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Statistical Modeling of Reference Evapotranspiration for Areas of the Peruvian Altiplano with Lack of Insolation Data

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Abstract**—***Empirical methods have been developed in the literature to estimate evapotranspiration from climatic elements which require rigorous local calibrations and have shown limited global validity; in addition, proving their accuracy requires much time and money. The objective of this research was to perform statistical modeling of reference evapotranspiration for highland areas with a lack of insolation data. The Puno altiplano has 42 meteorological stations; however, only 09 stations measure sunshine hours and only in these stations is it possible to determine the reference evapotranspiration (ETo) with the Penmam-Monteith (PM) method. In the present research, the relationship between ETo obtained with PM and the methods of Hargreaves-Samani (HS) and class "A" tank. Then, homogeneous zones were determined by cluster analysis where the relationship obtained between ETo by PM and H-S and tank "A" can be applied. An empirical model was also developed relating the ETo obtained with PM with an energy term (TE) and an aerodynamic term (TA) through multiple regression. The advantage of this model is that it does not need sunshine hours, since instead of net radiation it uses extraterrestrial radiation. The regression was examined for spuriousness with the Durbin-Watson < r^2 statistic, then detected for heteroscedasticity with White's test and corrected with weighted least squares estimation. The Hargreaves-Samani method was found to estimate PM ETo very well with r^2 ranging from 0.70 to 0.88 at several stations. With the cluster analysis, 10 homogeneous zones were determined to apply the empirical models obtained; the relationship between ETo and the TE and TA terms is significant with r^2 varying from 0.648 to 0.912, with statistically significant coefficients ($p \leq 0.05$) for several stations. The models with corrected heteroscedasticity have r^2 from 0.80 to 0.99 and statistically significant coefficients ($p \leq 0.05$). It is recommended to investigate the behavior of sunshine hours in the highlands since it is an under-measured variable.*

Keywords**—** *Altiplano, cluster analysis, Insolation, multiple regression, reference evapotranspiration, statistical modeling*.

I. INTRODUCTION

The determination of agricultural water demands has always been important; however, inappropriate determination methods are still used because of their poor suitability for areas where these methods have not been adequately developed and validated (Michel, 1997). The determination of demands is made using crop evapotranspiration, which is obtained with the reference evapotranspiration and the crop coefficient (Allen, Pereira, Raes, & Smith, 1998). ETo is a variable that depends on climate elements: temperature, solar radiation, wind speed, relative humidity and atmospheric pressure; and it also depends on climate factors: geographical position, relief, distances to water bodies and wind direction. Research on ETo is numerous, however, in the Puno altiplano there are few, considering even more the lack of data on sunshine hours to determine solar radiation to estimate ETo by the standard FAO Penman-Monteith method. The objective of the research was to perform statistical modeling of reference evapotranspiration for highland areas with a lack of sunshine data.

II. MATERIALS AND METHODS

The altiplano is within the endorheic hydrographic system of Lake Titicaca, between 14°03' and 20°00' South Latitude and between 66°21' and 71°07' West Longitude. Its local cold and dry climate is deeply affected by the altitude and proximity to Titicaca Lake. Meteorological records of 25 years on average from the National Meteorological and Hydrological Service stations were used, consisting of temperature, relative humidity, evaporation of tank type "A", daily sunshine and wind speed. The stations used were Acora, Capachica, Desaguadero, Ilave, Juli, Los Uros, Puno, Ananea, Cojata, Arapa, Ayaviri, Cabanillas, Chuquibambilla, Huancané, Lampa, Mañazo, Progreso, Santa Lucia, Taraco, Azángaro, Crucero, Capazo, Huaraya-Moho, Yunguyo, Llally, Santa Rosa, Mazocruz, Pizacoma, Juliaca, Putina, and Pampahuta.

