Analysis of three indirect methods for estimating the evapotranspiration in the agricultural zone of Chillán, Chile

María Jesús Bochetti¹, Enrique Muñoz², Pedro Tume² and Joan Bech³

¹ Procter & Gamble Chile Limiteda, Avenida Presidente Riesco 5335, piso 17, Las Condes, Santiago, Chile, jesus.bochetti@gmail.com
² Departamento de Ingeniería Civil, Universidad Católica de la Santísima Concepción, Alonso de Ribera 2850, Concepción, Chile, emunozo@upec.cl, ptume@upec.cl
³ Departamento de Astronomía y Meteorología, Universidad de Barcelona, Martí i Franques 1, Barcelona, Spain, jbech@ub.edu

Keywords: reference crop evapotranspiration, pan evaporation, Chillán–Chile

Introduction

Reference evapotranspiration $ET_o$ is a key component in many hydrometeorological and agricultural studies and applications. It is used for urban and agricultural planning, irrigation planning, water balance studies, and agro-climatic zoning studies, among others (Samani, 2000; Droogers and Allen, 2002). $ET_o$ is the most important component in the quantification and estimation of agricultural water usage. The estimations of $ET_o$ are widely used and required to define water needs for crops and are also required for designing and planning irrigation systems. These estimations are used both, in the planning process of these irrigation systems and in the management of water distribution of existing systems (Droogers and
Allen, 2002). Because of its importance in agriculture and because their values are essential to quantify the general water balance of a particular zone, it is critical to obtain the most accurate estimation of the amounts of real evapotranspiration $ET_r$ and reference evapotranspiration (Hube, 1989; Sumner and Jacobs, 2005). The importance of evapotranspiration has triggered the development of satellite-based retrieval methods (Wang and Dickinson, 2012), such as the approach recently proposed by Sánchez et al. (2008) based on LANDSAT imagery. However, given the current limitations of those methods, there is still a need to use ground based data for practical applications such as in irrigation management of crops, particularly in arid or semi-arid environments with Mediterranean climate (Rana and Katerji, 2000). Currently there are different methods available to estimate $ET_\text{o}$ from ground based automated observations. Therefore, evaluating these methods, knowing their advantages and limitations, their precision levels, and application limits, should be the first step before using them (Xiaoying and Erda, 2005).

There are many models based on meteorological data which allow estimating $ET_\text{o}$ in different climates and geographical conditions. The Penman-Monteith FAO model PMF is generally presented as a standard model for estimating $ET_\text{o}$ (Allen et al., 1998). The main limitation of this model is the need of many meteorological data entries which limits its applicability in areas where data is less available, especially in developing countries. Some simpler models that use parameters or variables that are commonly measured in meteorological stations are more advisable to estimate $ET_\text{o}$ in scarce-data areas (Tabari, 2009).

Among those simpler models to calculate $ET_\text{o}$ are the Priestley-Taylor PT method (Priestley and Taylor, 1972), and the Hargreaves-Samani HS method (Samani, 2000; Hargreaves and Allen, 2003). The HS method is a simple method that only requires data such as temperature and latitude of the area of study. Chillán, Chile is an area of intense agricultural development and production with a significant availability of hydric resources, therefore an accurate $ET_\text{o}$ estimation is necessary. The objective of this study is to evaluate the level of accuracy of the simpler and the traditional models in estimating the evapotranspiration in the area of Chillán in order to recommend an option that offers security in the estimation of this variable under the scenarios of limited data availability.

**Materials and methods**

**Study area and data**

The agricultural area of Chillán has a temperate Mediterranean climate with a thermal regime characterized by an annual average temperature of 14°C, ranging from 28.8°C, in the hottest month (January), to 3.5°C in the coldest month (July). The hydric regime is characterized by an average annual precipitation of 1025 mm and a four month dry season (December-March). The month of July is typically the rainiest with an average rainfall of 217 mm (Novoa et al., 1989). The Köepe-Geiger classification code of this area is Csb (Kottek et al., 2006), i.e. warm temperate with dry and warm summer, a code typically associated to Mediterranean climate. The pan evaporation reaches 1308 mm per year, with a minimum of 7 mm in June, and a maximum of 260 mm in January. Daily meteorological data (air temperature, relative humidity, wind velocity, solar radiation, and pan evaporation) recorded between 1996 and 2008 was used for the study. The data was collected at the meteorological stations of Universidad de Concepción Campus Chillán (36°34’S, 72°06’W, 149 masl) and INIA-Quilamapu Chillán (36°32’S, 71°55’W, 217 masl). It is important to point out that there is a gap of solar radiation data between: i) January and March of 1996, and ii) April and November of 1997. Therefore, these periods were not included for the analysis in the discussion section for the Penman-Monteith FAO and Priestley-Taylor methods because they depend on the solar radiation data for $ET_\text{o}$ estimations.

