7 cm in diameter. Water is added or removed to maintain water level and the pan is usually accompanied by a rain gauge to factor out the contribution of rainfall to the depth of water in the pan (Abitew, et al., 2010). The methodology as shown in Equation 1 was used to compute evaporation from pan (PEpan) (Norplan, 2003).

$$PEpan(mm/day) = 0.5xCUPSin + R - 0.5xCUPSout \quad [1]$$

Where $CUPSin$ and $CUPSout$ are the number of cups in and cups out respectively and R is the daily rainfall in mm. The factor 0.5 reflects that 1 cup=0.5mm. The possible errors of over estimated evaporation arise due to negligence of recording particularly during rainy seasons. During heavy rains it is possible that there is pan overflow and the component $0.5xCUPSout$ of Equation 1 was missing making the evaporation volume to be large. A pan coefficient of was used to convert the PEpan obtained by Equation 1 to PET.

2.3.2 Standard thornthwaite method

The standard Thornthwaite method (Thornthwaite, 1948) is a temperature based model and is one of the earliest methods for estimating PET (Jensen *et al.,* 1990). If estimates are made for periods of several weeks or a month, reasonable approximations are possible (Xu, 2002). In the present study the suitability of the method was assessed for the study areas. While detail computational steps are presented in the work of Xu (2002), Equation 2 briefly shows equations representing the method.

$$T_i' = \left(\frac{T_i}{5}\right)^{1.514}$$

$$E_i = C * a * \left(\frac{10 * T_i}{I}\right)^b \quad [2]$$

$$I = \sum_{i=1}^{12} T_i'$$

$$b = 6.75 * 10^{-7} * I^3 - 7.71 * 10^{-5} * I^2 + 1.792 * 10^{-2} * I + 0.4924$$

Where T_i is the monthly mean temperature in degrees, E_i is the monthly evaporation in mm for month i, a is a correction factor to account for the day length and C is constant (specific to the region).

2.3.3. Penman- monteith method

The Penman-Monteith equation combines components that account for energy needed to sustain evaporation, the strength of the mechanism required to remove the water vapor and aerodynamic and surface resistance terms. The Penman-Monteith equation is presented by Equation 3.

$$\lambda E = \frac{\Delta \cdot (H_{net} - G) + \rho_{air} \cdot c_p \cdot [e_z^o - e_z]/r_a}{\Delta + \gamma \cdot (1 + r_c/r_a)} \quad [3]$$

where λE is the latent heat flux density (MJ m^{-2} d^{-1}), E is the depth rate evaporation (mm d^{-1}), Δ is the slope of the saturation vapor pressure-temperature curve, *de/dT* (kPa $°C^{-1}$), H_{net} is the net radiation (MJ

m^{-2} d^{-1}), G is the heat flux density to the ground (MJ m^{-2} d^{-1}), ρ_{air} is the air density (kg m^{-3}), c_p is the specific heat at constant pressure (MJ kg^{-1} °C^{-1}), e_z^o is the saturation vapor pressure of air at height z (kPa), e_z is the water vapor pressure of air at height z (kPa), γ is the psychrometric constant (kPa °C^{-1}), r_c is the plant canopy resistance (s m^{-1}), and r_a is the diffusion resistance of the air layer (aerodynamic resistance) (s m^{-1}).

2.4. Estimation of Actual evapotranspiration (AET)

2.4.1. Water budget method

The Water budget approach is based on the principle of conservation of mass which requires for any given volume and during any period of time, the difference between the inflow and outflow rates is equal to the rate of change of the water stored. This is given mathematically as:

$$\left(P+\frac{(Q_{ri}+Q_{gi})}{A}\right)-\left(\frac{(Q_{ro}+Q_{go})}{A}+E\right)\pm\delta=\frac{\left(dS/dt\right)}{A} \quad [4]$$

Where P is mean precipitation rate directly on the given volume, Q_{ri} is surface inflow rate, Q_{ro} is surface outflow rate, Q_{gi} is groundwater inflow rate, Q_{go} is groundwater outflow rate, E is actual evaporation rate, A surface area under consideration, ds/dt is the rate of change of storage, and δ is measurement errors.