ETo was determined using the FAO Penman-Monteith equation (Allen et al., 1998).

$$ET_o = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad [1]$$

Where: ET_o = Reference evapotranspiration (mm d^{-1}), Rn = Net radiation at crop surface (MJ m^{-2} d^{-1}), G = Sensible soil heat flux (MJ m^{-2} d^{-1}), T = Mean daily air temperature at 2 m altitude (ºC), u_2 = Wind speed at 2 m altitude (m s^{-1}), e_s = Saturation vapor pressure (kPa), e_a = Instantaneous vapor pressure (kPa), e_s-e_a = Saturation vapor pressure deficit (kPa), Δ = Slope of the vapor pressure curve (kPa ºC-1), γ = Psychrometric constant (kPa $ºC^{-1}$). The type "A" tank method (Allen et al., 1998) was also used.

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$$ET_0 = K_p E_v \quad [2]$$

Where: E_v = evaporation of the class "A" tank (mm/day), Kp = empirical coefficient, valid for the ambient conditions of the tank and determined as a function of relative humidity, wind speed and the surface coverage over which the tank operates (Allen et al., 1998). The Hargreaves-Samani equation was used (Hargreaves & Samani, 1985).

$$ET_0 = 0.013(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} Ra \quad [3]$$

Where: ET_o = Evapotranspiration of the reference crop (mm/day), T_{mean} = Average daytime temperature (°C), T_{max} = Average maximum daytime temperature (°C), T_{min} = Average minimum daytime temperature (°C), and Ra = Extraterrestrial solar radiation (mm/day). It was determined whether the Hargreaves-Samani equation or the Type "A" Tank method best estimates the ETo obtained with FAO Penman-Monteith. The linear model was then used in stations belonging to homogeneous clusters grouped according to cluster analysis. The variables for the cluster analysis were the annual average of: mean maximum and minimum temperatures, precipitation, relative humidity, monthly evaporation, wind speed, altitude, south latitude, west longitude. The cluster analysis used the complete linkage method, Euclidean square distance measurement and standardized variables. To determine the relationship between ETo and climate elements, multiple linear regression was used. The following model was proposed.

$$ETo = a_0 + a_1 TE + a_2 TA \quad [4]$$

Where:

$$TE = \Delta \frac{Ra}{l_v} \quad [5]$$

$$TA = \frac{u_2}{l_v}(e_s - e_a) \quad [6]$$

Where: ET_o = reference evapotranspiration (mm d^{-1}), TE = energy term, TA = aerodynamic term, a_0, a_1, a_2 = parameters.

$$\Delta = \frac{4.098 e_s}{(237.3 + T)^2} \quad [7]$$

Where: Δ = slope of the saturation vapor pressure curve (Pa $°C^{-1}$), en = saturation vapor pressure (Pa) is determined by.

$$e_s = 611 \exp\left(\frac{17.27T}{237.3 + T}\right) \quad [8]$$

Ra = equivalent extraterrestrial radiation (mm d^{-1}) of table, lv = latent heat of vaporization (J kg^{-1}), given by.

$$lv = 2.501 \times 10^6 - 2370T \quad [9]$$

T = average temperature (°C), u2 = average wind speed (m s^{-1}), e_a = actual vapor pressure (Pa), determined by relative humidity (RH) in %.

$$e_a = \frac{HR}{100} \times e_s \quad [10]$$

The Durbin-Watson statistic, the variation and histogram plots of the errors, White's test for heteroscedasticity without cross terms and corrected for heteroscedasticity with weighted least squares estimation were determined.

III. Results and Discussion

The table I shows the regression equations between the ETo obtained with the FAO Penman-Monteith, Hargreaves-Samani and Tank class "A" method and the coefficient of determination r^2 for each station.

TABLE I. Regression equations by methods and r^2 by stations.

