CALIBRATION OF THE PRIESTLEY-TAYLOR EVAPORATION MODEL FOR ETHIOPIA

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ABSTRACT

In practice reservoir planning and operations, irrigation design and water balance studies require estimates of reliable evaporation. The universal standard models of the Penman E_0 and the Penman-Monteith ET_0 are used to estimate open water evaporation and evapotranspiration respectively. The models rely on accurate measurements of climatic elements such as temperature, humidity, wind speed, and solar energy with good spatial and temporal coverage. However, practicing hydrologists, irrigation engineers and planners face challenge of reliable estimate of evaporation when only temperature data are available as the case in many study areas of Ethiopia and elsewhere. To overcome this challenge, a number of simplified temperature-based evaporation models notably the Priestley-Taylor, Blaney-Criddle and Hargreaves have been developed. Their applicability is, nevertheless, subject to rigorous local calibrations and without calibration they have limited validity to tropical areas. There is a need, thus, to precise estimate of E_0 and ET_0 based on only temperature data for Ethiopia. This paper presents locally calibrated coefficients α for the Priestley-Taylor model applicable for Ethiopia to estimate open water evaporation E_o and Reference Evapotranspiration ET_0 based on maximum and minimum temperature as well as readily derivable elevation and radiation data. In order to calibrate α, regression is done between the Priestley-Taylor model estimate (independent variable) and E_o Penman model estimate as dependent variable for each month of the 167 Class I stations. Similarly, regression is done between the Priestley-Taylor estimate (independent variable) and ET_o Penman-Monteith model estimate (dependent variable). It is found that the Priestley-Taylor coefficients α applicable over Ethiopia to estimate monthly E_0 is 1.11 and to estimate ET_0 is 0.96.

Keywords: *Ethiopia***,** *Irrigation-water -requirement, Open water Evaporation, Priestley-Taylor, Penman-Monteith Reference-Evapotranspiration, Reservoir,*

INTRODUCTION

In practice reservoir planning, operation, irrigation scheduling design and catchment water balance studies require estimates of reliable evaporation which is dependent on accurate measurements of climatic elements such as temperature, humidity, wind speed, and solar energy with good spatial and temporal coverage. However, practicing hydrologists, irrigation engineers and planners face challenge of reliable estimate of evaporation when only temperature data are available as the case in many study areas of Ethiopia and elsewhere. The objective of this paper is to develop a locally calibrated open water evaporation and evapotranspiration estimates based on Priestley-Taylor [1] model dependent on only temperature, solar radiation (sunshine hours) and elevation data.

In this paper two idealized standard evaporation rates are defined following Shuttleworth [2] & McMahon [3]. The first is Potential Evaporation E_o which is defined as the quantity of water evaporated per unit area, per unit time from an idealized, extensive free water surface under ambient atmospheric condition. The second is *Reference Evapotranspiration* ET_o the rate of evaporation and transpiration from idealized actively growing, green grass crop, completely shading the ground, with a fixed crop height of 0.12m, an albedo of 0.23, and a surface resistance of 69 s/m and not short of water.

When reliable climatic data including maximum and minimum temperatures, relative humidity, wind speed and radiation are available at / near the project site, an improved estimate of E_0 and ET_0 can be made using well-established global standard Penman and Penman-Monteith models respectively in case where there are only temperature data, selecting reliable evaporation estimation models is still a challenge in Ethiopia.

To overcome this challenge, elsewhere, a number of temperature-based evaporation models notably the Priestley-Taylor, Blaney-Criddle and Hargreaves have been developed for non-tropical areas. Based on non-water-limited field data, Priestley-Taylor adopted $\alpha = 1.26$ for “advection-free” saturated surfaces [4]. Likewise based on field data in northern Spain, Castellvi et al. [5] found that α exhibited large variations seasonal (up to 27 %) and spatial from 1.35 to 1.67.

Shakir [6] evaluated performances of four evaporation estimate methods, namely; Bowen ratio energy balance, mass transfer, Priestley–Taylor and pan evaporation, based on 4 years experimental data over the semi-arid region of India and found that Priestley-Taylor model with $\alpha = 1.31$ has acceptable performance considering its limited data requirement.

Adem et. al. [7] found that Penman Monteith, Enku and Thornthwaite's method fitted well the observed Pan data of the Bahir Dar station. They further indicated that Blaney-Criddle, Priestley & Taylor, and Hargreaves methods should be recalibrated for local condition before use over the Ethiopian highlands.

As discussed above, the applicability of Priestley-Taylor model often subject to rigorous local calibrations. Shuttle worth [3] recommended that in the absence of wind, relative humidity and solar radiation measurements, E_0 & ET_0 estimate can be made using Priestley-Taylor model provided the Priestley–Taylor model is calibrated with local condition based on the Penman and Penman-Monteith methods.