**$ET_\text{o}$ estimation methods**

**Background and assumptions** (Savage et al., 2009). The transfer of water vapour between a surface and the atmosphere of the surface is a fundamental aspect of the water balance of a plant community. From a consideration of the simplified energy balance of a vegetable surface, in the absence of advection flux density and neglecting biochemical and physical storage by the canopy in comparison with other terms:

$$R_{\text{net}} + LE + H + S = 0$$  \hspace{1cm} (1)
where $R_{\text{net}}$, $LE$, $H$ and $S$ are the net irradiance, latent energy flux density, sensible heat flux density and soil heat flux density, respectively. All terms are in W/m$^2$. Combining the energy balance equation with the definition of the Bowen ratio (Bowen, 1926):

$$LE = \frac{- (R_{\text{net}} + S)}{1 + \beta}$$  \hspace{1cm} (2)

and

$$LE = -\frac{\beta (R_{\text{net}} + S)}{1 + \beta}$$  \hspace{1cm} (3)

where $\beta \neq -1$. When $\beta \to -1$, (2) and (3) cannot be applied and $R_{\text{net}} + S \to 0$ in (1). Assuming similarity between the exchange coefficients for $H$ and $LE$:

$$\beta = \frac{\gamma dT}{de}$$  \hspace{1cm} (4)

where $\gamma$ is the psychrometric constant in kPa/°C, $dT$ is the profile air temperature difference in °C and $de$ is the profile water vapour pressure difference in kPa. Both differences are averaged, typically over 20 min. If, in (4), $\beta = -1$, then $de = \gamma dT$ or $d\theta = de + \gamma dT = 0$ where the equivalent temperature $\theta(K)$ is defined by:

$$\theta = T + \frac{e}{\gamma}$$  \hspace{1cm} (5)

where $T(K)$ is the air temperature and $e$ in kPa is the water vapour pressure. The psychrometric constant may be written as $c_p \rho / \varepsilon L$ where $c_p$ is the specific heat capacity of air at constant pressure in J kg$^{-1}$C$^{-1}$, $P$ is the atmospheric pressure in kPa, $\varepsilon = 0.622$ is the ratio of the molecular mass of water vapour to that of dry and $L$ is the specific latent energy of vapourisation (≈2.45 MJkg$^{-1}$ at 20°C). When the Bowen ratio $\beta = \frac{\gamma dT}{de} = (c_p \rho / \varepsilon L) dT/de$ equals −1, then $c_p dT + Ldq = 0$ in terms of specific humidity $q$ (kgkg$^{-1}$) = $w/(1+w)$, where mixing ratio $w = e \rho/(P - e)$ or $c_p dT + (\varepsilon L/P) de = 0$ are in terms of water vapour pressure $e$. Noting that an adiabatic process is defined as one in which no energy is added or removed and considering what is referred to as a pseudoadiabatic process at constant pressure (a process used in meteorology), Byers (1974) showed that $c_p dT + Ldq = 0$. Hence, since $\beta = -1$, then $c_p dT + Ldq = 0$, the conditions under which $\beta = -1$ are pseudoadiabatic and isobaric. For the application of (2) and (3), data collecting during these conditions must be identified, excluded if necessary and replaced if possible. Such pseudoadiabatic conditions are depicted on the psychrometric chart by wet-bulb temperature isolines, since for such isolines $de/dT = -\gamma$ or $d\theta = 0$. Furthermore $\beta = -1$ implies $H = -LE$ and therefore that the available energy is zero which corresponds to adiabatic conditions. Also, assuming adiabatic conditions prevail for which $H + LE = 0$ and hence $R_{\text{net}} + S = 0$ from (1), $1 + \beta = 0$ is a possibility using (2).

