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Assessment of reference evapotranspiration methods in semi-arid regions: Can weather forecast data be used as alternate of ground meteorological parameters?

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Keywords: ALADIN model, Reference evapotranspiration, Semi-arid environment

1. Introduction

The Food and Agriculture Organization (FAO) recommends the use of the FAO Penman–Monteith (FAO-PM) equation for estimating reference evapotranspiration (ET₀). Makkink (Mak) and Priestley–Taylor (PT) (radiation-based) and Hargreaves–Samani (HARG) (temperature-based) were assessed in semi-arid regions. The values of ET₀ derived using these three methods were compared to those estimated using the reference FAO Penman–Monteith (FAO-PM) method under semi-arid conditions of the Tensift basin (central of Morocco) and the Yaqui Valley (Northwest Mexico). The results showed that the HARG method is the best one to estimate ET₀ over both semi-arid test sites. Conversely, the performance of the other two empirical methods was poor except under humid conditions. However, when the parameters α and Cₙ are calibrated in the PT and Mak equations are locally calibrated, the performance of these two methods greatly improved. Additionally, this study showed that, when measurements of meteorological parameters needed for estimating ET₀ (which are not always available especially in developing countries) are lacking, the climatic data generated with numerical weather prediction models provide an alternative and effective solution to estimate ET₀. In this regard, data generated using a weather forecast model (ALADIN) over the Tensift basin showed that the HARG model is the most accurate one for estimating the spatio-temporal variability of ET₀.

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in humid regions and to underestimate it in very dry regions
(Amatya et al., 1995; Droogers and Allen, 2002; Jensen et al., 1990;
Saeed, 1986; Xu and Singh, 2002). Therefore, the HARG equation
may require local calibration prior to its application (Dinpashoh,
2006; Jensen et al., 1997; Vanderlinden et al., 1999; Xu and
Singh, 2002). Makkink (1957) and Priestley and Taylor (1972)
proposed two empirical equations for calculating ET₀ when air
temperature and solar radiation data are available. The PT equa-
tion is used in many crop models (e.g. CERES model (Ritchie,
1985); EPIC (Williams et al., 1989), SWAP (Utset et al., 2004)).
Similarly, several studies have shown that this method under-
estimates ET₀ in dry and windy conditions (Benson et al., 1992;
Dugas and Ainsworth, 1983; Martinez-Cob, 2002).

When reliable climatic data are scarce or do not exist, an
alternative approach might be to use data generated with
numerical weather prediction models. These data present two
advantages: i) they are becoming more and more available
through the Internet; ii) the models provide spatially distributed
data, which are very relevant to the regional scale studies.
Unfortunately, there are two drawbacks associated with using this
type of data. The first is that, the lowest atmospheric model layer
is usually situated considerably higher than the reference height
recommended for climatic measurements. Secondly, the spatial
resolution of these models is very coarse. For example the ARPEGE
global model of Meteorological France (Déqué et al., 1994: http://
www.cnrm.meteo.fr/gnccv/arpege/arpege.html) provides the data
at a resolution of 20 km in France to 250 km in antipodes. The
local model (ALADIN: Aire Limitée, Adaptation Dynamique,
developpeement InterNational) of the Moroccan Meteorological
Agency runs with a slightly higher spatial resolution (16.7 km)
over Morocco.

The objective of this study is (1) to evaluate, under semi-arid
conditions, the performance of three empirical methods (PT, Mak
and HARG) for estimating ET₀ by comparing their values to those
estimated using the FAO-PM equation and (2) to evaluate the
potentiality of weather forecast prediction as an alternative to
measured climatic data.

2. Materials and methods

2.1. Area description and weather data

The three empirical methods (Eqs. (2)–(4)) were evaluated over
two sites described below (the Tensift region around Marrakech,
Morocco and the Yaqui Valley in the north of Mexico) against the FAO-
PM method. In addition, a weather forecast model (ALADIN) available
over the Tensift basin was used to estimate the spatial—temporal
distribution of ET₀.

