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Estimating reference crop evapotranspiration in New Zealand

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Abstract

Evapotranspiration data are needed for soil water balance calculations and irrigation scheduling. The approach recommended by the Food and Agriculture Organization of the United Nations (FAO) for estimating evapotranspiration from pastures and agricultural crops is becoming widely adopted. It uses a standardised version of the Penman-Monteith equation to find the reference crop evapotranspiration (E_0). The reference crop is an extensive area of short, green, relatively flat vegetation adequately supplied with water. Pasture in New Zealand commonly fits that description. Average monthly E_0 values are given for 16 sites. January values range from 5.1 mm/day in Blenheim to 3.3 mm/day in Hokitika, while July values range from 1.3 mm/day in Tauranga to 0.3 mm/day in Alexandra. The FAO-56 values for winter are about 0.3 mm/day higher than earlier published Penman values, while the summer values are about 0.3 mm/day lower.

Estimating E_0 requires values for solar radiation, air temperature, vapour pressure and wind speed. For Palmerston North in spring and summer the solar radiation and air temperature are the most critical weather inputs for estimating E_0, but in winter the wind speed is the most important. When full daily weather data are not available, the vapour pressure can be estimated from the minimum air temperature. Estimating the solar radiation from the difference between the maximum and minimum air temperatures is not recommended. When neither daily solar radiation nor sunshine hour data are available for a nearby site in the same climate zone, long-term average E_0 values for the area will probably be accurate enough for most water balance calculations, and for irrigation scheduling.

Introduction

There are many uses for a soil water balance: two of the commonest are for the design and management of irrigation systems and for modelling pasture production (Woodward *et al.*, 2001). The key requirements for a soil water balance are rainfall and evapotranspiration data. Rainfall is easy to measure, but hard to estimate from surrogate measurements. Conversely, monitoring evapotranspiration is so hard that measurements are obtained only for research purposes, however it is often possible to estimate evapotranspiration from weather data. This paper concerns such estimates.

Following extensive consultation under the auspices of the Food and Agriculture Organization of the United Nations (FAO), Allen *et al.* (1998) have published comprehensive guidelines for estimating crop evapotranspiration from weather data, as FAO Irrigation and Drainage Paper 56 (subsequently referred to as FAO-56). They define a new standard reference crop evapotranspiration (E_o), which can be modified by various coefficients where necessary to take into account different growth stages and ecological conditions. However this approach is not suitable for forests, which behave in quite a different way to the reference crop (Kelliher and Scotter, 1992). Allen *et al.* use the Penman-Monteith combination "big leaf" approach to obtain E_o, and assume that the hypothetical reference crop has a height of 0.12 m, a surface resistance of 70 s m^{-1}, and an albedo of 0.23. The surface resistance indicates how readily water vapour escapes from the crop, while the albedo is the fraction of incoming solar energy reflected by the crop. The reference crop fits the description of a "short green crop, completely shading the ground, of uniform height, and never short of water" referred to in Penman's (1956) definition of potential evapotranspiration. Most pastures in New Zealand also behave like the hypothetical reference crop for most of the year. The FAO-56 version of the Penman-Monteith equation for the daily reference crop evaporation (E_o) in mm d^{-1} is

$$E_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (1)$$

where R_n is the net radiation (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}), T is the average air temperature at 2 m height (°C), u_2 is the average wind speed at 2 m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), Δ is the slope of the saturated vapour pressure-temperature curve (kPa $°C^{-1}$) and γ is the psychrometric constant (kPa $°C^{-1}$). The net radiation is the difference between the incoming radiation, and what is reflected and re-radiated back to the atmosphere. The soil heat flux density is the energy going to warm the soil; it is negative if the soil is cooling. A number of other equations are needed to find E_o from standard meteorological data, for example the ones connecting R_n and the incoming solar radiation, and for estimating the wind speed at 2 m from measurements at another height. These equations are not given here, as FAO-56 is readily available, both in print and on the internet.

It is evident from equation (1) that quite extensive weather data are needed to calculate E_o at a certain location on a certain day. Values for the maximum and minimum air temperature, the vapour pressure, the solar radiation or number of sunshine hours, and the average wind speed at 2 m are required. It is recognized in FAO-56 that such detailed data are often not available. In such situations they do not recommend the use of simpler equations needing fewer data, such as the Priestley and Taylor (1972) or Thornthwaite (1948) equations. Rather they recommend that the FAO-56 version of the Penman-Monteith equation be used with estimated rather than measured values of the unknown weather variables. They also suggest techniques for obtaining such estimates, but comment that the techniques need to be locally calibrated and verified.

This paper gives average monthly E_o values for a number of New Zealand sites. We examine the sensitivity of E_o values to day-to-day variability in each of the required weather inputs. We then check and calibrate the approximations suggested in FAO-56 for estimating the solar radiation and vapour pressure when just maximum and minimum air temperature data are available. Lastly we suggest how best to estimate E_o when weather data are not available for the site and time period of interest.