**Penman Monteith FAO** (Allen et al., 1998). The PMF method is a traditional and standard method. It uses terms such as i) the aerodynamic foliage resistance to relate the altitude of the meteorological instruments with the altitude of the crops, and ii) the stomatic resistance to the minimum transpiration, as a function of the type of crop and its altitude. In general terms, the following equation defines $ET_0$ as the sum of evapotranspiration by radiation, plus the aerodynamic evapotranspiration, as shown in (6):

$$ET_0 = \frac{0.408\Delta (R_n - G) + \gamma \frac{900}{T + 273} - u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)}$$  \hspace{1cm} (6)

where $\Delta$ is the slope of the curve of saturation vapour pressure in kPa°C$^{-1}$ to the mean air temperature $T$; $R_n$ is the net radiation received over the surface or field being studied in MJm$^{-2}$day$^{-1}$, which is comprised by the short wave solar radiation $R_{\text{sw}}$ minus the net long wave radiation $R_{\text{lw}}$ both in MJm$^{-2}$day$^{-1}$; $G$ is the heat flow or thermal flow from the floor in cal/m$^2$s, which was considered negligible in this study because the magnitude of the heat wave under the surface of reference is very small; $\gamma$ is the psychrometric constant in kPa°C$^{-1}$; $u_2$ is the wind speed at 2 m high in m/s; and $(e_s - e_a)$ is the deficit of vapour pressure in kPa, which is determined by the difference between the vapour pressure saturation of the air $e_a$ at temperature $T$ minus the vapour pressure of the air mass $e_s$ at a temperature $T$.**Priestley-Taylor.** This method is a simplified version of the PMF, which proposes that reference evapotranspiration for a humid surface under conditions of minimum advection, is a function of $\Delta$ and $\gamma$ of the difference between the net radiation received by the soil minus the heat flow from it ($R_n - G$), and of a non-dimensional empirical correction factor $\alpha$, which Priestly and Taylor (1972) estimated in the
range between 1.08 and 1.34, with a mean of 1.26 (value used in this study):

\[
ET_o = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G)
\] (7)

**Hargreaves-Samani.** Samani (2000) and Hargreaves and Allen (2003) developed an expression to estimate \(ET_o\) as a function of the solar radiation that reaches the ground level and the mean temperature of the air, which is defined as follows:

\[
ET_o = \beta \alpha R_n \sqrt{TD (T_{mean} + 17.8)}
\] (8)

where \(\beta\) is an adjustment coefficient of the equation, which varies according to the area where it is used; \(\alpha\) is an empirical coefficient which can be estimated as a function of the difference between the maximum and minimum daily temperature \(TD\) in °C; \(R_n\) is the net radiation received at the highest level of the atmosphere over the study area in MJ/m²day, and \(T_{mean}\) is the mean daily temperature in °C in the area analyzed. The estimation of \(\alpha\) and \(\beta\) was done using daily measures of radiation and temperature. These values were previously estimated by Mercado (2006) as \(\alpha = 0.144\) and \(\beta = 0.0124\).

**Analysis of the different methods results**

Once estimated the daily \(ET_o\) according to the methods described above and for the period 1996 – 2008, the \(ET_o\) moving averages were calculated for periods of 30, 7, and 3 days. Then the moving averages of same time frames were compared with the reference evapotranspiration series, obtained from pan evaporation data \(ET_{oB}\), and using a pan coefficient of 0.85 (Mercado, 2006), which was estimated for the zone as a constant for the year. In order to complement the analysis and validate the methods, the differences between the \(ET_o\) estimated using a particular method \(X_i\) and the \(ET_{oB}\) values \(X_o\) (used as the benchmark) were quantified. The measurements used to evaluate the differences between series were the Root Mean Squared Error RMSE and the Relative Difference RD, expressions (9) and (10) respectively.

\[
RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (X_i - X_o)^2}
\] (9)

\[
RD = \frac{RMSE}{X_o} \times 100
\] (10)

where \(N\) is the number of data within the series and \(X_o\) is the average of \(ET_{oB}\) series.

**Results and discussion**

Firstly, a graphical comparison was performed for the daily \(ET_o\) series obtained from the methods PMF, PT, and HS, with the \(ET_{oB}\) series from pan evaporation used as benchmark (Figure 1). It shows how the HS method tends to underestimate the \(ET_o\) values, especially during dry season (boreal summer, December to March). The PMF and PT methods present better results, but with a slight tendency to underestimate (PT method) and overestimate (PMF) the \(ET_o\) values. Tabari (2009) presented similar results for a cold-humid region in Iran with annual precipitation of 1359 mm and an average temperature of 16°C, similar to the zone in this study, where the author observed that the HS method was the least accurate in relation to the reference values for the study area. In addition, these results are consistent with the ones reported by Jensen et al. (1990), Amatya et al. (1995), and Trajkovic and Kolakovic (2009), where the method HS was observed and defined as deficient for humid zones.

