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Estimating reference evapotranspiration under inaccurate data conditions

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Abstract. Reference evapotranspiration (ET_0) estimates have been computed on a global scale using a high-resolution monthly climate dataset. Penman-Monteith (PM) and Hargreaves (HG) methods have been compared, showing very reasonable agreement between the two methods. Fitting the two parameters of HG using the PM derived ET_0 values did not improve estimates by the HG method substantially. Modifying the original Hargreaves method to a Modified-Hargreaves (MH) method by including a rainfall term improved ET_0 estimates significantly for arid regions. When a certain level of inaccuracy in the meteorological observations was assumed, calculating ET_0 by PM and MH, given these inaccuracy in observations, showed that MH performed better than PM in reproducing original calculations of ET_0 as calculated by PM assuming no data error. It is concluded that the PM is a recommended methodology if accurate weather data collection can be expected, but otherwise MH should be considered.

Key words: evapotranspiration, Hargreaves, Penman-Monteith, reference ET

Introduction

Estimates of reference evapotranspiration (ET_0) are widely used in irrigation engineering to define crop water requirements. These estimates are used in the planning process for irrigation schemes to be developed as well as to manage water distribution in existing schemes. From the several existing ET_0 equations, the FAO-56 application of the Penman-Monteith equation (Allen et al. 1998) is currently widely used and can be considered as a sort of standard (Walter et al. 2000). The FAO-56 Penman-Monteith equation is referred to hereafter as PM. The PM has two advantages over many other methods. First of all, it is a predominately physically based approach, indicating that the method can be used globally without any need for additional parameter estimations. Secondly, the method is well documented, implemented in a wide range of software, and has been tested using a variety of lysimeters.

A major drawback to application of the PM, however, is the relatively high data demand, where the method requires air temperature, windspeed, relative humidity, and solar radiation data. The number of meteorological stations where all of these parameters are observed is limited in many areas of the globe. The number of stations where *reliable* data for these parameters exist is an even smaller subset. This is especially true in developing countries where reliable collection of windspeed, humidity, and radiation is limited. Allen et al. (1998) placed considerable emphasis and effort in describing alternative ways to estimate solar radiation and humidity data required for PM using simpler or fewer measurements. However accuracy of wind measurements continues to be difficult to assess and vapor pressure of air is difficult to measure accurately without modern electronic instrumentation.

The limitation of reliable data motivated Hargreaves et al. (1985) to develop an alternative approach where only mean maximum and mean minimum air temperature and extraterrestrial radiation are required (the 1985 Hargreaves method is referred to hereafter as HG). Because extraterrestrial radiation can be calculated for a certain day and location, only minimum and maximum temperatures are the parameters that require observation. The HG method has been tested using some high quality lysimeter data representing a broad range in climatological conditions (Hargreaves 1994). The results have indicated that this equation was nearly as accurate as PM in estimating ET_0 on a weekly or longer timestep, and was therefore recommended in cases where reliable data were lacking. However, it is possible that accuracy of this equation can be improved by adjusting the parameters to local conditions. Allen et al. (1998) and Temesgen et al. (1999) have indicated that high humidity conditions may result in an overestimation by HG of ET_0 and that conditions with high windspeed may result in an underestimation of ET_0.

Recently, a high resolution World Climate Atlas was developed (New et al. 2001) with data represented on a 16 km grid, that includes precipitation, air temperature, air temperature range (i.e., daily maximum – daily minimum), relative humidity, sunshine hours, wind speed, number of rainy-days, and number of frost-days. Data represent monthly means. The Atlas dataset represents an excellent source for comparing ET_0 estimates as it includes all available climatic conditions around the world. So far, most comparisons of different ET_0 methods have been based on local or national climatic datasets, preventing results and conclusions from being universally applicable.

The effect of the accuracy of the observed meteorological parameters on the ET_0 estimates is a reason for concern, especially for the PM with its relatively high data demand. A relevant question might be whether more realistic ET_0 estimates can be obtained by using a simplified approach such as the HG than with PM given a certain level of inaccuracy in the meteorological observations.