Station	PM(y)-Tank "A"(x) (r^2)	PM(y)-HS(x) (r^2)
Ananea	y = 0.2909x + 1.9471 (19.77)	y = 0.3889x + 1.5839 (38.15)
Chuquibambilla	y = 0.5038x + 1.6321 (32.42)	y = 0.7469x + 0.8642 (72.79)
Desaguadero	y = 0.0452x + 3.6519 (0.29)	y = 0.0422x + 3.645 (0.25)
Huancané	y = 0.6555x + 1.7409 (54.97)	y = 1.0426x + 0.3682 (70.38)
Juli	y = 0.5937x + 1.5505 (66.00)	y = 0.9889x + 0.6041 (79.71)
Juliaca	y = 0.6959x + 1.0936 (81.29)	y = 0.8174x + 0.3661 (87.64)
Lampa	y = 0.6399x + 1.5777 (59.64)	y = 0.9251x + 0.386 (88.22)
Puno	y = 0.6329x + 1.4362 (57.86)	y = 0.9992x + 0.8859 (74.75)
Putina	y = 0.75x + 1.44138 (60.10)	y = 0.5344x + 1.3142 (47.32)

Source: Own elaboration

The highest r^2 are presented in the regressions between the PM and HS method. Research conducted by Vásquez et al. (Vásquez, Ventura, & Acosta, 2011) indicates that the Hargreaves and Samani method performed better than the methods of Oudin, Jensen and Haise, McGuinness and Bordne, Romanenko; to estimate ETo measured in a gage station obtaining r^2 = 0.7 and with lower errors. In the present study, it was found that Hargreaves and Samani method is better at estimating ETo than the class "A" tank. Likewise, Vásquez et al. (Vásquez et al., 2011) found that the Penman-Monteith method is the best at different time scales, which contributes to the decision to estimate ETo with the method used in this research. Also in the research of Sanchez and Carvacho (Sanchez & Carvacho, 2006), Penman formula used to estimate potential evapotranspiration which is similar to ETo, a method that has been widely used in the world. They also used the method of Hargreaves and Samani in their work. On the other hand, Khan et al. (Khan, Gil, & Acosta, 1998) obtained a regression equation of the ETP measured in lysimeter based on the evaporation of tank class "A", finding r^2 = 0.65, a value higher than several of those obtained in the present investigation for a similar equation, the evaporation of tank class "A" combines in a single data the effect of: temperature, radiation, relative humidity, wind speed and atmospheric pressure. The performance of the tank is inferior to the Hargreaves and Samani method for estimating ETo with Penman-Monteith. The results of Ruiz-Álvarez et al. (Ruiz-Álvarez, Arteaga-Ramírez, Vázquez-Peña, Ontiveros-Capurata, & López-López, 2012) where linearly relating ETo with tank class "A" to Hargreaves and Samani ETo show a high value of r^2 = 0.883. However, they did not consider the ETo with the Penman-Monteith method because they only worked with temperature and evaporation data, whereas in the present research the ETo with tank is not linearly related to the Penman-Monteith ETo.

The result of the cluster analysis is the dendogram shown in following Figure 1, resulting in 10 homogeneous groups.

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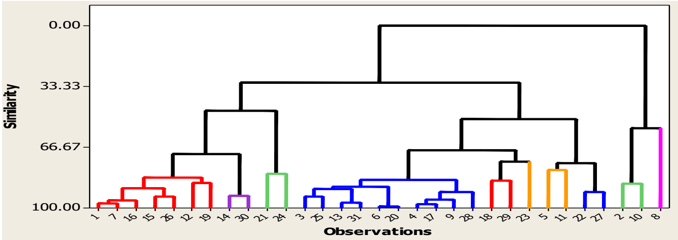

Fig. 1. Dendogram obtained from the cluster analysis.

The dendogram resulting from the cluster analysis presents the 10 homogeneous groups shown in Table II.

TABLE II. Homogeneous groups according to cluster analysis able styles.