The objective of this paper is thus to develop regional evaporation estimation method under inadequate data using the well-known Priestley-Taylor model for Ethiopia covering various climatic zones.

DATA

Ethiopia has a total area of 1.13 million km^2 of which 1.12 million km^2 is land area and the remaining 7,444 km^2 is lakes and ponds. Ethiopia climate is diverse, 10% is hot-arid *(Berha)* with elevation < 500 mals; 52% of the area is warm semi-arid (Kola) with elevation between 500-1500 masl; 27% is cool *sub-humid* (Weynadega) with elevation between 1500-2300 masl; 10% is cool to humid (Dega) with elevation between 2300-3200 masl and 1% Cold to moist (Wurch) with elevation > 3,200 masl. High spatial variability of temperature is observed in Ethiopia following altitude [8].

Meteorological measurements and data management and dissemination over diverse Ethiopia climate is a responsibility Ethiopian Meteorological Agency. The Agency in 2016 operates 909 meteorological stations including: (a) 167 Principal (Class I) stations with key observations on rainfall amount, maximum and minimum temperature, relative humidity, wind speed at 2 m and at 10 m, sunshine duration and pan evaporation; (b) 359 ordinary stations (Class III station) which only three meteorological elements are observed, i.e. maximum and minimum air temperatures of the day, and total rainfall amount in 24 hours; and (c) 383 (Class IV) daily rainfall amount manual observation stations.

For this study the National Meteorological Agency kindly provided 167 stations monthly maximum and minimum temperatures, relative humidity, wind speed and radiation (sunshine hour) data for the period 2011-2015 inclusive representing Ethiopia diverse climate. Figure 1 shows the locations of these stations.

Elevation wise, 11 stations are located below 600 masl, 19 stations are located between 600-1200 masl, 45 stations are located between 1200-1800 masl, 58 stations are located between 1800-2400 masl and 34 stations are located above 2400 masl.

The average percent of monthly missing data over 2011-2015 period for 167 stations for temperature is 6%, sunshine hours is 8%, relative humidity is 12% and wind speed is 15%. Part of the missed data for each station is filled using average climatic data produced in the Ethiopian river basin master plan studies by the Ministry of Water, Irrigation and Electricity of Ethiopia with the assumption that observation value of the five elements remains stationary in the last 30 years.

The remaining stations average data is estimated based on nearby (with 40 km radius and similar elevation) stations observed data. Outlier data have been observed in particular wind speed data (monthly average wind speed greater than 4 m/s) and such data has been excluded by comparing with neighboring stations data and its own monthly data of other year.

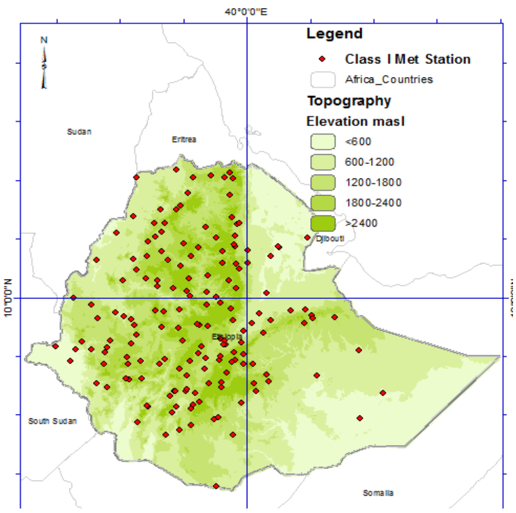

Figure1: Location of Class I meteorological stations used in this study overlaid on elevation raster

METHOD

There is a need to reliable estimate of E_0 and ET_0 based on readily available local data such as temperature, solar radiation and elevation. The Priestley-Taylor model accounts the local available data but the coefficients α should be locally calibrated to account the aerodynamic effect.

The method employed in this paper is to calibrate Priestley-Taylor coefficients α applicable for Ethiopia to estimate E_o and ET_0 using regression equations between the Priestley-Taylor model estimate (independent variable) and E_o Penman model estimate as dependent variable using monthly data. Similarly, regression is done between the Priestley-Taylor estimate (independent variable) and ET_0 Penman-Monteith model estimate (dependent variable). Detailed description of E_0 and ET_0 models are given below.

It is well known that the two main factors influencing evaporation from an open water surface (lakes, reservoirs) are the supply of energy at the evaporative surface and the ability to transport vapor away from the evaporative surface which depends on the wind velocity over the surface and the specific humidity gradient in the air above it. Model used for estimating E_0 and ET_0 are discussed below.