2.1.1. Tensift basin

The Tensift basin situated in central of Morocco is located
between 30.75°–32.4°N and 7.05°–9.9°W, occupying an expanse
around 30 000 km². The climate is semi-arid, typically Mediterranea-
nean; with an average annual precipitation of about 250 mm. Air
temperature is very high in summer (38°C) and low in winter (5°C).
The mean annual value for ET₀, calculated using the FAO-PM equa-
tion, is about 1600 mm (Allen et al., 1998). In the Tensift basin, a large
area is dedicated to agriculture. The Haouz plain covers around
6000 km², and is delimited to the north by the ‘biolet’ hills and to the
south by the High-Atlas mountain range (that culminates up to
4000 m). Weather data sets were obtained from the 8 stations
installed in the framework of the SudMed project (Chehbouni et al.,
2008) (see Fig. 1). Locations of the stations are given in Table 1. In
addition, the aridity index defined as the ratio of the annual rainfall
to the annual ET₀ (UNEP, 1997) is calculated for each Tensift stations.
Each station measures with a 30 min time step and at a 2 m height:
air temperature, relative humidity, solar radiation, wind speed and
direction and rainfall. In some stations (Agdal, Saada and Agafay),
net radiation (Rn) was measured with a Kipp and Zonen CRN1 net
radiometer. The daily values of the meteorological variables
were used to compute daily ET₀. The network stations were deployed
in order to cover the spatial variability of the climate over the whole
Tensift basin. Based on the calculated aridity index (Table 1) during
2004, the Tensift area can be divided into two distinct climatic
regions. The first one situated in the Haouz plain characterized by

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the semi-arid climate, in which all stations (Agdal, Agafay, Chichawa, Grawa, Saada and R3) have an aridity index less than 0.2. The second region located in the Atlas mountain range, characterized by the sub-humid conditions (Okaimden and Armed stations) where the aridity index was relatively higher (0.4–0.53).

Fig. 2 shows the daily evolution of the meteorological variables recorded by the station located in R3 zone (Table 1, Fig. 1) during 2003–2004. The mean annual solar radiation is about 17 MJ/m²/day, and ranges between 4 MJ/m²/day in December–January and 28 MJ/m²/day in May–June. The seasonal variation of daily air temperature was similar — with respect to the shape — to that of solar radiation, between 5 °C in January and 36 °C in August, with an annual mean of about 18.5 °C. The evolution of relative humidity is out of phase with the solar radiation, and tends to increase in the winter and decrease in summer. Wind speed remained almost constant during the year around 2.1 m/s, but in some days its values exceeded 4 m/s. The cumulative precipitation during 2003 was 530 mm with most rain falling in the autumn and winter seasons. Note that this year was wetter in comparison with the average annual precipitation (250 mm). It should be mentioned that due to power supply problems, some data were missing during a few days.

Table 1
Weather stations used in the study.

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude (degrees)</th>
<th>Longitude (degrees)</th>
<th>Elevation (m)</th>
<th>Surface</th>
<th>Aridity index</th>
<th>Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agdal</td>
<td>31° 60'11&quot;N</td>
<td>7° 97'38&quot;W</td>
<td>506</td>
<td>Olives</td>
<td>0.2</td>
<td>Sub-humid</td>
</tr>
<tr>
<td>Agafay</td>
<td>31° 50'27&quot;N</td>
<td>8° 25'02&quot;W</td>
<td>479</td>
<td>Grass</td>
<td>0.18</td>
<td>Semi-arid</td>
</tr>
<tr>
<td>Chichawa</td>
<td>31° 44'92&quot;N</td>
<td>8° 63'75&quot;W</td>
<td>517</td>
<td>Bare soil</td>
<td>0.09</td>
<td>Semi-arid</td>
</tr>
<tr>
<td>Graoua</td>
<td>31° 58'73&quot;N</td>
<td>7° 92'07&quot;W</td>
<td>523</td>
<td>Grape</td>
<td>0.12</td>
<td>Semi-arid</td>
</tr>
<tr>
<td>Saada</td>
<td>31° 62'73&quot;N</td>
<td>8° 16'56&quot;W</td>
<td>430</td>
<td>Citrus</td>
<td>0.19</td>
<td>Semi-arid</td>
</tr>
<tr>
<td>R3</td>
<td>31° 66'74&quot;N</td>
<td>7° 59'57&quot;W</td>
<td>593</td>
<td>Bare soil</td>
<td>0.16</td>
<td>Semi-arid</td>
</tr>
<tr>
<td>Okaimden</td>
<td>31° 12'42&quot;N</td>
<td>7° 86'28&quot;W</td>
<td>3230</td>
<td>Mountain</td>
<td>0.53</td>
<td>Sub-humid</td>
</tr>
<tr>
<td>Armed</td>
<td>31° 60'11&quot;N</td>
<td>7° 92'07&quot;W</td>
<td>2050</td>
<td>Mountain</td>
<td>0.40</td>
<td>Sub-humid</td>
</tr>
</tbody>
</table>