Group	Group stations	Seasons with hours of sunshine	Best model
1	Acora, Capachica, Desaguadero, Ilave, Juli, Los Uros, and Puno	Desaguadero, Juli, Puno	Juli PM = 0.9889HS + 0.6041 (R2=79.71)
2	Ananea and Cojata	Ananea	Ananea PM = 0.3889HS + 1.5839 (R2 = 38.15)
3	Arapa, Ayaviri, Cabanillas, Chuquibambilla, Huancané, Lampa, Mañazo, Progreso, Santa Lucia, and Taraco.	Chuquibambilla, Huancané, Lampa	Lampa PM = 0.9251HS + 0.386 (R2 = 88.22)
4	Azángaro, and Crucero	None	None
5	Capazo	None	None
6	Huaraya-Moho, and Yunguyo	None	None
7	Llally, and Santa Rosa	None	None
8	Mazocruz, and Pizacoma	None	None
9	Juliaca, and Putina	Juliaca, Putina	Juliaca PM = 0.8174HS + 0.3661 (R2 = 87.64)
10	Pampahuta	None	None

Source: Own elaboration.

Table III presents the regression models for each weather station, the coefficients of determination, the Durbin-Watson statistics (D-W), the number of data used (N) and indicates which regressions are spurious with the criterion D-W < r^2. The regressions were determined only for 17 stations out of 42 stations, because these 17 stations are homogeneous to other stations where the relationship between ETo obtained with Hargreaves-Samani and Penman-Monteith was obtained.

Regressions are spurious at 9 stations and non-spurious at 8 meteorological stations; but at the following stations: Ilave (not spurious) with 40 data, Los Uros (spurious) with 69 data, Mañazo (not spurious) with 87 data, Juliaca (not spurious) with 98 data and Putina (not spurious) with 75 data; it is observed that the number of data is small: then, in these stations the result is not conclusive if the regression is spurious, of the 8 stations where the regressions are not spurious, in 4 of these stations the number of data is less than 100.

The results of the detection of heteroscedasticity with White's test at 0.05 of significance level are presented in Table IV showing whether or not heteroscedasticity exists.

TABLE III. Equations of the regression models by stations

Station	Equation	r^2 (%)	D-W	Regression	N
Capachica	ETo = 1.72 + 3817983 TE + 101 TA	64.8	0.449111	Spurious	318
Juli	ETo = 1.38 + 4032457 TE + 579 TA	87.2	0.649291	Spurious	405
Ilave	ETo = 1.33 + 4574715 TE + 1567 TA	91.2	1.01110	Not spurious	40
The Uros	ETo = 1.97 + 3850893 TE + 69 TA	78.8	0.321794	Spurious	69
Puno	ETo = 1.87 + 4321823 TE + 174 TA	82.4	0.561601	Spurious	538
Arapa	ETo = 1.47 + 3806837 TE + 321 TA	78.2	0.652736	Spurious	512
Cabanillas	ETo = 1.29 + 4391875 TE + 407 TA	83.2	0.534394	Spurious	523
Mañazo	ETo = 1.14 + 4394006 TE + 1278 TA	90.7	1.36924	Not spurious	87
Lampa	ETo = 1.59 + 3613418 TE + 985 TA	76.7	0.940388	Not spurious	526
St. Lucia	ETo = 1.09 + 4098928 TE + 2270 TA	79.4	0.855006	Not spurious	104
Ayaviri	ETo = 2.01 + 3188134 TE + 95.0 TA	73.1	0.685189	Spurious	390
Chuquibambilla	ETo = 1.91 + 3130991 TE + 753 TA	75.6	0.723960	Spurious	671
Progress	ETo = 1.52 + 4359218 TE + 622 TA	80.8	0.855678	Not spurious	527
Taraco	ETo = 1.93 + 3355352 TE + 1027 TA	74.1	0.960295	Not spurious	177
Huancané	ETo = 1.87 + 3584474 TE + 458 TA	77.7	0.720362	Spurious	539
Juliaca	ETo = 1.62 + 3032048 TE + 2257 TA	81.0	1.17411	Not spurious	98
Putina	ETo = 2.76 + 301170 TE + 952 TA	22.1	1.04887	Not spurious	75

Source: Own elaboration.