In practice Potential Evaporation E_0 (mm/day) is estimated using internationally accepted Penman Model (Equation 1) provided all climatic data required by the model are available [4].

$$E_o = \frac{\Delta}{\Delta+\gamma} E_r + \frac{\gamma}{\Delta+\gamma} E_a \qquad (1)$$

with

$$E_r = 8.64 * 10^7 \frac{1}{l_v \rho_w} (R_n - H_s - G) \qquad (2)$$

Where E_r *and* E_a are evaporation estimate (mm/day) based on energy balance method and aerodynamic method respectively; R_n is net radiation (W/m^2); H_s is sensible heat flux diffused to surroundings atmosphere to raise the temperature (W/m^2); G is ground heat flux (W/m^2); l_v is latent heat of vaporization (J/kg) = $2.501*10^6$ - 2361T and T is average air temperature (^oC); and ρ_w is water density (kg/m^3). If Hs and G is approximated as 0, Model 1 is the Penman model. The gradient of the saturated vapor is pressure curve $\Delta = de_s/dT$ ($Pa/^oC$) at air temperature is calculated using Equation 3.

$$\Delta = \frac{4098\, e_s}{(237.3+T)^2} \qquad (3)$$

$$e_s = 611\left(\begin{array}{l} \exp\left(17.27\dfrac{T_{\max}}{237.3+T_{\max}}\right)+ \\ \exp\left(17.27\dfrac{T_{\min}}{237.3+T_{\min}}\right) \end{array} \right)/2 \qquad (4)$$

$$R_h = \frac{e}{e_s} \qquad (5)$$

Where e_s is air saturation vapor pressure at the ambient temperature in Pascal (Pa = N/m^2), T_{max} and T_{min} are maximum and minimum air temperature in ^oC, e_a is actual vapor pressure (N/m^2), and R_h is relative humidity (%).

The psychrometric constant, γ, (kPa °C^{-1}) is given by:

$$\gamma = \left(\frac{C_p\, p}{\varepsilon\lambda}\right) \qquad (6)$$

Where p is atmospheric pressure (kPa), λ is Latent heat of vaporization (MJ kg^{-1}), C_p is specific heat at constant pressure, 1.013 10^{-3} (MJ kg^{-1} °C^{-1}), and ε is ratio molecular weight of water vapor / dry air = 0.622. Atmospheric pressure at a given altitude is estimated from Equation (7):

$$p = 101.3\left(\frac{293-0.0065\,Z}{293}\right)^{5.26} \qquad (7)$$

*Where p is a*tmospheric pressure (kPa) and Z is site elevation above sea level (m).

Besides the supply of heat energy, the second factor partly controlling the evaporation rate from an open water surface is the ability to transport water vapor away from the evaporative surface. The transport rate is governed by the humidity gradient in the air near the surface and the wind speed across the surface. The second term of evaporation equation Ea is estimated using

Aerodynamic method (m/s) (multiply by [1000 mm/m *86400 s /day] to get in mm/day), e_s is saturation vapor pressure at the ambient temperature T (Pa), e_a = e_d = actual vapor pressure estimated using dew

$$E_a = B(e_s - e_a) \qquad (8)$$

$$B = \frac{0.622\, k^2 \rho_a u_2}{p\, \rho_w [\ln(z_2/z_0)]^2} \qquad (9)$$

point temperature T_d or by multiplying e_s by the relative humidity R_h (Pa), B is the vapor transfer coefficient (m $Pa^{-1}s^{-1}$), k is the Von Karman constant is 0.4, u_2 is the wind velocity (m/s) measured at height z_2 (200 cm) and z_0 roughness height taken as 0.08 cm for open water body, p is atmospheric pressure in Pa, ρ_a is density of moist air (kg/m^3) and ρ_w is density of water (kg/m^3).

Density of water and air at given location as function of temperature T (^oC) and pressure p (Pa) are estimated using Equation 10 and 11, respectively.

$$\rho_a = \frac{p}{287(1+0.608\frac{0.622e_a}{p})T(K)} \qquad (10)$$

$$\rho_w = -0.0002T^3 + 0.0119T^2 - 0.3968T + 1003 \qquad (11)$$

The net radiation, the difference between net radiation absorbed and emitted is estimated using Equation 12 as given in FAO #56 paper:

$$R_n = (1-\alpha)(0.25+0.50\frac{n}{N})S_o - \left(1.35\left(\frac{(0.25+0.5n/N}{0.75+2Z/100{,}000}\right)-0.35\right)\sigma T^4 \quad (12)$$
$$(0.34-0.14\sqrt{e_a})$$

Where R_n is Net radiation (MJ m^2 day^{-1}); α *is* albedo and is 0.08 for open water; *n/N is* ratio of actual (n) to maximum possible hours of sunshine (N); S_0 is mean solar radiation from cloudless sky from (MJ m^2 day^{-1}); e_a *is a*ctual vapor pressure (kPa); σ is the Stefan Boltzmann constant = 4.903×10^{-9} M J m^{-2} day^{-1} K^{-4}; *T is* the absolute average air temperature of the evaporating surface in degrees Kelvin (°C + 273); Z site elevation masl; and N is $(24/\pi)^* \omega_s$.