a Degrees, minutes and seconds.

b The aridity index was calculated as the ratio of annual rainfall to annual ET0.
c Some natural vegetation may be present especially in the winter.
d The snow is present in the winter.

d The semi-arid climate, in which all stations (Agdal, Agafay, Chichawa, Grawa, Saada and R3) have an aridity index less than 0.2. The second region located in the Atlas mountain range, characterized by the sub-humid conditions (Okaimden and Armed stations) where the aridity index was relatively higher (0.4–0.53).

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2.1.2. The forecasted climatic data from the ALADIN model (Morocco)

When the meteorological parameters needed for estimating spatially ET0 are not available due to the scarcity of weather stations, it is possible to use the climatic data generated over a large area with the numerical weather prediction models. The numerical model used in this study is the ALADIN model adapted by the national meteorological services of Morocco (DMN) which generates all climatic parameters needed for ET0 estimate. ALADIN is a spectral model of numerical forecast in a limited area, based on the assimilation of daily measurements, and driven using the outputs of the ARPEGE global model (provided by French meteorological services). ARPEGE is an operational tool in the limited area modelling in Central Europe, and it is also used in several other regions (Morocco and Tunisia). The global model (ARPEGE) provides the data at resolution of 20 km in France to 250 km in antipodes, while the local model (ALADIN) is running at a higher spatial resolution (16.7 km) over Morocco. The ALADIN model over Morocco is named AL BACHIR and its main characteristics are:

- Spectral model with elliptical truncation.
- Horizontal resolution: 16.7 km.
- Vertical resolution: 37 levels.
- Hydrostatic dynamic.
function and $T_{\text{max}}$ and $T_{\text{min}}$ are the daily maximum and minimum air temperature respectively. The value 0.408 corresponds to the conversion factor from [MJ/m$^2$/day] to mm/day. The parameters $\alpha$, $C_a$ and $a$ that appear in Eqs. (2)–(4), respectively, are empirical constants. Their original values are 1.26, 0.61 and 0.0023 respectively (Allen et al., 1998; Makkink, 1957; McAneny and Itier, 1996; Priestley and Taylor, 1972).

2.3. Statistical analysis

The comparison between the three empirical methods (Eqs. (2)–(4)) and the FAO-Penman–Monteith method was carried out first using ground data. The comparison is evaluated using: (1) a linear regression equation ($Y = mX + c$), through least square regression, between ET$_0$ computed by FAO Penman–Monteith equation and ET$_0$ estimated from the above mentioned three methods ($m$ and $c$ are the slope and the intercept of the regression equation, respectively); (2) the coefficient of determination ($R^2$); (3) the Root Mean Square Error (RMSE). In the case of a perfect correlation with no bias, $c = 0$ and $m = 1$, $R^2 = 1$ and RMSE = 0.