Further insight can be obtained by examining the differences between \(ET_o\) estimated values from each method and the \(ET_{oB}\) data series quantified for different moving averages (Table 1). Additionally, for the 7-day moving average, scatter plots are shown with a linear regression analysis between \(ET_o\) and \(ET_{oB}\) for each method and for three different periods: i) the whole year, ii) the irrigation season (October-March), and iii) the humid season (April-September). On one hand, quantifying the differences using moving averages allows us to compare the methods through statistical parameters (Salas et al., 1980), while scatter plots and regression analysis allows us to evaluate the quality of the methods being studied. Therefore, precise estimations should result in a linear correlation with 1:1 slope and a high correlation coefficient, while a deficient method should vary away from the 1:1 slope and/or present a lower correlation coefficient, indicating more dispersion and uncertainty in estimations.

Table 1 shows that when increasing the time length of moving averages, the quality of ET$_o$ values improves for the three methods being studied, suggesting that the errors in the ET$_o$ estimation and the variability within the series tend to be compensated with larger temporal length of evaluation. This is logical because as the time length increases, the local effects are reduced, and the temporal variability, not included into the equations, or not measured by the instruments, is smoothed.

Table 1: Differences between estimated ET$_o$ values by different methods with the ET$_{o,B}$ for different moving averages. RMSE: Root Mean Squared Error, RD: Relative differences of the Penman Monteith – FAO PMF, Priestley-Taylor PT, and Hargreaves-Samani HS methods for estimating reference evapotranspiration.

<table>
<thead>
<tr>
<th>Mobile Mean days</th>
<th>PMF</th>
<th></th>
<th>PT</th>
<th></th>
<th>HS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMSE mm/day</td>
<td>RD %</td>
<td>RMSE mm/day</td>
<td>RD %</td>
<td>RMSE mm/day</td>
<td>RD %</td>
</tr>
<tr>
<td>30</td>
<td>1.07</td>
<td>34.7</td>
<td>1.04</td>
<td>33.8</td>
<td>1.19</td>
<td>38.8</td>
</tr>
<tr>
<td>7</td>
<td>1.22</td>
<td>39.7</td>
<td>1.01</td>
<td>32.8</td>
<td>1.36</td>
<td>44.6</td>
</tr>
<tr>
<td>3</td>
<td>1.26</td>
<td>40.9</td>
<td>1.17</td>
<td>37.9</td>
<td>1.49</td>
<td>48.3</td>
</tr>
<tr>
<td>1</td>
<td>1.47</td>
<td>47.8</td>
<td>1.41</td>
<td>46.0</td>
<td>1.67</td>
<td>54.3</td>
</tr>
</tbody>
</table>

From the analysis of values and figures of RMSE and RD, it can be concluded that the RMSE values for the HS method are the result of an underestimation of ET$_o$, becoming the model with the values that are the furthest from the benchmark. The PMF and PT methods present better goodness of fit values, but the PT model presents the smallest differences in relation to the ET$_{o,B}$ values (Table 1).

The regression analysis presented in Figure 2 reveals that the HS method underestimates the ET$_o$ for reference values above 2 mm/day, and it overestimates ET$_o$ for values below 2 mm/day (Figure 2c). Such differences are more noticeable for the humid period and slightly reduced for the irrigation period (see slope of the linear regression in Figure 2f and 2i respectively). However, the differences are still important in comparison to the ET$_{o,B}$ values. A similar behaviour, but with a slope closer to 1:1, can be observed with the PT method and for the whole period under analysis (Figure 2b). The PT method underestimates for values above 3.5 mm/day and overestimates for values below 3.5 mm/day. This trend was also reported for humid zones by George et al. (2002) and Tabari et al. (2013). On the other hand, the PMF method presents a more logic behaviour (1:1 slope), but with the disadvantage of an offset in the regression curve, indicating a tendency to overestimate the ET$_o$ values by an average of 0.8 mm (Figure 2a).
For the irrigation season the PT method appear to be better than the PMF method since the regression is more close to the 1:1 slope and lesser dispersion in the results is observed (Figure 2d and 2e). These results suggest that the PMF method is better if \( ET \) values are intended to estimate for the whole year, however if more precision is required for the irrigation season, PT seems to be more adequate. When analyzing only the determination coefficient R², it is observed that the best correlation is obtained with the HS method (Figure 2c, R² = 0.912). However, when complementing this result with the prior analysis it can be concluded that the method presents a smaller dispersion in relation to the \( ET_B \) values. In other words, this method reproduces the temporal variability in a better way than the other methods but with a higher deviation from the benchmark values, which suggests that this method is inadequate for \( ET \) estimation in the area of Chillán. Comparing the PMF and PT methods with benchmark data, it is clear that PMF presents better scores (in terms of R² and RMSE) than the PT. However, PT presents smaller relative differences. Furthermore, considering that the series of data used as benchmark contains a great number of zeroes during periods where there was no registered pan evaporation due to rain (see Figure 1 during winter seasons, and Figure 2 in the \( ET_B \) axis), there should be a deviation in the slope of the regression curves that is only observed in the PT method, making it the most representative of the evaporation processes for the Chillán area.