The extraterrestrial radiation, S_o, $MJ/m^2/day$ for each day of the year and for different latitudes can be estimated from the solar constant, the solar declination and the time of the year by

$$S_o = \frac{24*60}{\pi} Gsc\, d_r$$
$$(\omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s) \quad (13)$$

Where G_{sc} is solar constant = 0.0820 $MJ/m^2/min$; d_r the inverse of the square of the relative distance Earth-Sun is estimated by $d_r = (1+ 0.033 \cos(2\pi J/365))$; J is the Julian day number (with J=1 for Jan 1 and J= 365 for 31 Dec); φ is the altitude in radian; sunset hour angle in radian $\omega_s = \arccos(-\tan\varphi \tan\delta)$; and the solar declination (in radian) $\delta = 0.4093\sin(2\pi J/365 - 1.39)$. For monthly calculations, J at the middle of the month is used in calculating S_0 as recommended in FAO # 56 Paper.

Monthly S_o value of with smaller interval applicable for 2^0 -15 ^{0} North which cover Ethiopia is calculated and average sunshine hour to be used on Priestley-Taylor model in the absence of local data nearby the project site are given in Table 1.

FAO-Allan et al [9] adopted the Penman-Monteith combination method as a new standard for estimating Reference Evapotranspiration ET_o in both arid and humid climates and is given by:

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1+0.34U_2)} \qquad (14)$$

Where ET_o *is* Reference Evapotranspiration (mm/day); R_n is net radiation at crop surface ($MJ/m^2/d$); *G* is soil heat flux ($MJ/m^2/d$) and estimated from *G* = 0.4 ($T_{month\ n\ mean\ temperature}$ ^oC - $T_{month\ n-1\ mean\ temperature}$ ^oC); 900 is conversion factor; *T* is average air temperature at 2 m (^oC); U_2 is wind speed measured at 2 m height (m/s); $(e_s - e_a)$ *is* vapor pressure deficit (kPa); Δ is slope of vapor pressure curve ($kPa/^oC$); and γ is hygrometric constant ($kPa/^oC$).

The crop evapotranspiration ETc of another crop growing under the same conditions as the *reference crop* is calculated by multiplying ETo by *crop coefficient* k_c the value of which changes with the stage of growth of the crop. It is to be noted that the k_c predicts ETc under standard conditions. This represents the upper envelope of crop evapotranspiration and represents conditions where no limitations are placed on crop growth or evapotranspiration due to water shortage, crop density, or disease, weed, insect or salinity pressures [9].

Table 1: Estimated extraterrestrial radiation, S_o, MJ/m^2/day from 2.0-15. 0 North and average sunshine hour.

N(deg)	Jan	Feb	Mar	Apr	May	Jun
2.0	35.38	36.90	37.80	37.05	35.28	34.17
2.5	35.17	36.76	37.77	37.12	35.43	34.36
3.0	34.97	36.62	37.73	37.20	35.59	34.54
3.5	34.76	36.48	37.70	37.27	35.74	34.73
4.0	34.55	36.34	37.66	37.33	35.89	34.91
4.5	34.34	36.19	37.62	37.40	36.03	35.09
5.0	34.12	36.04	37.57	37.46	36.18	35.27
5.5	33.91	35.89	37.52	37.52	36.32	35.44
6.0	33.69	35.74	37.47	37.57	36.46	35.62
6.5	33.47	35.58	37.42	37.63	36.60	35.79
7.0	33.25	35.42	37.37	37.68	36.73	35.96
7.5	33.02	35.26	37.31	37.73	36.86	36.12
8.0	32.79	35.10	37.24	37.77	36.99	36.29
8.5	32.57	34.93	37.18	37.81	37.12	36.45
9.0	32.33	34.76	37.11	37.85	37.24	36.61
9.5	32.10	34.59	37.04	37.89	37.36	36.76
10.0	31.87	34.42	36.97	37.92	37.48	36.92
10.5	31.63	34.24	36.89	37.95	37.60	37.07
11.0	31.39	34.06	36.81	37.98	37.71	37.22
11.5	31.15	33.88	36.73	38.01	37.83	37.37
12.0	30.91	33.70	36.65	38.03	37.94	37.52
12.5	30.66	33.51	36.56	38.05	38.04	37.66
13.0	30.42	33.33	36.47	38.07	38.15	37.80
13.5	30.17	33.14	36.38	38.08	38.25	37.94
14.0	29.92	32.94	36.28	38.09	38.35	38.07
14.5	29.66	32.75	36.19	38.10	38.44	38.21
15.0	29.41	32.55	36.09	38.11	38.54	38.34