2.4.2. Modified Turc and Pike's method

Turc (1954) proposed a simpler formula based on measurements from African catchments, which later was somewhat modified by Pike (1964) on the basis of further measurements. Equation 5 shows the Turc & Pike methods.

$$\frac{AE}{PE}=\frac{\frac{P}{PE}}{\sqrt{1+\left(\frac{P}{PE}\right)^2}} \quad [5]$$

Where AE is Actual ET, PE is Potential ET and P is precipitation.

2.5. Review of Previous Evaporation Studies in Tanzania

Previous research works on evaporation using different techniques in tropical African catchments (Nyenzi 1980; Nattabi, 1995; Kivegalo, 1999; Katambara, 2002; Yawson, 2002; Rohr, 2003) put forward various ranges of evaporation estimates. For example, using Morton's complementary model (Morton, 1969), annual PET values ranging between 250 to 750mm in the semi-arid/arid areas of Tanzania were reported (Nattabi, 1995; Nyenzi, 1980). Similarly PET values ranging from 1000 to 1690mm in the coastal belt of tropical African catchments and highlands and areas near the Lake Victoria basin have been reported (Nyenzi, 1980). PET estimates in the Pangani river basin of Tanzania, that lie within the EAM region (Kikuletwa, Mkomazi Gomba, Rau and Ruvu) range from 1030 to 1550 mm (Kivegalo, 1999). The studies reported overestimation of PET by methods like Bruitsaert and Stricker (1979) and Bouchet (1963), and Morton's Complementary method (Kivegalo, 1999) for the areas of application. Katambara (2002) reported that using 14 meteorological stations in the Pangani basin of Tanzania, Morton's Complementary estimations were found to be higher than the Penman-Monteith (Monteith, 1981) model. The monthly and annual PET estimates from four towns of Tanzania, i.e. Dar es Salaam (1J6), Tanga (1C1), Moshi (1DC2A) and Iringa (1KA2A) by Nattabi, (1995) using Morton's complementary relation (Morton, 1969) and Turc and Pike's (Pike,1964) models showed over estimation of PET values by Morton's method, while the Turc and Pike's method showed a good relationship for annual estimates of actual ET in the semi-arid regions of Tanzania.

Therefore it is worth mentioning that simpler models having empirical nature and less data requirement need to be assessed in the data scarce regions.

3. RESULTS AND DISCUSSIONS

3.1. Potential Evapotranspiration (PET)

From the available climatic stations, six stations have sufficient data to compute PET using the P-M method (Figure 2). Accordingly, in the southern part of the EAM catchments, the mean annual PET (MAPET) in mm are 996, 952, and 1523 at Udzungwa (983506), Mapanda (983508) and Uhafiwa (983509) respectively. In the central EAM catchments, the MAPET estimates are 1938mm and 2366mm respectively for Morogoro (9637076) and Iringa (9735013) stations respectively. Similarly at Arusha climatic station (9336033), which represents the northern part of the EAM catchments, the estimate is 1554mm. From the corrected pan data that was available at Morogoro (9637060), Iringa (9735013) and Arusha (9336033), it was possible to confirm that reasonable estimates were found using the P-M method (Figure 2). The mean annual estimates using the corrected Pan are 1938mm, 2366mm and 1496mm respectively for Morogoro, Iringa and Arusha climatic stations.

Even though P-M method is suitable to estimate PET in tropical catchments availability of enough climatic data was a limitation for its wider application in the EAM catchments. Among all weather parameters it is the temperature data that covers the longest time span with minimum missing data. In this regard temperature data was used to compute PET.