Average monthly evaporation

Average monthly values for the FAO-56 reference crop evaporation (E_o) at 16 New Zealand locations are shown in Table 1. These 16 locations were chosen to be representative

Table 1 – Average monthly FAO-56 evaporation for a range of New Zealand sites. The symbol * indicates solar radiation data were available. Sunshine hour data were used to estimate solar radiation at the other sites. 'A' stands for Airport.

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Kaitaia A *	133	109	97	67	49	36	39	47	63	86	101	125	951
Whenuapai A*	126	105	92	59	40	30	33	41	57	82	100	119	884
Hamilton (Rukuhia) *	127	108	92	61	40	30	32	43	58	81	102	120	893
Tauranga A	141	116	101	69	46	35	40	47	66	92	113	132	999
Rotorua A *	133	109	93	62	41	29	32	41	60	87	107	125	918
Gisborne A *	141	111	93	62	46	36	37	46	66	93	120	136	987
New Plymouth A	121	103	89	64	46	36	38	45	57	78	93	114	884
Napier	142	112	96	63	43	31	32	43	66	97	119	136	978
Masterton (Waingawa)	133	107	86	53	32	24	24	35	55	83	103	123	857
Palmerston North	123	103	86	55	35	24	25	37	53	77	97	116	831
Blenheim	158	130	108	73	47	35	36	48	73	103	125	146	1080
Hokitika A *	101	84	70	45	32	27	28	38	48	67	86	101	727
Lincoln	133	107	85	53	34	25	25	36	57	90	109	128	881
Alexandra *	131	104	81	43	21	11	10	23	50	84	110	129	795
Dunedin A *	117	93	78	53	39	26	27	40	59	85	101	116	832
Invercargill A *	104	85	69	45	33	22	23	35	52	75	90	107	741

of the main agricultural regions. The E_0 values were calculated using climatological data from the New Zealand Meteorological Service (1983).

For nine of the locations in Table 1, solar radiation data were available. For the other seven locations sunshine hour data were used to calculate solar radiation, using the equation

$$R_s = (a_s + b_s \frac{n}{N}) R_a \qquad (2)$$

where R_s is the solar radiation (MJ m^{-2} d^{-1}), a_s and b_s are dimensionless regression constants, n is the duration of sunshine (h), N is the maximum possible duration of sunshine (h), and R_a is the extraterrestrial radiation (MJ m^{-2} d^{-1}). Values of 0.25 for a_s and 0.54 for b_s for New Zealand were taken from de Lisle (1966). These values are close to the default values of 0.25 and 0.50 given in FAO-56 for use where local calibration is not available. Equation (43) in FAO-56 was used to estimate the monthly soil heat flux. Equation (2) assumes relatively flat land. On hill country, slope and aspect need to be taken into account to estimate the solar radiation received.

The highest monthly E_0 value is 158 mm for Blenheim in January, and the lowest is 10 mm for Alexandra in July. The high January value for Blenheim is due to a combination of high sunshine hours, and a relatively large vapour pressure deficit. The low July value in Alexandra occurs because of the unusually low average wind speed of 0.5 m s^{-1}.

The numbers in Table 1 invite a further question. What sort of year-to-year variation is there in the evaporation for each month? To investigate this, twelve years of daily E_0 values were calculated for January, July and October for Palmerston North and are given in Table 2. The coefficients of variation for the monthly E_0 values were 8% for January and October and 14% for July. Given the average coefficient of variation for monthly rainfall in Palmerston North is 50% (New Zealand Meteorological Service, 1979), this illustrates how much less variable the reference evapotranspiration is than the rainfall.

Also of interest is how the FAO-56 Penman-Monteith E_o values compare with evapotranspiration estimates found using earlier versions of the Penman equation. Coulter (1973) gives some values, and a more extensive data set is given in New Zealand Meteorological Service (1986). The FAO-56 values for winter are typically about 10 mm/month higher than the earlier values, while the summer values are about 10 mm/month lower.

Sensitivity analysis

Before considering how best to estimate E_o when not all the required input data are available, the sensitivity of E_o to the weather variables of solar radiation, vapour pressure, wind speed and air temperature needs to be considered. There is a problem here, as these variables are not independent. For example, as is shown in Figure 2 below, the daily minimum temperature is strongly correlated with the dew point, and thus the vapour pressure. The approach taken was to find the correlation between the daily values for each of the weather variables and E_o over 12 years during the months of January, July and October in Palmerston North. The R^2 values, along with the means and standard deviations of the variables, are given in Table 2. All the R^2 values are significant at the 1% level, except for the correlation with wind in January and October, and with vapour pressure in July.

Table 2 – Correlation between FAO-56 E_o and weather variables in Palmerston North for January, July and October for the 12 years from 1989 to 2000. Also given are the means and standard deviations of the variables.