N(deg)	Jul	Aug	Sep	Oct	Nov	Dec
2.0	34.59	36.15	37.28	36.94	35.61	34.75
2.5	34.76	36.25	37.28	36.84	35.43	34.53
3.0	34.93	36.36	37.29	36.73	35.24	34.31
3.5	35.10	36.46	37.29	36.63	35.05	34.09
4.0	35.26	36.55	37.29	36.51	34.86	33.86
4.5	35.43	36.65	37.28	36.40	34.67	33.63
5.0	35.59	36.74	37.27	36.28	34.47	33.40
5.5	35.74	36.83	37.26	36.16	34.27	33.17
6.0	35.90	36.91	37.25	36.04	34.07	32.93
6.5	36.05	37.00	37.23	35.92	33.87	32.69
7.0	36.20	37.08	37.21	35.79	33.66	32.46
7.5	36.35	37.16	37.19	35.66	33.46	32.22
8.0	36.50	37.23	37.16	35.53	33.25	31.97
8.5	36.64	37.30	37.14	35.39	33.04	31.73
9.0	36.78	37.38	37.11	35.26	32.82	31.48
9.5	36.92	37.44	37.07	35.12	32.61	31.23
10.0	37.06	37.51	37.04	34.97	32.39	30.98
10.5	37.19	37.57	37.00	34.83	32.17	30.73
11.0	37.32	37.63	36.95	34.68	31.95	30.48
11.5	37.45	37.69	36.91	34.53	31.72	30.22
12.0	37.58	37.74	36.86	34.38	31.49	29.96
12.5	37.70	37.79	36.81	34.22	31.27	29.70
13.0	37.82	37.84	36.76	34.06	31.04	29.44
13.5	37.94	37.89	36.70	33.90	30.80	29.18
14.0	38.06	37.93	36.64	33.74	30.57	28.92
14.5	38.17	37.97	36.58	33.57	30.33	28.65
15.0	38.28	38.01	36.52	33.40	30.09	28.38

Average sunshine hour to be used on Priestley-Taylor model in the absence of data

Jan	Feb	Mar	Apr	May	Jun
8.30	8.17	7.56	7.53	7.03	6.41
Jul	Aug	Sep	Oct	Nov	Dec
4.88	4.87	6.13	7.47	8.30	8.33

Priestley-Taylor method

The Priestley–Taylor model (mm/day) allows potential evaporation E_o (mm/day) to be computed in terms of energy fluxes without an aerodynamic component is given by:

$$E_o \ or \ ET_o = \alpha \frac{\Delta}{\Delta + \gamma} E_r \quad (15)$$

Where α is Priestley-Taylor regional coefficient to be calibrated; Δ is slope of vapor pressure curve (kPa/^{o}C); γ is hygrometric constant (kPa/^{o}C); and E_{PT} *is* evaporation estimate (m/s) based Priestley-Taylor method. E_{PT} is in mm/day if Equation 15 is multiplied by 8.64x10^7.

In order to calibrate α, for Ethiopia condition, monthly regression is done between the Priestley-Taylor model estimate as independent variable and universal standard Penman model estimate E_o as dependent variable (benchmark data generation). Similarly, regression is done between the Priestley-Taylor estimate (independent variable) and Reference Evapotranspiration Penman-Monteith model ET_o estimate as dependent variable (benchmark data generation). Regressions validity are checked using R^2 criteria along with parameter significance. Models residuals are also checked for randomness. Such calibration approach has been employed elsewhere [10, 11].

Finally, for comparison of the performance of the calibrated Priestley-Taylor method is done with known temperature-based models of Blaney-Criddle and Enku's Simple Temperature Method [12] which are described below.

The Blaney-Criddle equation is expressed as

$$ET_O = p(0.46T_{mean} + 8) \qquad (16)$$

Where:

ET_0 = estimate of Reference Evapotranspiration (mm/day) averaged over the month

T_{mean} = mean daily temperature (˚C), and p is mean monthly percentage of annual daytime hours and varies between 0.26 and 0.29.

The new simple empirical temperature method developed by Enku [12] is given by

$$ET_O = \frac{(T\max)^n}{k} \qquad (17)$$

Where ET_0 is the Reference Evapotranspiration (mm day−1);

n = 2.5

k = 48∗T_{mm} – 330 for combined wet and dry conditions

k = 73∗T_{mm} – 1015 for dry phase

k = 38∗T_{mm} – 63 for the rain phase

T_{mm} (^oC) is the long term daily mean maximum temperature for the seasons under consideration.

RESULTS AND DISCUSSION

Climatic variables such as maximum and minimum temperature, relative humidity, sunshine hours and wind speed relationships with altitudes are checked. If significant, it has a potential for regionalization and to be used in absence of data. It is found that based on 167 stations data, annual minimum and maximum temperatures have significant linear correlations with altitude over Ethiopia (Figure 2) and are given by:

*$T_{min\ daily\ annual\ average}$ (^oC) = - 0.0061*Z (m) + 24.4 with R^2 = 0.81;* *(18)*

*$T_{min\ daily\ annual\ average}$ (^oC) = - 0.0065*Z (m) + 38.9 with R^2 = 0.86* *(19)*

In the absence of temperature data at a given location, estimate of the monthly distribution of temperatures as percentage of the mean annual average daily temperature estimated by Equations 18 and 19 are given in Table 2.