3. Results and discussions

3.1. Evaluation of predicted and measured climatic data accuracy over Tensift

The accuracy and quality of the measured weather data is evaluated over Tensift as the weather station network is quite dense (8 stations) with regard to the Yaqui Valley. The quality of meteorological measurement is simply evaluated by checking the overall consistency of the annual average of the climatic parameters (solar radiation, wind speed, air temperature and relative humidity) among different stations. Table 2 summarizes the annual average of the climatic variables over the 8 stations. The measurements appear consistent and coherent among different stations. Regarding to air temperature ($T_a$), the higher values are recorded in the Haouz plain (Agdal, Agafay, Chichaoua, Grawa, Saada and R3) characterized by a semi-arid climate and the lower $T_a$ is observed in the mountains (Okaimden and Armed). For relative humidity (RH), it is higher over irrigated areas (e.g. Agdal and Agafay stations) due to high evapotranspiration than in dry areas (mountain and bare soil). The measurements of wind speed ($U$) are also consistent between different stations. The lower $U$ is encountered in the locations affected by the surrounding. The friction tends to decrease the wind as in the stations installed in tall vegetation (e.g. Agdal where the olive trees dominate). The higher $U$ is observed in the opened locations as the mountain (ouakime- den) and bare soil (R3, Chichaoua). For solar radiation ($R_i$), it is almost similar for all stations with a mean annual value of 19 MJ/m$^2$/day. Additionally, the performance of solar radiation measurements is evaluated by comparing the measured net radiation (R$_{\text{net}}$) against the estimated one (R$_{\text{sim}}$) from FAO-56 (Eq. (40)). Fig. 3 displays the scatter plot between measured and FAO-predicted $R_{\text{net}}$ over the stations where the measurements of $R_{\text{net}}$ are available. This figure reveals a very good agreement (slope = 0.96, with $R^2 = 0.94$ and RMSE = 1.09 MJ/m$^2$/day) between the measured and FAO-predicted $R_{\text{net}}$. In addition, the coefficient of variability (CV) defined as the ratio of the standard deviation to the mean value is calculated for each climatic parameter. It was equal 3.66, 31, 8.35 and 35.8% for $R_{\text{net}}$, $T_a$, $T_h$ and $U$, respectively. Clearly, variation in $U$ and $T_h$ was larger than that in $R_{\text{net}}$ and $T_a$.

As the measured weather data, the predicted ones by ALADIN were also evaluated before using them for estimating the spatial ET$_0$. The quality of the ALADIN prediction in generating weather variables is evaluated by comparing the estimated climatic
Table 2: Annual average of climatic parameters among the stations of study.

<table>
<thead>
<tr>
<th>Station</th>
<th>Annual average of $R_a$ (MJ/m$^2$/day)</th>
<th>Annual average of $T_a$ (°C)</th>
<th>Annual average of RH (%)</th>
<th>Annual average of $U$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agdal</td>
<td>18.74</td>
<td>19.46</td>
<td>60.20</td>
<td>0.80</td>
</tr>
<tr>
<td>Agafay</td>
<td>19.30</td>
<td>18.24</td>
<td>60.07</td>
<td>1.06</td>
</tr>
<tr>
<td>Chichaoua</td>
<td>20.55</td>
<td>18.01</td>
<td>59.20</td>
<td>2.07</td>
</tr>
<tr>
<td>Goaza</td>
<td>19.35</td>
<td>18.99</td>
<td>58.76</td>
<td>1.35</td>
</tr>
<tr>
<td>Saada</td>
<td>18.05</td>
<td>19.69</td>
<td>52.21</td>
<td>1.48</td>
</tr>
<tr>
<td>R3</td>
<td>18.67</td>
<td>20.51</td>
<td>45.59</td>
<td>2.22</td>
</tr>
<tr>
<td>Okaimden</td>
<td>19.61</td>
<td>4.61</td>
<td>56.59</td>
<td>1.23</td>
</tr>
<tr>
<td>Armed</td>
<td>18.83</td>
<td>11.18</td>
<td>56.19</td>
<td>2.53</td>
</tr>
<tr>
<td>Max</td>
<td>20.55</td>
<td>20.51</td>
<td>60.20</td>
<td>2.53</td>
</tr>
<tr>
<td>Min</td>
<td>18.05</td>
<td>4.61</td>
<td>45.59</td>
<td>0.80</td>
</tr>
<tr>
<td>Mean</td>
<td>19.14</td>
<td>16.34</td>
<td>56.04</td>
<td>1.59</td>
</tr>
<tr>
<td>CV (%)</td>
<td>3.66</td>
<td>31.00</td>
<td>35.90</td>
<td>35.90</td>
</tr>
</tbody>
</table>

$R_a$: solar radiation (MJ/m$^2$/day); $T_a$: air temperature (°C); RH: relative humidity (%); $U$: wind speed (m/s).
CV: coefficient of variability (%) defined as the ratio of the standard deviation to the mean value.