In summary, the objectives of this study are: (i) to compare global estimates of reference evapotranspiration using Penman-Monteith and Hargreaves, (ii) update the Hargreaves method using a global climate data set, and (iii) estimate the sensitivity of both methods to deviations in meteorological measurements.

Methods and materials

Global climate dataset

A relatively high spatial resolution global climate dataset was recently presented by the International Water Management Institute (IWMI 2000). This dataset includes precipitation, temperature, daily temperature range, relative humidity, hours of sunshine, wind speed, number of rain days, and, number of frost-days. These parameters are available on a mean monthly basis, describing average conditions over the last 30 years. The spatial resolution is 10 minutes-Arc (about 16 km at equator). The dataset has been developed using observations from about 56,000 stations around the world from the last 30 years. These stations were predominately temperature stations with measurements of humidity, sunshine and wind speed available on a sparser grid. These data were cleaned and gridded to monthly average values to a resolution of 10 minutes-Arc using a spline gridding methodology. A more detailed description of the dataset and its development is found in New et al. (2001).

The database has been compared with selected stations from the well-known Climwat database (Smith 1993) and deviations were found to be negligible for daily minimum and maximum temperature ($r^2 > 0.98$), low for precipitation and humidity ($r^2 \approx 0.90$) (Droogers 2000). However, deviations were found to be high for wind speed ($r^2 = 0.50$). The IWMI database is currently the most extensive global climate database in terms of resolution, coverage and number of parameters. The dataset is in the public domain and can be ordered or downloaded from the Internet (IWMI 2000).

The IWMI dataset is considered to be an excellent source of information to compare different ET_0 estimates, as the range in variation in climatological conditions is large, while the spatial resolution is much higher than other global datasets used in climate change studies.

Reference evapotranspiration

The concept of reference evapotranspiration has been used for decades (Doorenbos & Pruitt 1977), and has been discussed widely (Pereira et al.

1999). Allen et al., (1994) introduced a clear definition of ET_0 based on PM and a well defined hypothetical reference crop which is now being widely accepted and used by a broad audience ranging from researchers to practitioners. This hypothetical reference crop has a crop height of 0.12 m, a canopy resistance of 70 s m^{-1}, and an albedo of 0.23.

As mentioned, the lack of reliable meteorological data brought Hargreaves et al. (1985) and Hargreaves (1994) to a derived function that is based on only mean daily maximum and mean daily minimum temperature:

$$ET_0 = 0.0023 \cdot 0.408RA \cdot (T_{avg} + 17.8) \cdot TD^{0.5} \tag{1}$$

where *RA* is extraterrestrial radiation expressed in (MJ m^{-2} d^{-1}), T_{avg} is average daily temperature (°C) defined as the average of the mean daily maximum and mean daily minimum temperature, and *TD* (°C) is the temperature range, computed as the difference between mean daily maximum and mean daily minimum temperature. The constant 0.408 is used to convert the radiation to evaporation equivalents in mm. RA can be obtained from tables (Hargreaves 1994), equations (Allen et al. 1998) or computer software (Droogers 2000). The two other parameters, 0.0023 and 17.8, were obtained by Hargreaves et al. (1985) by fitting measured ET_0 values to Equation (1). The validity of this equation was tested and improved during this study using data from the IWMI Climate Atlas.

The potential for errors in meteorological observations

One of the most important reasons for advocating a simpler method than PM is the substantial likelihood for inaccuracy in weather data measurement and collection, especially for developing countries and meteorological stations managed by non-experts. In these situations, accuracy of data and especially of more advanced parameters such as radiation and humidity, can be very low. Table 1 shows data requirements for PM, HG, and the hereafter described Modified Hargreaves (MH) with estimates of error ranges (95% confidence intervals, i.e. 2 standard deviations) for measurement errors for average conditions in developing countries. Obviously, no detailed information on the accuracy is available, but standard deviations represented in Table 1 were discussed with specialists having extensive experience in observing meteorological parameters, especially in developing countries.