Table 2: Ratio of monthly distribution of temperatures.

Monthly Temperature /Annual average	Ratio for Min. Temp	Ratio for Max. Temperature
Jan	0.86	1.02
Feb	0.95	1.05
Mar	1.04	1.07
Apr	1.09	1.06
May	1.10	1.04
Jun	1.08	1.00
Jul	1.07	0.92
Aug	1.06	0.91
Sep	1.05	0.96
Oct	0.98	0.98
Nov	0.89	0.99
Dec	0.83	1.00

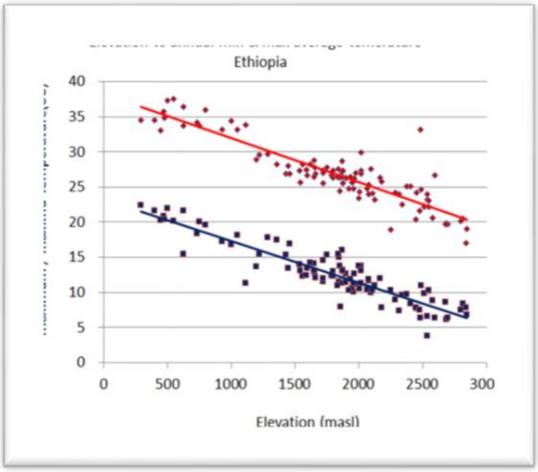

Figure 2: Correlations between annual mean maximum and minimum temperatures with station elevations based on 167 stations data.

On the other hand, as expected no significant correlations are found between relative humidity and altitude although there is a tendency to increase with altitude. It is also noted that Sunshine hours with altitude and wind speed with altitude do not have significant correlations although they have a tendency to decrease with altitude.

Priestley-Taylor coefficient α valid for Ethiopia has been developed based on 167 stations full climatic data representing all climatic zones and seasons. It is found that the Priestley-Taylor coefficient α for use in the estimate of open water evaporation E_0 is 1.11. The goodness of fit of the derived model is acceptable with R^2 is 0.91 and the residual is found to be random (Figure 3).

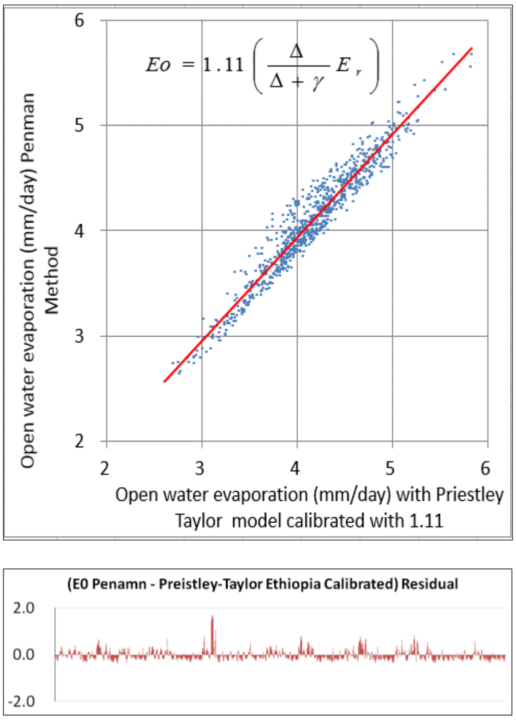

Figure 3: Regression between the Priestley-Taylor model estimate (independent variable) and Eo Penman model estimate (Open water evaporation) using full climatic data as dependent variable for each month of the 167 Class I stations in Ethiopia. Priestley-Taylor coefficient α is found to be 1.11 with R^2 = 0.91. The residual is random.

The calculated model standard error is found to be 0.26 (mm/day) and the 95% confidence interval of calibrated Priestley-Taylor α = 1.11 used for estimating E_0 is from 1.08 to 1.12.

To extend the Priestley-Taylor model applicability for irrigation water demand assessment, similar regression is made on Reference Evapotranspiration ETo estimated based on Penman-Monteith benchmark model as recommend in FAO 65 paper (Figure 4).