The MAPET estimate using Standard Thornthwaite method in the southern part of the EAM catchment in mm are 726, 725, and 755 respectively for the station Udzungwa (983506), Mapanda (983508) and Uhafiwa (983509). The estimates for the central EAM catchments are 944mm and 1394mm respectively at Iringa (9735013) and Morogoro (9637076) climatic stations. In the northern part of the EAM catchments an estimate of 1044mm was obtained at Arusha climate station (9336033). These estimates are considerably lower than the P-M (Figure 2). As temperature data was easily available for most of stations and as results in this study show temperature based model underestimates PET, it was important to calibrate the estimates of the Standard Thornthwaite against the P-M estimate to develop new PET equations that can be used widely using temperature data. The approach is described in the following section**.**

3.2. Calibration of Standard Thornthwaite Model in the EAM Catchments

The PET estimates using Standard Thornthwaite method as explained above was underestimated at all climatic stations. Dagg and Blackie (1970) also showed the Thornthwaite method very seriously underestimates evaporation demand at high altitudes in the tropics and fails to show the seasonal variation in evaporation. Therefore in the present study there was a need to systematically develop suitable temperature based evaporation models for the EAM catchments. The underestimation was corrected by modifying the coefficients of the model of Equation 2 to arrive at a suitable evaporation model. Figure 3 shows fitted evaporation models using temperature data at the six climatic stations of the EAM. Table 3 shows equations of the fitted evaporation models together with the coefficient of determination of the linear regression coefficient (R^2) and number of data used to derive the relation (N). These new Equations of Table 3 were arrived at by changing the parameters of the Thornthwaite model, systematically, until the estimated values of PET matched reasonably well with the values that were calculated by the application of the P-M method. One interesting feature of this approach is, as the number of data (N) used increases, the more closer is the fitted evaporation model towards the P-M estimate (Figure 3 and Table 3).

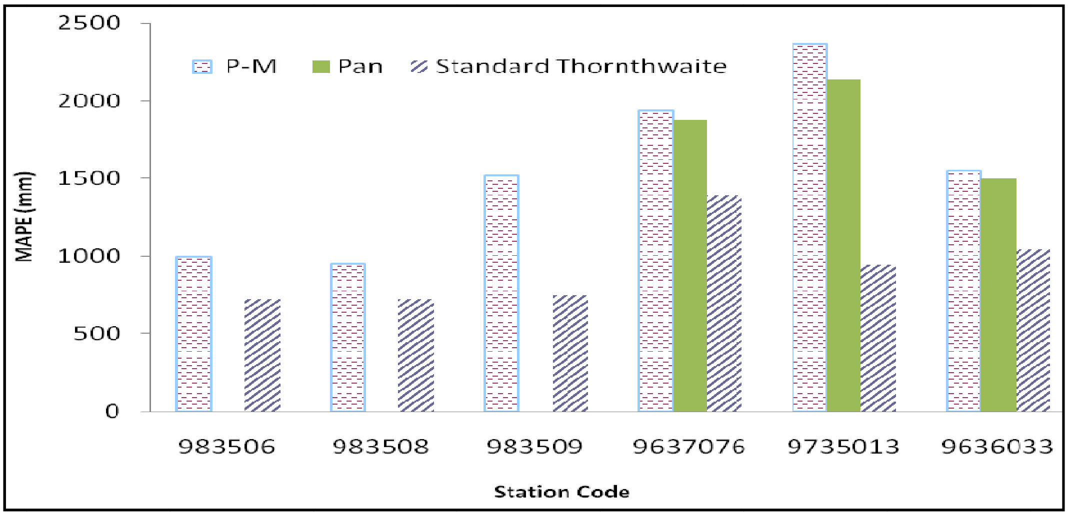

Figure 2: Estimates of PET using P-M , Standard Thornthwaite and Pan.