Inaccuracies in data were introduced into the PM and MH equations by assuming a normal distribution with a mean as observed value and 2× standard deviation as represented in Table 1, resulting in a 95% confidence interval. The numerical approach used was similar to that by Coleman & DeCoursey (1976) and Camillo & Gurney (1984). For each land pixel, month, and para-

Table 1. Data requirements for the ET_0 methods applied and assumed range of measurement errors for a 95% confidence interval (2 Std. Dev.) in developing countries expressed as °C or as a percentage of the mean value. PM is Penman-Monteith, HG is Hargreaves and MH is Modified Hargreaves.

	PM	HG	MH	2 × Std Dev
MinTemp	√	√	√	1°C (∼5%)
MaxTemp	√	√	√	1°C (∼5%)
Humidity	√			25%
Windspeed	√			25%
Radiation	√			25%
Precipitation			√	10%

meter, a random value was taken from this normal distribution. The PM and MH equations were applied to each land grid point of the global atlas.

Considering the PM values from the Climate Atlas as reference values, deviations from these values for PM as well as HM were analyzed when the given inaccuracies in observations were included. In practical terms, the question is: given a situation were a low accuracy in measurements is expected, would it be better to apply PM or HM?

Results

Hargreaves ET_0

Annual ET_0 using PM are shown in Figure 1. The general trend of having regions with the highest ET_0 around the tropics of Cancer and Capricorn and intermediate values beyond and between these regions was observed. Predicted ET_0 for these regions ranges upward to values of 3000 mm y^{-1}. Values of 1000 mm y^{-1} and lower were found at latitudes beyond 40° N and 40° S.

Monthly values of ET_0 using PM were compared to values obtained using HG. Figure 2 (top) shows the annual average difference between PM and HG. HG tends to underestimate PM largely in the very dry regions and to overestimate PM in the very wet regions. A scatter plot shows that this deviation occurs primarily for the higher ET_0 values (Figure 3). The root mean square difference, RMSD, between the two estimates, defined as:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N}(Pen_i - Harg_i)^2}{N}} \tag{2}$$

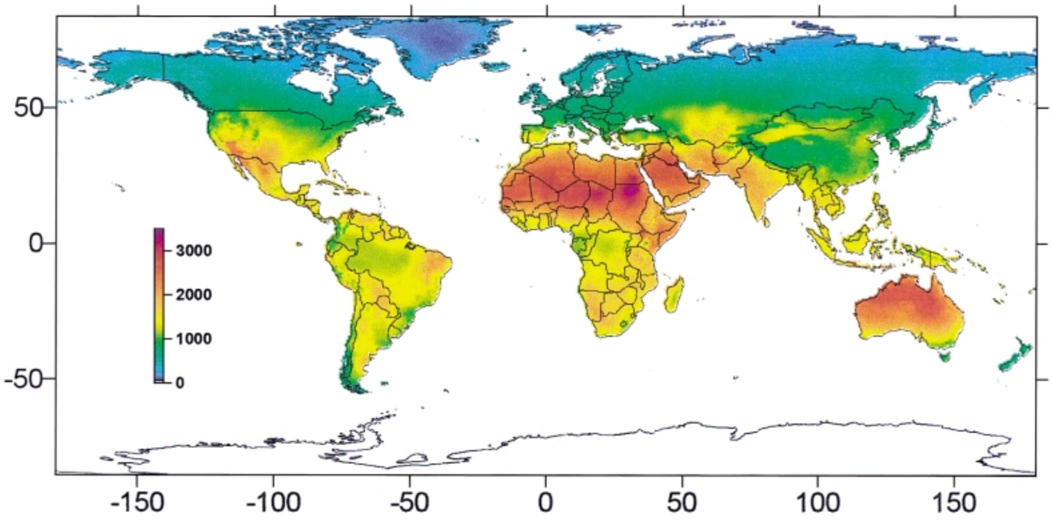

Figure 1. Annual ET_0 (mm d^{-1}) as calculated using FAO-56 Penman-Monteith using IWMI's Climate Atlas.

and correlation coefficient r^2 values are shown in Table 2.