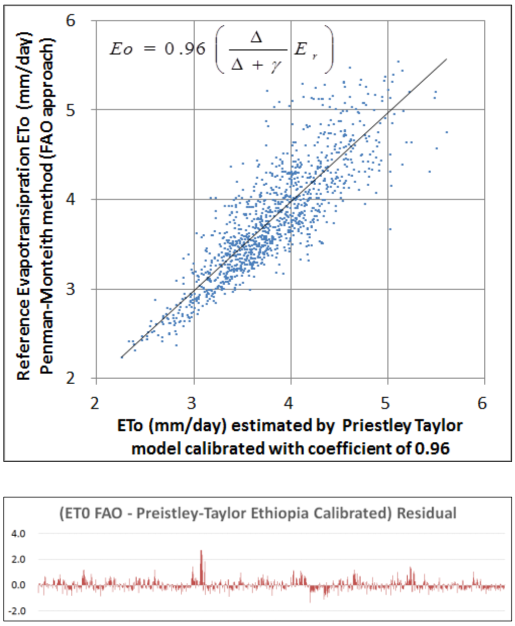

Figure 4: Regression between the Priestley-Taylor model estimate (independent variable) and ET_o

Penman-Monteith model estimate using full climatic data as dependent variable for each month of the 167 Class I stations in Ethiopia. Priestley-Taylor coefficient α is found to be 0.96 with R^2 = 0.91. The residual is random.

It is found that Priestley-Taylor coefficient α is 0.96. Estimated standard error is 0.39 (mm/day) and the 95% confidence interval of calibrated α = 0.96 for estimate for ET_0 is from 0.93 to 0.97.

Furthermore, seasonal variation of α is checked by using month to month regression. It is found that α used for open water evaporation value across the months is practically constant with maximum percentage of change from the average 1.11 is 3.6% in rainy months (Table 3), thus α = 1.11 is adopted for estimating monthly open water evaporation using Priestley Taylor model in Ethiopia.

Table 3: Calibrated monthly Priestley-Taylor coefficient α for estimating open water evaporation

	α	*Stand Error of α*	*Lower 95% of α*	*Upper 95% of α*	*Model Stand error (mm/day)*	R^2
Jan	1.13	0.006	1.119	1.144	0.233	0.997
Feb	1.13	0.006	1.121	1.146	0.256	0.997
Mar	1.13	0.006	1.118	1.141	0.247	0.998
Apr	1.11	0.006	1.098	1.120	0.252	0.998
May	1.11	0.006	1.096	1.120	0.258	0.987
Jun	1.11	0.007	1.099	1.127	0.283	0.985
Jul	1.09	0.007	1.078	1.104	0.235	0.986
Aug	1.08	0.006	1.065	1.088	0.206	0.987
Sep	1.07	0.004	1.064	1.081	0.164	0.988
Oct	1.09	0.004	1.080	1.098	0.179	0.988
Nov	1.10	0.005	1.094	1.114	0.190	0.987
Dec	1.12	0.005	1.109	1.131	0.192	0.987

Seasonal variation of the Priestley-Taylor coefficient α for estimating Reference Evapotranspiration ET_0 has a maximum percentage change of 6.5% from base α = 0.96. Lower values of α occurred in rainy months of August, September and October (Table 4). thus α = 0.96 is adopted for estimating monthly the reference evapotranspiration using the Priestley-Taylor model in Ethiopia.

Table 4: Calibrated monthly Priestley-Taylor coefficient α for estimating Reference Evapotranspiration

	α	*Stand Error of α*	*Lower 95% of α*	*Upper 95% of α*	*Model Stand error (mm/day)*	R^2
Jan	1.01	0.010	0.993	1.033	0.375	0.980
Feb	1.02	0.010	1.003	1.043	0.408	0.980
Mar	0.99	0.009	0.976	1.013	0.404	0.982
Apr	0.97	0.009	0.949	0.984	0.409	0.981
May	0.97	0.009	0.947	0.984	0.399	0.981
Jun	0.98	0.010	0.955	0.996	0.417	0.979
Jul	0.95	0.009	0.929	0.966	0.338	0.980
Aug	0.92	0.008	0.902	0.932	0.281	0.983
Sep	0.91	0.006	0.895	0.917	0.227	0.986
Oct	0.94	0.006	0.922	0.948	0.263	0.985
Nov	0.96	0.008	0.948	0.980	0.456	0.978
Dec	0.99	0.008	0.974	1.007	0.302	0.983

The present study clearly confirmed that the Priestley-Taylor evaporation model is required to be calibrated for local condition as there is more than 20% difference between the current estimates of α = 1.11 for open water evaporation estimate in Ethiopia and elsewhere. To illustrate, Priestley-Taylor coefficient adopted a general α = 1.26 Chow [3]. Castellvi et al [4] for the northern Spain recommended α between1.35 to 1.67. Shakir (2008) recommends for semi-arid region of India α = 1.31.

It is to be noted that recent development in USBR [13] study found that for accurate estimate of reservoir evaporation, measurement of weather variables should be done directly over the water surface (buoy weather station).