3.3. Actual Evapotranspiration (AET)

Suitable hydro-climatic data were available at Kihansi gauging stations in the southern part of EAM catchments to estimate AET from the long term water balance and the Turc and Pike's method. These gauging stations are shown in Figure 4. The potential estimates using the P-M are also presented (Table 4). The AET estimates using Turk and Pike's method (shown in Equation 5) used the P-M estimate in conjunction with daily rainfall data .The use of the P-M estimate, in preference to an estimate derived from evaporation pan data, was justified by the inappropriateness of the pan evaporation data as presented in section 2.2.

The long term water balance result of Table 4 indicates higher estimation of AET than PET in two subcatchments (FSU3 and, FSU5). These areas are located in the eastern sloppy highland of the Uduzungwa protected forest which receive high amount of rainfall (greater than 1950mm annually). In these stations a systematic error in AET (loss) from a catchment using the water budget method may arise as a consequence of unmeasured leakage from the catchment (i.e. errors in the measurement of flow, probably during heavy storms). Therefore it is advisable to supplement water budget estimates of AET with parallel and independent meteorological or lysimetric measurements (Shuttleworth, 1993). Due to lack of direct AET measurements in the study areas, the AET estimates could not be verified. Instead they were compared with other method like the empirical Turk and Pikes method (Table 4).

The empirical Turc and Pike's estimate that uses rainfall and P-M estimates were found to be closer to the water balance estimates in areas where mean annual rainfall values are lower than 1950mm. At the outlet of the catchment (NC3) the mean annual AET estimates using the long term water balance and the Turc and Pikes were nearly identical (Table 4). The advantage of Turk and Pike's method lies also in its ability to predict flows for un gauged catchments once reliable rainfall and PET data exist (probably from Pan records).

This means, once PET is obtained either by P-M estimate or by Pan data after suitable corrections were made or using the modified temperature based Thornthwaite model, the loss from the catchment, i.e. AET is easily computed using Equation 5. And AET by definition is the difference between long term rainfall and flow; hence mean annual flow for a catchment can be obtained. In this study AET was estimated using rainfall and corrected Pan data for other catchments of the EAM using the Turc and Pike's method (Table 5). At the same time mean annual flow was estimated using water balance method. As a result the estimated mean annual flow was found to be in close agreement with the observed flow, implying that the approach can be used to estimate flow from un gauged catchments if reliable rainfall and evaporation data exist.