3.2. Assessment of $ET_0$ estimation methods

As mentioned above, the evaluation of the three methods (Eqs. (2)–(4)) is undertaken through the comparison with the FAO-PM equation. This evaluation was performed in two stages. In the first stage, $ET_0$ from the three empirical methods was computed with the original parameter values given above. In the second stage, $ET_0$ was computed with locally calibrated parameter values. Based on the above conditions, the Tensift study area can be divided into a semi-arid climate region (the Haouz plain) and a semi-humid climate region (the Atlas mountains). Two sites considered to be representative of each sub-region were chosen to assess the performance of the three empirical methods. The first one is R3 which characterized the semi-arid climate in the Haouz plain. The second one is Armed situated in the Atlas mountain range, characterized by the sub-humid conditions (see Fig. 1 and Table 1).

3.2.1. Assessment of the method performances without calibration

Using the data collected in the year 2003 in the Haouz plain (station R3), daily evolution of $ET_0$ values was calculated using the three empirical methods (Eqs. (2)–(4)). These values were then compared with those obtained using the FAO-PM method (Fig. 4). The statistical results are reported in Table 4. According to these results, the HARG method seems to be the best one to calculate $ET_0$ in the Haouz plain (semi-arid climate). The coefficient of determination ($R^2$) and the slope are close to 1 and the value of RMSE = 0.67 mm/day can be also considered acceptable with regard to the average value of $ET_0 = 4.10$ mm, especially during the representative between the ground station data and the ALADIN forecast grid point.

Fig. 3. Scatter plot between measured net radiation ($R_n$-mes) and estimated one ($R_n$-sim) by FAO-56 (Eq. (40)).
summer (Fig. 4). This is in agreement with other studies (e.g. Hargreaves, 1994; Henggeler et al., 1996; Jensen et al., 1990).

However, on some dates (DOY 71, March 12, 2003; DOY 263, September 20), a large difference between \(ET_0\) estimated by HARG and FAO-PM methods was observed. This is certainly due to the effect of wind speed which exceeded 3 m/s on these days (Fig. 2). Indeed, Martínez-Cob and Tejero-Juste (2004) reported that when the wind speed is strong, the Hargreaves equation could underestimate \(ET_0\). In the same way, Berengena and Gavilán (2005) showed that, when the advection is severe, the Hargreaves equation tends to underestimate \(ET_0\) up to 25% for daily periods.

In contrast to HARG model, the performance of the two other methods (PT and Mak) was poor, the corresponding RMSE were 1.30 and 1.52 mm/day for PT and Mak, respectively (see Table 4 for other statistical analysis). However, Fig. 4 indicates that two distinct periods should be considered when using these methods, a dry period (when the daily mean air relative humidity is lower than 70%) from DOY 140 to DOY 270 and the humid period (when RH is higher than 70%) for the remaining days. It appears that the PT and Mak methods clearly underestimate the values of \(ET_0\) calculated using FAO-PM model during the dry period. Such behaviour can be explained by the fact that the values of \(\alpha = 1.26\) and \(C_m = 0.61\), used in Eqs. (2) and (3), are only valid under humid conditions (Jensen et al., 1990; Priestley and Taylor, 1972). This explanation is confirmed by the results of the second period (when the cumulative rainfall was about 470 mm). The statistical values (RMSE) is equal to 0.97 mm/day for the PT method and 0.98 mm/day for the Mak) are consistent with those obtained for the HARG method. This is corroborated by other studies (e.g. Benson et al., 1992; Dugas and Ainsworth, 1983; Xiaoying and Erda, 2005).