TABLE IV. White's test by meteorological stations

Station	Stat. F	Probab. F	r^2 obs (%)	Probab. r^2 obs	heteroscedasticity
Capachica	9.082904	0.000001	33.07	0.000001	There is
Juli	5.266717	0.000383	20.26	0.000443	There is
Ilave	2.00842	0.114726	7.47	0.113158	Does not exist
The Uros	2.230838	0.075442	8.44	0.076626	Does not exist
Puno	24.00868	0.000	82.14	0.000000	There is
Arapa	4.844502	0.000767	18.85	0.000842	There is
Cabanillas	9.126296	0.000	34.43	0.000001	There is
Mañazo	3.138406	0.018736	11.55	0.021024	There is
Lampa	11.68833	0.000	43.32	0.000000	There is
St. Lucia	2.297904	0.064241	8.84	0.065345	Does not exist
Ayaviri	15.03093	0.000	52.68	0.000000	There is
Chuquibambilla	24.0103	0.000	84.57	0.000000	There is
Progress	5.838455	0.000133	22.57	0.000154	There is
Taraco	2.957304	0.021428	11.39	0.022516	There is
Huancané	9.258823	0.000	34.96	0.000000	There is
Juliaca	7.449895	0.00003	23.78	0.000088	There is
Putina	2.306427	0.066621	8.73	0.068113	Does not exist

Source: Own elaboration

There is no heteroscedasticity in the stations: Ilave, Los Uros, Santa Lucia and Putina. Heteroscedasticity exists in the remaining 13 stations and was corrected. Excess probabilities ranging from 0 to 0.0214 were obtained for the F statistic, as well as excess probabilities ranging from 0 to 0.0225 for the observed r^2 statistic. These probabilities are lower than the significance level of 0.05. In the 4 stations where there is no heteroscedasticity, the excess probabilities for F vary from 0.064 to 0.114, and the excess probabilities for observed r^2 vary from 0.065 to 0.113, in both cases the probabilities are greater than 0.05 and there is no heteroscedasticity.

The results of the heteroscedasticity correction show that in the equations the coefficients of the heteroscedasticity

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correction models are significant at 0.05. The r^2 obtained in the corrected models varies from 0.80 to 0.99. High r^2 values between 0.648 and 0.912 were obtained for uncorrected models with coefficients different from 0 at 0.05 of significance level. In the corrected models, r^2 values of 0.80 to 0.99 were obtained, further improving efficiency.

TABLE V. Correction for heteroscedasticity

Station	Var. Dep.	Var. Indep.	Coefficients	r^2
Capachica	ETO/TA	1/TA TE/TA TA/TA	1.952139 3010788 281.5901	0.965466
Juli	ETO/TE	1/TE TE/TE TA/TE	1.398588 4089735 488.4813	0.89301
Puno	ETO/TA	1/TA TE/TA TA/TA	2.024332 4014772 142.0177	0.983175
Arapa	ETO/TE	1/TE TE/TE TA/TE	1.500884 3825303 256.1723	0.800417
Cabanillas	ETO/TA	1/TA TE/TA TA/TA	1.590789 3714084 426.4659	0.985322
Mañazo	ETO/TE	1/TE TE/TE TA/TE	1.229288 4436413 984.8377	0.88364
Lampa	ETO/TE	1/TE TE/TE TA/TE	1.611362 3785022 751.0655	0.857443
Ayaviri	ETO/TE	1/TE TE/TE TA/TE	2.004377 3247859 62.38342	0.917249
Chuquibambil la	ETO/TA	1/TA TE/TA TA/TA	2.093423 3520995 -449.3106	0.989436
Progress	ETO/TA	1/TA TE/TA TA/TA	1.823788 3565729 798.7257	0.994253
Taraco	ETO/TE	1/TE TE/TE TA/TE	1.992047 3585710 671.5984	0.910819
Huancané	ETO/TE	1/TE TE/TE TA/TE	1.859258 3690531 394.7095	0.875563
Juliaca	ETO/TA	1/TA TE/TA TA/TA	1.773885 2649354 2344.535	0.982531

Source: Own elaboration.