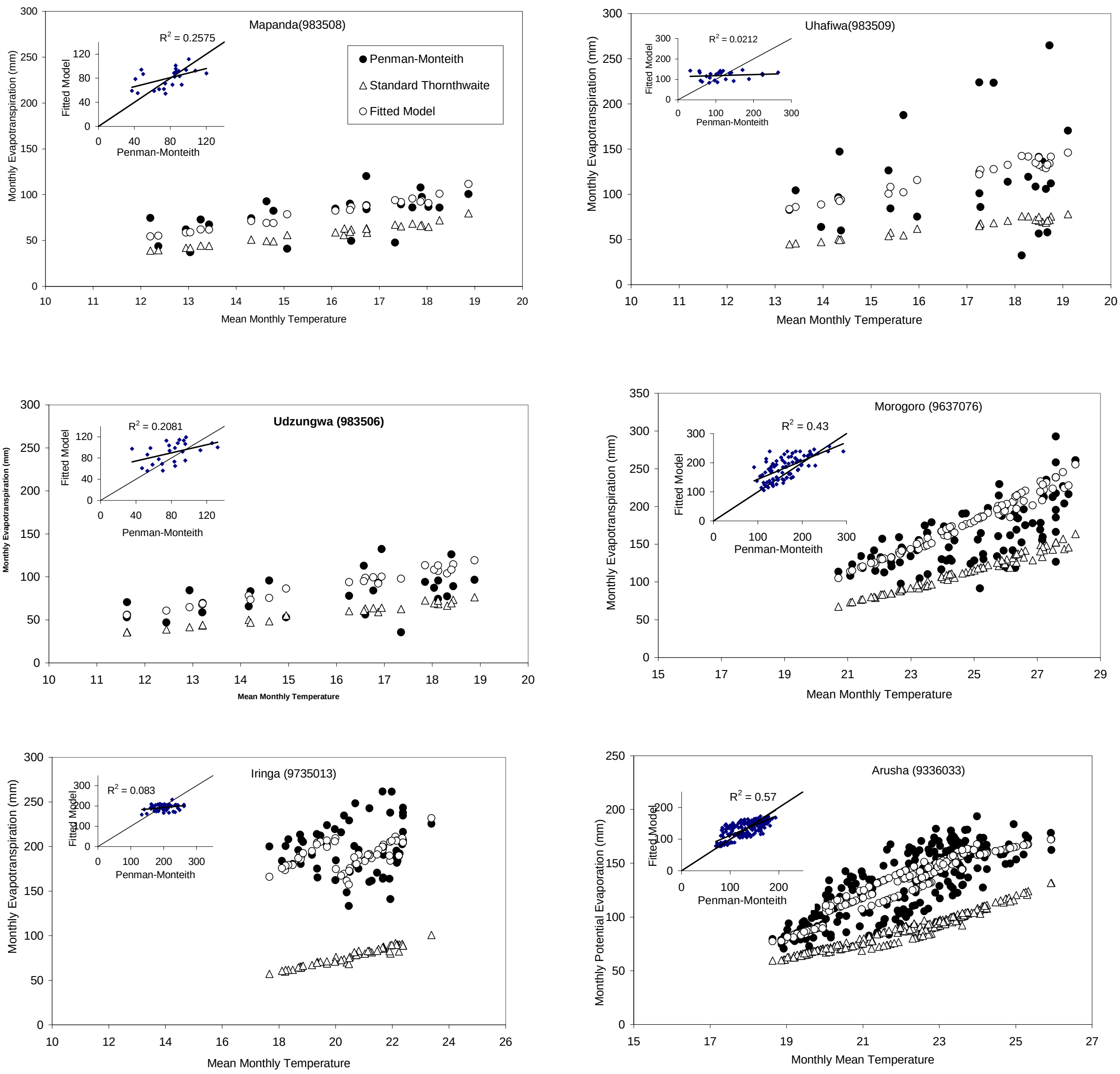

Figure 3: Fitted Evaporation model using temperature data (Thornthwaite) and P-M Model