To confirm the reliability of PT and Mak models for estimating daily \(ET_0\) with original parameter values (\(\alpha = 1.26\) and \(C_m = 0.61\)) under sub-humid conditions, a comparison with the FAO-PM method is performed using climatic data collected in a sub-humid region situated in the high-Atlas mountain (Armed station, Table 1 and Fig. 1). Plotting daily values of \(ET_0\) estimated by FAO-PM against those estimated by both methods at this region (data not presented) revealed practically perfect agreement between the FAO-PM and the estimates from the two other methods. The values of RMSE are 0.65 and 0.59 mm/day for the PT and Mak methods respectively. These values of RMSE are acceptable, given the average value of \(ET_0\) (3.22 mm). Additional statistical results are presented in Table 4. The performance of the Hargreaves approach was lower in sub-humid conditions (RMSE = 0.83 mm/day) in comparison to the other methods. This is consistent with the results of other studies (Jensen et al., 1990; Xu and Singh, 2002) when they found that the HARG method tends to overestimate \(ET_0\) in a humid climate.

According to the above results, one can conclude that it is appropriate to use the HARG method without calibration to estimate \(ET_0\) in a semi-arid region (as far as the wind remains low). However, a calibration of two parameters (\(\alpha\) and \(C_m\)) in the PT and Mak equations is needed, especially for the dry periods.

### Table 4

<table>
<thead>
<tr>
<th>Statistics parameters</th>
<th>DOY 140–270</th>
<th>DOY 270–360</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE (mm/day)</td>
<td>1.30</td>
<td>1.52</td>
</tr>
<tr>
<td>(R^2)</td>
<td>0.97</td>
<td>0.98</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>1.26</td>
<td>1.26</td>
</tr>
<tr>
<td>(C_m)</td>
<td>0.61</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Fig. 4. Comparison between daily \(ET_0\) computed by the FAO-PM model against those obtained by the three empirical methods (PT, Mak and HARG), with their original parameter values at two regions in the Tensift basin: semi-arid (R3 station) and sub-humid (Armed station).

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\( \alpha = 0.014 \text{RH} + 2.33 \quad R^2 = 0.98 \) \hfill (5)

It can be noted that this equation estimates \( \alpha = 1.26 \) when daily mean RH = 76% and \( \alpha = 1.74 \) when RH = 42%. This indicates that the calibration of \( \alpha \) (Eq. (5)) could be applied in many areas depending on the climate (arid, humid...).

Similarly, the Makkink constant \( C_m \) was adjusted by a linear regression to (RH):

\[ C_m = -0.0062 \text{RH} + 1.15 \quad R^2 = 0.96 \] \hfill (6)

This calibration of the Makkink constant \( C_m \) is similar to that done by Doorenbos and Pruitt (1977), where their Radiation method of FAO-24 was multiplied by a correction that was based on RH and on daytime wind speed.

After the calibration of two parameters \( \alpha \) and \( C_m \), the RMSE was reduced to 0.70 and 0.60 mm/day (Table 5) for the PT and Mak...
methods respectively. This means an improvement of 46% and 60% of the values obtained with respect to the original values of $\alpha$ and $C_m$ (Table 4).

3.2.2.2. Model validation. The data collected during 2004 from the experimental site of the Haouz plain (R3 station) were used together with additional data set collected over the experimental site of the Yaqui Valley (Northwest Mexico) for model validation purposes.

By using the calibrated parameters (Eqs. (5) and (6)) and the original value (0.0023) of the parameter $\alpha$, daily values of $E_{T0}$ calculated by the PT, Mak and HARG models are compared to those obtained by the FAO-PM method. The performance of each method is shown for the Haouz plain in Fig. 5, as well as the associated statistical parameters. As shown in the previous paragraph, the HARG method always presents the best agreement to the FAO results. The coefficient of determination ($R^2$) and the slope are close to 1, the value of RMSE = 0.70 mm/day can be also considered very acceptable with respect to average value of $E_{T0}$ (5.07 mm) (Fig. 5).