Allen (1993) attempted to improve upon Eq. 1 by fitting coefficients based on monthly calculations of ET_0 by the PM using the FAO Climwat data set (Smith 1993) comprised of 3200 stations and using lysimeter measurements of ET_0 from Davis, California. The result was the following form for the HG:

$$ET_0 = 0.0030 \cdot 0.408RA \cdot (T_{avg} + 20) \cdot TD^{0.4} \tag{3}$$

However, the improvement in accuracy of this form of the HG relative to the PM was less than 3% and Allen (1993) recommended retention of the original form (i.e., Eq. 1).

Table 2. Comparison between Penman-Monteith (PM) and Hargreaves (HG) for the original HG, the original HG with fitted parameters, and the modified HG. a, b, c, and d are multiplier and offset parameters as used in the HG and MH equations.

	R^2	RMSD	ET_0 (mm d^{-1})	a	b	c	d
Hargreaves	0.895	0.81	2.86	0.0023	17.8		
Hargreaves fitted	0.895	0.79	3.00	0.0025	16.8		
Modified Hargreaves	0.927	0.67	2.96	0.0013	17.0	– 0.0123	0.76

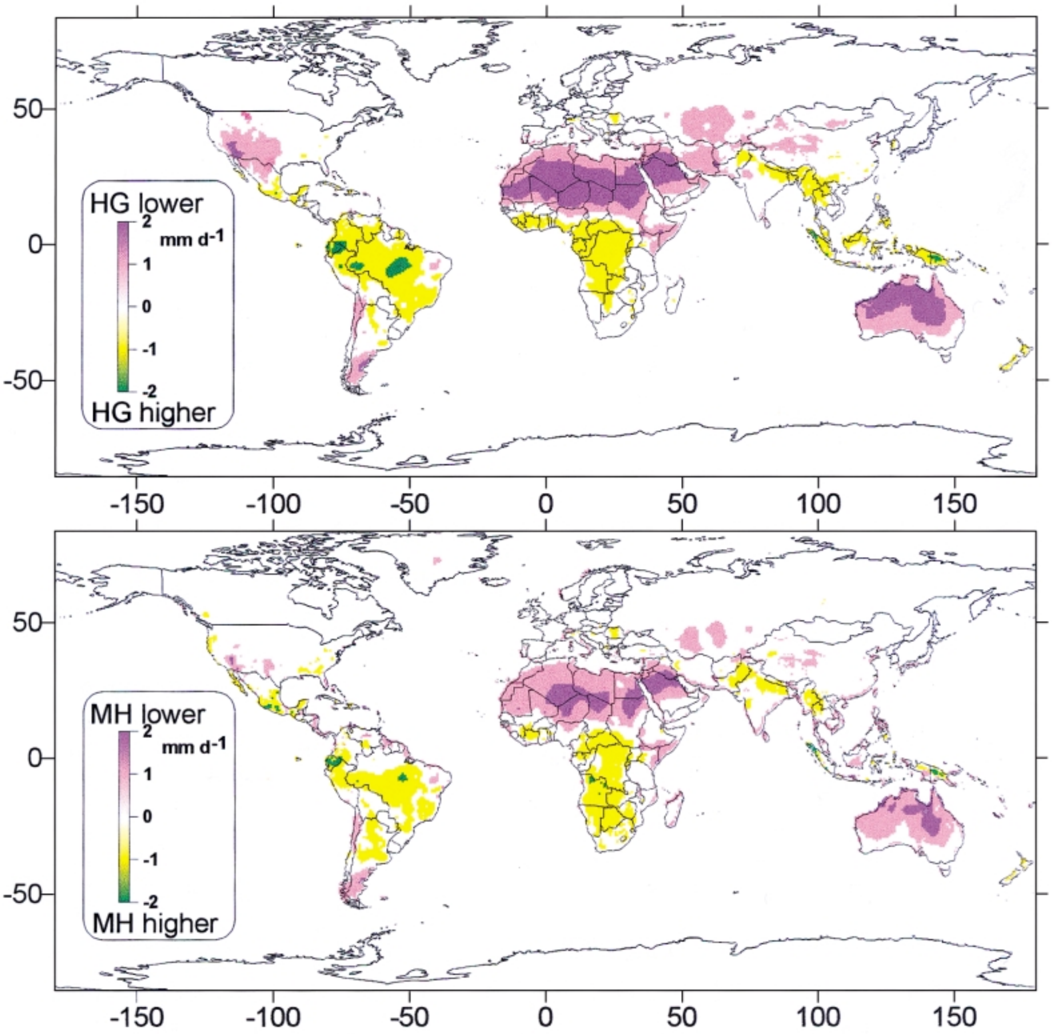

Figure 2. Difference between annual ET_0 estimates using FAO-56 Penman-Monteith and Hargraves (HG) and Modified Hargreaves (MH).

A second attempt was made during this study to improve the agreement of the HG with the PM using the IWMI Climate Atlas data grids. Comparisons around the globe using the grid were used to adjust two parameters in the original HG equation, resulting in:

$$ET_0 = 0.0025 \cdot 0.408RA \cdot (T_{avg} + 16.8) \cdot TD^{0.5} \qquad (4)$$

Although r^2 and RMSD values improved with Equation (4) (Table 2), ET_0 in humid areas was still overpredicted relative to the PM. Adding a humidity

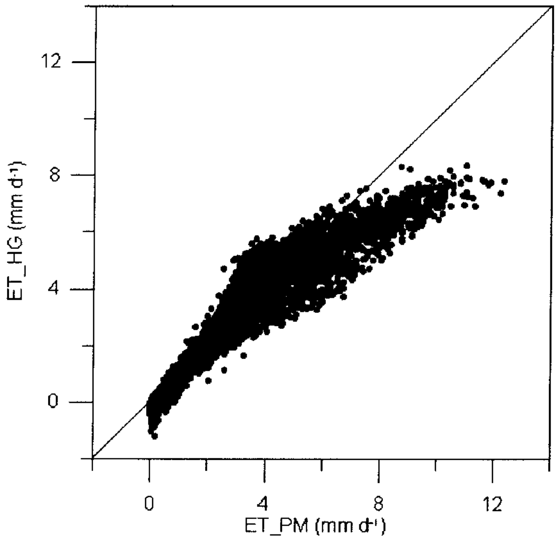