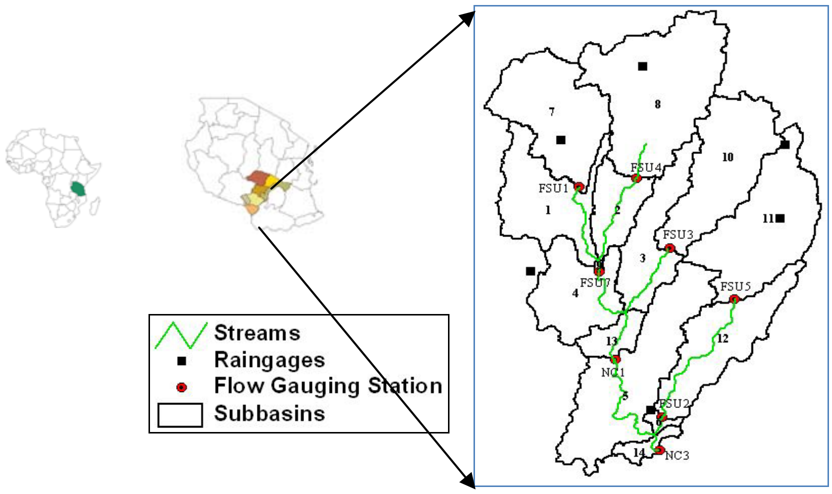

Figure 4: Kihansi river catchment with sub catchments

Table 3: Thornthwaite fitted model for EAMs climatic stations

S. No	Climatic Station	*Fitted Model*	R^2	*N*
1	Mapanda (983508)	$E_i = 22.4 * a * \left(\frac{10 * T_i}{I}\right)^b$	0.26	*26*
2	Uhafiwa (983509)	$E_i = 30 * a * \left(\frac{10 * T_i}{I}\right)^b$	0.02	*26*
3	Udzungwa (983506)	$E_i = 25 * a * \left(\frac{10 * T_i}{I}\right)^b$	0.21	*26*
4	Morogoro (9637076)	$E_i = 25 * a * \left(\frac{10 * T_i}{I}\right)^b$	0.43	*85*
5	Iringa (9735013)	$E_i = 36 * a * \left(\frac{10 * T_i}{I}\right)^b$ for $T_i \le 19.6$ $E_i = 30 * a * \left(\frac{10 * T_i}{I}\right)^b$ for $19.6 < T_i \le 21$ $E_i = 16 * a * \left(\frac{10 * T_i}{I}\right)^b$ for $T_i > 21$	0.08	*60*
6	*Arusha (9336033)*	$E_i = 20.8 * a * \left(\frac{10 * T_i}{I}\right)^b$ *for* $T_i < 20$ $E_i = 25 * a * \left(\frac{10 * T_i}{I}\right)^b$ *for* $T_i \ge 20$	*0.57*	*228*

R^2 refers to coefficient of determination in decimal and N refers to number of data used for the relationship

Table 4: AET estimates from long term averages (1997-2004)

Sub-Catchment/ Gauging station code	Gauging Station Name	Rainfall (mm)	Flow (mm)	AET Water balance (mm)	AET Turc & Pike's (mm)	P-M PET (mm)
FSU1	Kihansi at Ilogombe	1146	326	820	770	952
FSU3	Mkalasi at Kipanga	1973	807	1166	952	992
FSU4	Muhu at Ilogombe	1145	446	699	850	952
FSU5	Ruaha at Kipanga	2911	1608	1303	956	996
FSU7	Kihansi at Muhu d/s	1165	397	768	766	952
NC3	Kihansi at Lutaki	1890	793	1097	1094	1157

Table 5: EAM catchments AET and mean annual flow estimates

Catchment	Gauging Station	Data Available From	Data Available To	No. of Years	Rain (mm)	Pan Evap (mm)	AET (mm)	Estimated Flow (mm)	Observed Flow (mm)
Sigi	1C1	1973	1989	17	1551	2168	1261	290	302
	1G1	1973	1982	10	672	2031	638	34	22
	1G2	1973	1981	9	652	1978	619	33	44
	1G5	1974	1982	9	1073	1921	937	136	177
Wami	1GD29	1974	1981	8	1310	1917	1082	228	181
Ruvu	1H10	1973	2001	29	1130	1835	962	168	161.5
	1KB9	1958	1989	32	1865	1954	1349	516	419
Kilombero	1KB8	1958	1985	28	1820	1945	1329	491	486

4. CONCLUSSION AND RECOMMENDATIONS

Lack of sufficient meteorological data is a constraint to estimating the regional PET from the EAM catchments of Tanzania widely using well known models such as the P-M method. Similarly direct estimation of AET was not possible as the methods recommended are not available in the catchments. However data of rainfall, temperature, flow, and pan evaporation do exist commonly, and in this study several indirect methods were developed to estimate PET and AET. The approach is presumably simple, cheap, but provided reliable estimates in the data scarce conditions of the EAM region. We propose that the methodology applied in this work be extended to wider areas so as to understand the regional hydrological phenomena and water resources research in tropical regions.

5. ACKNOWLEDGEMENT

Authors are grateful to the staff of Water Resources Engineering of the University of Dar es salaam and Ministry of Water Resources of Tanzania for provision of data and for their invaluable support in verifying the consistency of data.