**Conclusions**

The comparison between PMF, PT and HS methods with the reference evapotranspiration values obtained from pan
evaporation shows that the PT and PMF methods present
the better adjustments to the reference evapotranspiration
values than the HS method for the agricultural area of
Chillán. Evaluating comparative differences between the
PMF and PT methods was observed that the PT presented
the smallest relative differences and an expected and
realistic behaviour in the $ET_o$ estimations, and moreover
showed the closest estimation of $ET_o$ values for the irrigation
season. Therefore, the PT method can be prescribed as
the most adequate for estimating $ET_o$ for the agricultural
area of Chillán. In order to obtain more precise results, it
is necessary to incorporate a correction factor to the pan
evaporation series, in particular for those periods where
the measured values were 0 mm. This problem is observed
on rainy days, where the evaporation pan registers the
difference between evaporation and precipitation instead
of the real evaporation generating values close to 0. This
alters the results, and could be observed on slopes above 1
and/or displacement of the regression curve.

Acknowledgements
The authors would like to thank to the Instituto Nacional
de Investigaciones Agropecuarias INIA-Quilamapu, and to
Dr. Octavio Lagos from the Department of Water Resources
of Universidad de Concepción, for providing the data for
this study. This project has been partially founded by the
Project CENSOR, EC-INCO-CT2004-511071.

References
evapotranspiration - Guidelines for computing crop water
requirements. FAO Irrigation and Drainage paper 56, UN-FAO,
Rome 300(9), D05109

of methods for estimating REF-ET. Journal of Irrigation and
Drainage Engineering 121(6), 427–435

Bowen, I.S. (1926). The ratio of heat losses by conduction and
by evaporation from any water surface. Physical Review 27(6),
779-787

New York

evapotranspiration under inaccurate data conditions. Irrigation
and Drainage Systems 16(1), 33-45

George, B.A., Reddy, B.R.S., Raghunwanshi, N.S. and Wallender,
W. (2002). Decision support system for estimating reference
evapotranspiration. Journal of Irrigation and Drainage
Engineering 128(1), 1–10

Hargreaves, G. and Allen, R. (2003). History and evaluation of
Hargreaves evapotranspiration equation. Journal of Irrigation
and Drainage Engineering 129(1), 53-63

cuenca del Bío Bío. Master thesis, Universidad de Concepción

Evapotranspiration and irrigation water requirements. ASCE
Manual 70:332–333

World map of the Köppen-Geiger climate classification updated.
Meteorologische Zeitschrift 15(3), 259-263

 referencia utilizando información de temperatura del aire.
Master thesis, Universidad de Concepción

Novoa, R., Villaseca, S., Del Canto, P., Rouanet, J., Sierra, C. y
Investigaciones Agropecuarias, Santiago, Chile

heat flux and evaporation using large scale parameters. Monthly
Weather Review 100(2), 81-92

of actual evapotranspiration in the field under Mediterranean
climate: a review. European Journal of Agronomy 13(2), 125–
153

Salas, J.D., Delleur, J.W., Yevjevich, V. and Lane W.L. (1980).
Applied modeling of hydrological time series. Water Resources
Publications, Michigan, USA

evapotranspiration using minimum climatological data. Journal
of Irrigation and Drainage Engineering 126(4), 265-267

micro-meteorology and Landsat imagery to monitor daily
evapotranspiration at a regional scale. Tethys 5, 37–46

Bowen ratio evaporation measurement in a remote montane
grassland: data integrity and fluxes. Journal of Hydrology
376(1), 249-260