Also both calibrated methods (PT and Mak) estimate $E_{T0}$ with an acceptable accuracy, the values of RMSE are 1.02 and 1.17 mm/day respectively for the PT and Mak methods. In some days (DOYs 180-183, 206-209, 234-237 and 253-254), the values of $E_{T0}$ obtained by the three methods are lower than those of FAO-PM method. This was due to the high values of wind speed which exceeded 3 m/s on these days (see Fig. 2), which lead to high values for the aerodynamic term (advection) that is one of the main differences between the FAO-PM method and other empirical equations (Berengena and Gavilan, 2005).

For the Yaqui Valley site (Fig. 6), the validation also provides an accuracy estimate of $E_{T0}$ by three models. The obtained values of RMSE, 0.79, 0.80 and 0.76 mm/day for the PT, Mak and HARG methods respectively, are considered relatively acceptable with regard to the average value of $E_{T0}$ which reached about 5.17 mm/day (Fig. 6). Also the HARG method is the best one to estimate $E_{T0}$ over this other semi-arid region.

According to these results, it can be concluded that the HARG model is the most reliable method for estimating $E_{T0}$ over both semi-arid test sites (Tensift basin and the Yaqui Valley) when the availability of climatic variable is limited and when wind speed not exceeded 3 m/s.

3.3. Spatially distributed modelling of $E_{T0}$

The spatial variation of $E_{T0}$ over the Tensift region is analyzed thanks to the ALADIN model forecast data. The good performance of the HARG model at the local scale together with the accurate estimation of air temperature by the ALADIN model, which is the main input of the HARG method, lead us to choose this model for estimating the spatial distribution of $E_{T0}$ with regard to the Mak and PT methods. In addition, the spatial estimation of $E_{T0}$ by the HARG model is compared to the FAO-PM method using ground based measurements of climatic parameters. Indeed, the FAO-PM is expected to be penalized by the strong discrepancy between ALADIN forecast and measured climatic data in terms of wind and air humidity.

Fig. 7 shows the cumulative monthly $E_{T0}$ (mm/month) maps for the whole Tensift basin by applying the HARG model to each grid point of the ALADIN model from January to December 2004. This figure exhibits a coherent spatial and temporal variation of $E_{T0}$. Temporally, the $E_{T0}$ appears to be highest in the summer (June—August), ranging from 45 to 230 mm/month during the peak period for air temperature, and the smallest $E_{T0}$ in November-January (16-68 mm/month). Spatially, the higher $E_{T0}$ is observed in the low altitude (like Haouz plain), and lower $E_{T0}$ is encountered in the mountain when the altitude is high and air temperature is low. It should be mentioned that lower values of $E_{T0}$
are observed over the mountain in winter when the snow covering is high and precludes from evaporation. Such maps of ET0 could be used by decision makers to assist in water management and irrigation scheduling at regional scale.

In order to go further in the evaluation of the spatial distribution of ET0 predicted by the HARG model, the HARG ET0 is compared to ET0 calculated by the FAO-PM method from the meteorological data measured by the weather stations for 12 months at the eight stations (Table 1) with the spatially modelled results for the corresponding months at the corresponding equivalent grid points (Fig. 8). The associated statistical parameters are included in this figure. It should be mentioned that due to power supply problems, some data of ET0 estimated by FAO-PM were missing in some days and the data during the corresponding month were not available. The coefficient of determination ($R^2 = 0.92$) and the slope (1.09) are close to 1. The value of RMSE = 16.01 mm/month can be also considered acceptable relative to the mean values of cumulative monthly ET0 (120 mm/month). It is clear from Fig. 8 that the correlation is best when the monthly value of ET0 was below 160 mm. When the monthly ET0 was above this value, the HARG method underestimates ET0 similarly to the local scale evaluation of the method. As already stated above, this is certainly due to the advection term that is not taken into account in the HARG model.