It is also known that in both arid and semi-arid areas air temperature is lower, relative humidity is higher, and wind speed is elevated when collected over water verses land. As there is no buoy based climatic weather station available in Ethiopia, all calibration of Priestley-Taylor model for Open water evaporation estimate was done based on weather data collected at land base 2 m height. It is recommended to conduct further research to refine the present finding of Priestley-Taylor α = 1.11 for Open water evaporation estimate by correlating buoy based and ground-based temperature measurements.

Finally, the performance of the calibrated Priestley-Taylor model for Reference Evapotranspiration is compared to Blaney-Criddle model and Enku's simple temperature model using bench mark ET_o Penman-Monteith model. Blaney-Criddle method consistently over estimate ET_0 across Ethiopia by more than 26% when compared to bench mark ET_0 Penman-Monteith model estimate. Enku's model, which was developed based on Ethiopia data, is able to estimate ET_0 Penman-Monteith model using only mean daily maximum temperature with only 2.6% variation with bench mark ET_0 Penman-Monteith model estimate.

The present calibrated Priestley-Taylor model has less than 1% deviation and thus has a better performs due to its inclusion of local radiation and elevation data in the model. The local net radiation can be estimated using sunshine hours regional values and coordinate of project site using Eq.12 and Table 1.

CONCLUSIONS

Estimating reliable reservoir evaporation and crop water requirements under inadequate data continue to be a challenge for practicing hydrologist and irrigation engineers and planners. This paper has developed reliable method for tropical Ethiopia under inadequate data condition for estimating evaporation by calibrating the Priestley-Taylor model which uses maximum and minimum temperature data and local data such as solar radiation and elevation. The Priestley-Taylor model applicable over Ethiopia for estimating open water evaporation E_0 and Reference Evapotranspiration ET_0 are given by $E_o \cong 1.11 \frac{\Delta}{\Delta + \gamma} E_r$ *and* $ET_o \cong 0.96 \frac{\Delta}{\Delta + \gamma} E_r$ respectively.

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REFERENCES

[1] Priestley, C.H.B. and Taylor, R.J. (1972). *"On the assessment of surface heat flux and evaporation using large-scale parameters."* Monthly Weather Review, 100: PP. 81–92.

[2] Shuttleworth, W.J. (1992). *"Evaporation."* In: Handbook of Hydrology, 551 pp., D.R. Maidment (Ed.). McGraw-Hill, New York.

[3] McMahon, T.A., Peel, L.M., Lowe, R,S, and McVicar, T.R, *"Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis",* Hydrological Earth System Science 17:1331–1363, 2013.

[4] Chow, V.T., Maidment, D.R. and May, L.W, *"Applied Hydrology"*, McGraw-Hill: New York, 1988.

[5] Castellvi, F., Stockle, C.O., Perez, P. J. and Ibanez, M, *"Comparison of methods for applying the Priestley-Taylor model at a regional scale",* Hydrological Process 15: PP.1609–1620, 2001.

[6] Shakir, A., Narayan, C.G. and Ranvir, S. (2008). *"Evaluating best evaporation estimate model for water surface evaporation in semi-arid region, India."* Hydrological Process: Vol. 22, Issue 8, Pages 1093–1106

[7] Adem, A.A., Aynalem, D.W., Tilahun, S.A. and Steenhuis, T.S, "*Predicting Reference Evaporation for the Ethiopian Highlands"*, Journal of Water Resources and Protection. Journal of Water Resource and Protection, 9,1244-1269. https://doi.org/10.4236/jwarp.2017.911081, 2017.

[8] Berhanu B., Melesse, A.M. and Seleshi, Y. *"GIS-based hydrological zones and soil geo-database of Ethiopia",* Elsevier - Catena Vol 104: 21–31, 2013.

[9] Allen, R.G., Pereira, L.S., Raes, D., Smith, M, *"Crop evapotranspiration, guideline for computing crop water requirements",* FAO Irrigation and Drainage Paper # 56, 1998.

[10] Fisher, D.K. and Pringle Iii, H, "*Evaluation of Alternative Methods for Estimating Reference Evapotranspiration",* Agricultural Sciences, 4, 51. https://doi.org/10.4236/as.2013.48A008, 2013.

[11] Gotardo, J.T., Rodrigues, L.N. and Gomes, B.M, *"Comparison of Methods for Estimating Reference Evapotranspiration: An Approach to the Management of Water Resources within an Experimental Basin in the Brazilian Cerrado. Engenharia Agricola"*, 36, 1016-1026. https://doi.org/10.1590/1809-4430-eng.agric. v36n6p1016-1026/2016, 2016.

[12] Enku, T. and Melesse, A.M. "*A Simple Temperature Method for the Estimation of Evapotranspiration",* Hydrological Processes, 28, 2945-2960. http://onlinelibrary.wiley.com/doi/10.1002/hyp.9844, 2014.

[13] USBR, *"Improving Reservoir Evaporation Estimates."* Research and Development Office Science and Technology Program, Final Report ST-2012-7662-1, 2016.