Figure 3. Scatter plot of the difference between monthly ET_0 estimates using Penman-Monteith (PM) and Hargreaves (HG). A random 0.1% of the total points for each month are plotted.

term to Equation (4) would have resulted in a substantially better fit of the HG to the PM, but reliable measurements of relative humidity are often lacking. Allen (1993) similarly developed a wind function for Equation (1) that improved its agreement with the PM and with the Davis lysimeter, but the function was not encouraged due to the scarcity of accurate wind data around the globe. Furthermore, one can make the argument that if quality wind or humidity data are available, that one should use the PM method.

During the current study, monthly precipitation was added to the HG equation, considering that the observations of precipitation are collected at a reasonably reliable level for a majority of meteorological stations around the world, and with the assumption that monthly precipitation can in some regards represent relative levels of humidity. After testing various combinations based on Equation (1), the following equation was derived for application with monthly data:

$$ET_0 = 0.0013 \cdot 0.408RA \cdot (T_{avg} + 17.0) \cdot (TD - 0.0123P)^{0.76} \qquad (5)$$

where P is precipitation in mm per month. This equation, termed the modified Hargreaves (MH), was better able to reproduce ET_0 as calculated using the PM in situations were weather data availability is limited (Table 2). A scatter plot (Figure 4) shows a substantial improvement in agreement with the PM, especially for higher values of ET_0. Figure 2 shows that the deviations for the