Finally, the FAO-PM method is run using the model forecast data. The scatter plot between ET0 calculated by the FAO-PM method from the measured meteorological data and the calculated one using the forecast data (not shown) revealed practically an overestimation of ET0 by the FAO-PM method with regard to the HARG method together with a strong scattering on the stations where the difference between measured and generated climatic parameters is high. For information, the statistical characteristics of the linear fit are as follows: slope = 1.10, intercept = -17.42, $R^2 = 0.85$ and RMSE = 21 mm/month. By comparing those relevant statistical parameters with those obtained when using HARG method (Fig. 8), it is clear that this latter performs best although its simplicity. A good performance of the HARG method over the studied semi-arid sites has been expected, because it was originally developed for semi-arid environments. Several studies have shown that the HARG method provides good estimates of ET0 under semi-arid conditions in different countries, as done by Vanderlinden et al. (1999), Martinez-Cob and Tejero-Juste (2004), and Berengena and Gavilan (2005) in Spain, by Dinapashoh (2006) for Iran, and by Jensen et al. (1990), Choisy et al. (1992), Hargreaves (1994) and Henggeler et al. (1996) for different locations.

As a conclusion, HARG method provides a simple yet robust alternative to the complex, physically-based, FAO-PM method when the availability of climatic variables is limited and in particular, concerning the wind speed.

4. Summary and conclusions

The FAO-PM equation has a sound physical background and has proven to accurately estimate ET0. Nevertheless, a drawback which limits its widespread use is that it requires measurements of several meteorological variables: air temperature and relative humidity, solar radiation and wind speed. The lack of the availability of these variables in most parts of the world has led to the development of simpler ET0 estimation equations requiring only a few climatic variables which are most likely to be available worldwide. In this context, the main objectives of this paper were to test, calibrate and validate, in semi-arid regions of central Morocco (Tensift basin) and Northwest Mexico (Yaqui Valley), three methods computing ET0 based on solar radiation (PT and Mak) and temperature (HARG) against the standard FAO-PM method.

The results showed that the HARG method, with its standard constant value (0.0023), worked quite well under moderate wind conditions (<3 m/s) while the performance of the other two empirical methods was poor except in humid conditions. A local calibration of the two parameters $\alpha$ and $C_0$, which appear respectively in the PT and Mak equations is needed especially for the dry periods.

Air relative humidity (RH) appeared to affect the accuracy of the PT and Mak equations. An adjustment of two parameters $\alpha$ and $C_0$ with RH by using the data collected in the semi-arid region of Tensift basin was proposed. Thus, the original coefficients 1.26 and 0.61 should be replaced by a linear regression with RH (Eqs. (5) and (6)). These locally adjusted coefficients produced a significant improvement in the equations performance. The Root Mean Square Error (RMSE) was reduced to 0.70 and 0.60 mm/day for the PT and Mak methods respectively, which meant an improvement of 46% and 60% compared to the values obtained without calibration (1.30 and 1.52 mm/day). A further validation of the adjusted coefficients $\alpha$ and $C_0$ was performed using another semi-arid site in the Yaqui Valley (Northwest Mexico) where the estimates of ET0 produced by these methods were found to be very reliable.

To overcome the difficulty associated with the scarcity of weather stations measuring the needed meteorological parameters for ET0 estimates, the possibility of using climatic data generated with numerical weather prediction model (ALADIN) has been assessed over the Tensift basin. The evaluation of the quality of this model in generating weather variables showed that the ALADIN model estimates accurately air temperature, which is the main input of the HARG method. This leads us to choose this method for estimating the spatial and temporal distribution of ET0. This approach is of particular interest since it not only allowed us to overcome the problem of the lack of weather data, but it also able to predict water needs with a forecast lead time of few days, which is of great importance for irrigation water managers. Another interest of this research paper consists of identifying which the most reliable method for estimating ET0 can be used in hydrological models. This will certainly improve the performance of this type of models as reported by Oudin et al. (2005) when they showed that the lumped rainfall-runoff model works well in simulating streamflow when using a simple temperature-based ET0 instead of the Penman-type model.

Finally, it should be noted that this study was based on a limited data set. Further study including longer series of climatic data is.
desirable for considering climate variability and for improving the reliability of the proposed calibrations.

However, it should be noted that this study was based on the analysis of a limited data set. A more comprehensive study, including longer series of data, is advisable to improve the reliability of the proposed calibrations.

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