6. REFERENCES

1. Abitew,W., Obeysekera, J.and Iricani, N. (2010), *Pan Evaporation and Potential Evapotranspiration Trends in South Florida*. Hydrol. Process. DOI: 10.1002/hyp.7887
2. Ali,S., Narayan, C., Ghosh., C. and Singh, R.(2008), *Evaluating Best Evaporation Estimate Model for Water Surface Evaporation in Semi-arid Region*, India Hydrol. Process. 22, 1093–1106 (2008)
3. Birhanu, B.Z.(2008), *Development and Application of a Distributed Hydrological Model for the Central Eastern Arc and Kihansi Catchments*. PhD Thesis. University of Dar es Salaam, Tanzania
4. Bouchet, R.J.(1963), *Evapotranspiration reele et Potentielle, Signification Climatique Gen.Assem*. Berkley, Int. Assoc. Sci. Hydrol.,62.
5. Brutsaert, W. and Stricker,H. (1979), *An Advection Aridity Approach to Estimate Actual Regional Evapotranspiration*, Water Resources Research,1592),443-450.
6. Brutsaert, W.(1982), *Evaporation into the Atmosphere*. Reidel:Dordrecht.
7. Chase, L.D.C . (1992), *Kilombero Valley Teak CO LTD Tanzania*, Soil Advisory Visit 1992. Commonwealth Development Corporation.
8. Dagg, M. and Blackie J.R.(1970), *Estimates of Evaporation in East Africa in Relation to Climatological Classification*, The Geographical Journal, Vol.136,No.2.(Jun.,1970),pp.227-237.
9. Guitjens, J.C. (1982), *Models of Alfalfa Yield and Evapotranspiration,* Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers 108(IR3): 212-222.
10. Igbadun,H., Mahoo,H., Tarimo,A. and Salim, B. (2006), *Performance of Two Temperature-Based Reference Evpotranspiration Models in the Mkji Sub-Catchment in Tanzania,* Agricultural Engineering International: the CIGR Ejournal. Manuscript LW 05 008. Vol.VIII. March,2006