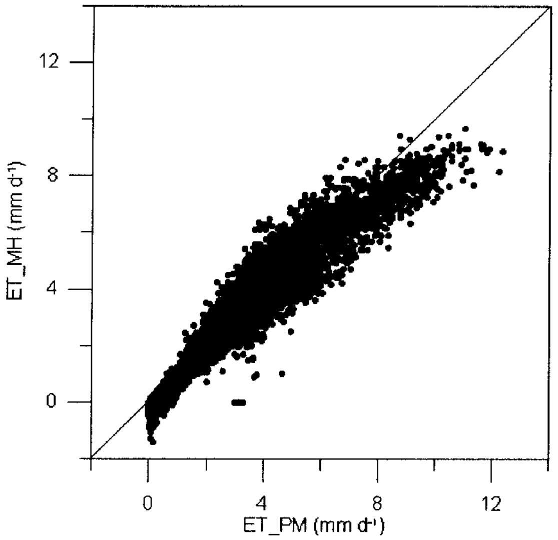

Figure 4. Scatter plot of the difference between monthly ET_0 estimates using Penman-Monteith (PM) and the Modified Hargreaves (MH). A random 0.1% of the total points for each month are plotted.

MH are smaller for the dry areas (for example, Sahara and Australia) and for very wet areas (for example, Amazon basin) in comparison to estimates made using the original HG.

Accuracy

The assumed measurement errors given in Table 1 were introduced into the IWMI data base for all global grid points by adding the 2 × Std.Dev. values multiplied by a randomly generated normal variate (z(0,1)). Deviations of PM and MH calculations with these errors were summarized based on PM values made without the introduced errors. Results are presented in Table 3 and as scatter plots in Figure 5. The globally averaged daily ET_0 using PM with introduced measurement errors was similar to the PM without introduced errors (3.0 mm d^{-1}), which is expected, while the values for MH with introduced data errors were slightly lower (2.9 mm d^{-1}). The deviation of the PM with introduced error from the PM without error was relatively constant over the whole range of ET_0 values (Figure 5, top), and tended toward overestimation in the higher ranges of ET_0. The RMSD for all values was 0.93 mm d^{-1}, or 30% of the mean ET_0, over the globe. This indicates that the sensitivity coefficient to all weather parameters, when errors are introduced corporately, is about 0.3 for the globe, based on the Std.Dev. values expressed

Table 3. Effect of data measurement errors on Penman-Monteith (PM) and the Modified Hargreaves (MH) as compared to the standard ET_0 as calculated using PM without introduced measurement errors. The ET_o is the global average daily reference ET.

	R^2	RMSD ($mm\ d^{-1}$)	ET_0
Penman Monteith	0.871	0.93	3.00
Modified Hargreaves	0.915	0.72	2.90

in Table 1. Sensitivity coefficient is defined as the ratio of the change in ET_o given change in a data parameter.

The MH with introduced measurement errors was less sensitive to inaccuracies in measurements, since the inaccuracies occurred only in maximum and minimum air temperature and precipitation. This was especially in the lower ranges of ET_0 (Figure 5, bottom). In contrast to the PM with introduced error, the MH tended to underestimate ET_0 values in the higher ranges, similar to the MH with no introduced error (Figure 4). The RMSD values in Table 3 represent a 95% confidence interval about mean ET_0 as predicted by the FAO-56 Penman-Monteith method with no introduced weather measurement error.

The results imply that for situations where accuracy in weather measurements is expected to be low, it may be better to opt for using a limited data set, or to implement limited data collection of only maximum and minimum temperature and precipitation, than to attempt to establish a full meteorological station. With the reduced data set, one can apply the MH equation to simulate ET_0 as predicted by the PM method.

Conclusions

A global climatic dataset was applied here as a useful tool for comparing different methods to estimate ET_0 under all existing climatic conditions on the globe. A drawback to this approach is that the “real” ET_0 is unknown and can only be obtained using lysimeters or other precision measuring devices. However, numerous studies have been performed using lysimeter data and have shown, in most cases, the PM to be the best method for estimating ET_0.