In Fennessey and Vogel's research (Fennessey & Vogel, 1996) multiple linear regression was applied, however, they only analyzed the obtained r^2 values that were high (greater than 0.7) and the significance with the t-test resulting in significant coefficients at 0.05, however, they did not analyze if the regressions were spurious. In the study by Vasquez et al. (Vasquez et al., 2011), regression models were determined to estimate ET_o from climatic variables (net solar radiation, relative humidity, mean temperature and wind speed) obtaining $r^2 = 0.8$, 0.82 and 0.9 for daily, weekly and monthly time scales. Comparing the results at the monthly level with those of the present study, the r^2 is even higher for the same time scale in several meteorological stations. Similarly, Sánchez and Carvacho (Sánchez & Carvacho, 2006) used multiple regression to estimate potential evapotranspiration based on surface temperature and the normalized difference vegetation index, both independent variables obtained from NOAA-AVHRR satellite images. They obtained the ETP with the Penman method and related it to the surface temperature (Ts) and the difference of this with the mean air temperature (Ts-TAm), obtaining an $r^2 = 0.756$ which is lower than that obtained in several of the stations of the present investigation and a form of the Penman equation was also used to estimate ETo.

In the research of Khan et al. (Khan et al., 1998), a high relationship between ETo and evaporation of the class "A" tank was determined, obtaining $r^2 = 0.65$, being the only climatic element that would combine the effect of temperature, radiation, relative humidity, wind speed and atmospheric pressure.

The regression equation obtained in the present research did not consider evaporation as a climatic element due to the overlapping effects with the energy and aerodynamic terms. In the research of Garcia et al. (Garcia et al., 2000), it was found that the best fit models were nonlinear of potential and exponential type with independent variables such as diurnal range of temperature and extraterrestrial solar radiation. They obtained r^2 values between 0.12 to 0.561 significantly different from zero according to F test, low r^2 values in relation to those obtained in the present research, in the works of Vasquez et al. (Vasquez et al., 2011), Sánchez and Carvacho (Sánchez & Carvacho, 2006) Khan et al. (Khanet al., 1998) and Ruiz-Álvarez et al. (Ruiz-Álvarez et al., 2012), the detection of hetorocedasticity of ETo regression and climatic elements was Ruiz-Álvarez (Ruiz-Álvarez et al., 2012) not performed, the present research has, therefore, originality in analyzing this aspect.

IV. Conclusion

The relationship between ETo with the Penman-Monteith and Hargreaves-Samani methods is statistically significant with an r^2 that varies from 0.70 to 0.88 in 6 stations and in 3 stations. It varies from 0.0025 to 0.473, the 09 stations have sunshine hour's data. The Hargreaves-Samani method estimates ET_o better than the class "A" tank, it obtained an r^2 that varies from 0.0029 to 0.8129, being only high in Juliaca and in the rest of 08 stations it is less than 0.67. The cluster analysis determined 10 homogeneous zones to apply the relationship between Hargreaves-Samani and Penman-Monteith to a total of 17 meteorological stations. The relationship between ETo in the highlands and climate elements is statistically significant with high r^2 ranging from 0.648 to 0.912 at most stations. The relationship is not direct, since ETo is related to an energy balance term and an aerodynamic term. The Durbin-Watson statistic obtained varies from 0.32 to 1.37 and spurious (D-w < r^2) and non-spurious regressions exist. In all stations, the coefficients are statistically different from zero at the 0.05 significance level and the analysis of variance also indicates that the coefficient of determination is statistically different from zero at the 0.05 significance level. The regressions are spurious at 09 stations and non-spurious at 08 stations of the total, ETo was obtained as a function of climate elements. Heteroscedasticity was detected in the errors of the ETo model as a function of climatic elements in 13 of 17 stations and none

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in 04. In White's test, excess probabilities ranging from 0 to 0.0214 were obtained for the F statistic, and excess probabilities ranging from 0 to 0.0225 were also obtained for the observed r^2 statistic. Heteroscedasticity was corrected with weighted least squares estimation obtaining r^2 values in the correction models ranging from 0.80 to 0.99 and the coefficients are different from zero at 0.05 significance.

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