11. IUCN (2003), *Development of a Computerized Flood Warning Model and Study of Hydrological Characteristics of the Lower Rufiji Flood Plain and Delta*. Volume 1-Main Report. IUCN-The World Conservation Union Eastern Africa Regional Office
12. James,L.G.(1988), *Principles of Farm Irrigation System Design,* New York: John Wiley and Sons, Inc.
13. Jensen, M.E., Burman,R.D. and Allen, R.G. (1990), *Evapotranspiration and Irrigation Water Requirements*. American Society of Civil Engineers, New York, 1990.
14. Katambara, Z.(2002), *Development and Application of Evaporation Models in the Pangani River Basin*. A Dissertation submitted for degree of Master of Science in Water Resources Engineering at University of Dar es Salaam. University of Dar Salaam Press. Tanzania.
15. Kimaro, D.N., Msanya, B.M., Mwango, S.B., Kimbi, G.G., and Kileo, E.P. (2001), *Land suitability evaluation for the production of the major crops in the Southwestern part of the Uluguru Mountains, Morogoro Rural District, Tanzania*. Soils and Land Resources of Morogoro Rural and Urban Districts, Volume 2. Department of Soil Science,Faculty of Agriculture, Sokoine University of Ariculture, Morogoro, Tanzania.
16. Kirono,D.G.C., Jones,R.N. and Cleugh,H.A. (2008), *Pan-evaporation Measurements and Morton-Point Potential Evaporation Estimates in Australia: are their trends the same?*. Int. J. Climatol. (2008) Published online in Wiley InterScience www.interscience.wiley.com) DOI: 10.1002/joc.1731.
17. Kivegalo, C.L.(1999), *Estimation of Actual Evaporation from Pangani River Basin,* A Dissertation submitted for degree of Master's of Science in Water Resources Engineering at University of Dar es Salaam. University of Dar Salaam Press. Tanzania.
18. Lovett, J.C. and Wasser, S.K. editors., (1993), *Biogeography and Ecology of the Rainforests of Eastern Africa*, Cambridge: Cambridge University Press. Text by World Wide Life Fund@2001.
19. Monteith, J.L.(1981), *Evaporation and Surface Temperature*, Quartely Journal of the Royal Meteorological Society,107:1-27
20. Morton, F.I.(1969), *Potential Evaporation as a Manifestation of Regional Evaporation*, Water Resour. Res.,5:1244-1255.
21. Msanya, B.M., Kimaro, D.N., Kileo, E.P., Kimbi, G.G. and Mwango, S.B. (2001), *Land Suitability Evaluation for the Production of Food Crops and Extensive Grazing: A case study of Wami plains in Morogoro rural district, Tanzania*. Soils and Land Resources of Morogoro Rural and Urban Districts, Volume 1. Department of Soil Science,Faculty of Agriculture, Sokoine University of Ariculture, Morogoro, Tanzania.
22. Nattabi, H.(1995), *Study of Morton's Complementary Relationship Model and Turc & Pike's Model for Estimation of Regional Evaporation*, M.Sc. thesis University of Dar Salaam, Tanzania.
23. Norplan, (2003), *Kihansi catchment Modelling*, TANESCO Kihansi Catchment Management.
24. Nyenzi B.S.(1980),*The Distribution of Actual Evaporation/ Evapotranspiration over East Africa*, East Africa Institute for Meteorological Training and Research.
25. Pike, J.G.(1964),*The Estimation of Annual Runoff From Meteorological Data in a Tropical Climate,* Journal of Hydrology 2, 116-123.
26. Rohr, P.C. (2003), *A Hydrological Study Concerning the Southern Slopes of Mt.* Kilimanjaro, Tanzania, Dr.-ing:- thesis 2—3:39 NTNU, Norway.
27. Shuttleworth, W.J.(1993), *Evaporation, Hand Book of Hydrology/ David R. Maidment*, editor in chief. Pp 2.1-2.11.
28. Thornthwaite, C.W.(1948), *An Approach Toward a Rational Classification of Climate*. Geogr. Rev., 38(1): 55-94.
29. Turc,L.(1954),*The water balance of soils. Relation between precipitation evaporation and flow,* Ann. Agron. 5, 491-569.
30. Xu,C.Y.(2002),*Textbook of Hydrological Models, Department Of Earth Sciences Hydrology*, Uppsala University. Second eds.
31. Xu,C.Y and Singh,V.P.(2000), *Evaluation and Generalization of Radiation based Methods for Calculating Evaporation,* Hydrol. Process. 14, 339-349 (2000).
32. Yawson, D.K.(2002), *Development of a Decision Support System for the Rufiji River Basin – Tanzania*, PhD Thesis, University of Dar es Salaam, Tanzania.
33. Yin, H.C. (1988), *A Composite Method for Estimating Annual Actual Evapotranspiration,* Hydrological Sciences-Journal-des Sciences Hydrologiques, 33,4,8/1988

AUTHORS BIOGRAPHY

Birhanu Zemadim is a Post Doctoral Research Scientist at the International Water Management Institute (IWMI), East Africa and Nile Basin office, Addis Ababa, Ethiopia.

Felix Mtalo is a Professor of Water Resources and Environmental Engineering at the University of Dar es salaam, Tanzania.

Simon Mkhandi is a Senior Lecturer at the University of Dar es salaam, Tanzania.

Raj Kachroo is a visiting Professor at the University of Dar es salaam, Tanzania.

Matthew McCartney is a Principal Researcher at the International Water Management Institute (IWMI), East Africa and Nile Basin office, Addis Ababa, Ethiopia.