This study has assumed that the PM can be used to represent a standard for ET_0 estimates, which is true in terms of practical applications found around the world. However, concerns exist on the accuracy of PM under arid conditions, especially under conditions where the meteorological data originate

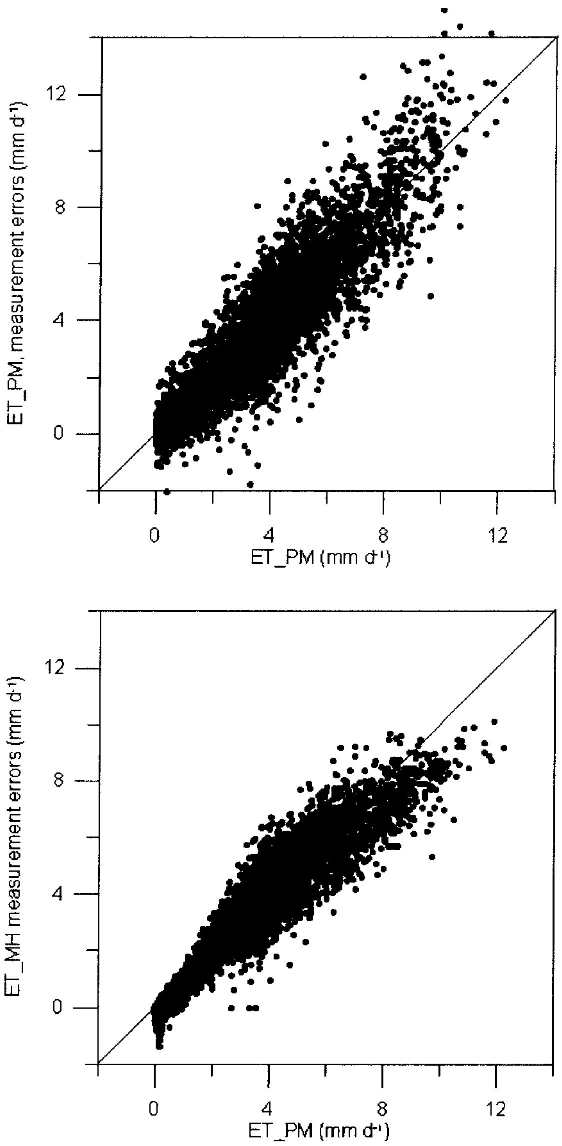

Figure 5. Scatter plot of the difference between monthly ET_0 estimates using PM without measurement errors and PM with errors (top) and MH with measurement errors (bottom). A random 0.1% of the total points for each month are plotted.

from environments that have insufficient water supply to support ET_0 (dry), but where the ET_0 estimates are to represent water use under well-watered conditions. This topic is not addressed here, and the PM was used with the worldwide data set with no adjustment.

The performance of HG and especially MH for monthly ET_0calculation is remarkable in comparison to PM. The very low data demand of MH and reasonable reproduction of estimates by the physically based PM makes the MH attractive when inaccuracy in weather measurements is common. MH may perform even better than PM under conditions of substantial data error (RMSE = 0.72 mm d^{-1} vs. 0.93 mm d^{-1}). Updating the parameters in the original HG method did not improve the ET_0 estimates much, but the inclusion of the additional rainfall term made the MH a reasonably accurate substitute for the PM for reproducing monthly ET_0.

The errors in meteorological observations included here are assumed to be random errors rather than systematic errors. In practice, it is expected that many errors will be systematic, making the situation even more favorable to MH.

Finally, we would like to emphasize that the PM remains the most desirable method for computing ET_0, if accuracy of data collection is considered to be good, especially since the MH is a regression function derived from the PM. But in many cases, especially in developing countries where accurate data collection is difficult, the consideration of MH is encouraged, rather than attempting to setup a complex weather data collection system. Alternatively, the PM can be used with solar radiation and humidity estimated from temperature data and estimates of mean wind speed, according to recommendations in FAO-56 (Allen et al. 1998; Annandale 2001) or using these secondary data from the IWMI global data set.

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