Month	Variable	mean	s.d.	R^2 with E_o
January	E_o (mm d^{-1})	3.9	1.0	–
	R_s (MJ m^{-2} d^{-1})	21.8	6.7	0.75
	e_a (kPa)	1.6	0.3	0.04
	u_2 (m s^{-1})	2.4	1.1	0.00
	T_{max} (°C)	22.3	2.9	0.18
July	E_o (mm d^{-1})	0.8	0.3	–
	R_s (MJ m^{-2} d^{-1})	6.3	2.4	0.01
	e_a (kPa)	1.0	0.2	0.00
	u_2 (m s^{-1})	1.7	1.1	0.24
	T_{max} (°C)	12.8	2.0	0.05
October	E_o (mm d^{-1})	2.6	0.7	–
	R_s (MJ m^{-2} d^{-1})	16.1	5.8	0.72
	e_a (kPa)	1.2	0.2	0.02
	u_2 (m s^{-1})	2.3	1.2	0.01
	T_{max} (°C)	16.9	2.4	0.21

If we consider solar radiation (R_s) first, E_o is much more sensitive to this variable than to any other in January and October. This is because most of the energy for evaporation is coming directly from solar radiation in spring and summer, so the first term in the numerator of equation (1) is larger than the second term. In contrast, in July the day-to-day variation in evaporation is only weakly dependent on variation in solar radiation. There are two reasons for this. Firstly, in New Zealand in winter, the second term in the numerator of equation (1) dominates, presumably because more energy for evaporation comes via advection from the surrounding ocean than comes directly from solar radiation. Secondly, the day-to-day variation in the incoming short-wave radiation due to variable cloudiness is largely balanced by a corresponding variation in the long-wave back radiation. So varying the solar radiation has little effect on the computed net radiation in winter.

The day-to-day variation in E_o was not strongly correlated with the vapour pressure (e_a) in any of the three months. For July, this lack of significant correlation was due to counterbalancing effects. In July there is a positive correlation between e_a and the net radiation (through its effect on the long-wave back radiation), and the positive indirect effect of this on E_o roughly balanced the negative direct effect of an increase in e_a in equation (1).

Folklore has evaporation highly dependent on wind speed. While the evaporation from taller vegetation such as forest is affected by wind, particularly when the foliage is wet (Thom and Oliver, 1977), Table 2 shows that wind speed (u_2) was not significantly correlated with the FAO-56 estimates of the reference crop evaporation in Palmerston North in January or October. Wind speed appears in both the numerator and denominator of equation (1) and the magnitudes of the other variables were such that it affected both similarly, so its influence was largely cancelled out. The effect of wind speed on E_0 was highly significant in July however, when the second term in the numerator dominated. It can also be significant in summer in regions such as Canterbury and Hawkes Bay, which are prone to the föhn effect and advection from the prevailing westerly wind, as shown below.

Day-to-day variation in E_0 was more strongly correlated with the maximum temperature than the minimum or mean temperatures, so this is the variable given in Table 2. Except in July, it was the second most important variable after solar radiation. Together, solar radiation and maximum temperature accounted for nearly all the day-to-day variation in E_0, given these two variables were only weakly correlated with each other. This observation is consistent with the finding by Clothier *et al.* (1982) that in the Manawatu the Priestley and Taylor equation, calculated from just the measured air temperature and net radiation, was as accurate as the Penman (1956) equation, which required vapour pressure and wind speed data as well.

The Priestley-Taylor equation may not be as accurate in environments that are less humid than the Manawatu. For example, for an average January day at Lincoln in Canterbury, equation (1) gives an E_0 value of 4.3 mm d^{-1} and the Priestley-Taylor equation gives a similar value of 4.5 mm d^{-1}. But if all the weather variables remain the same except for the maximum temperature, which is increased by a hot westerly from the average value of 22.1°C to the average January maximum of 31.2°C, the E_0 value calculated with equation (1) increases by 49% to 6.4 mm d^{-1}, while the Priestley-Taylor value increases by only 9% to 4.9 mm d^{-1}. If on the day with the 31.2°C maximum the wind speed is double the average January value, equation (1) gives an E_0 value of 8.0 mm d^{-1}, 86% higher than the average value, even though the solar radiation and vapour pressure still have average values.

Estimating solar radiation

Where neither solar radiation nor sunshine hour data are available for the site, or for one nearby, FAO-56 recommends the use of Hargreaves' radiation formula

$$R_s = k(T_{\max} - T_{\min})^{1/2} R_a \qquad (3)$$

where k is an adjustment coefficient (°$C^{-1/2}$), $T_{\max}$ is the maximum air temperature, $T_{\min}$ is the minimum air temperature, and R_a is the extraterrestrial radiation (MJ m^{-2} d^{-1}). The authors comment that k is about 0.16 for interior locations, and about 0.19 for coastal locations where the thermal mass of the sea buffers the diurnal temperature oscillation. Equation (3) is based on the fact that, other things being equal, higher daytime temperatures and lower night time temperatures occur when clear skies allow both more short-wave radiation in during the day and more long-wave radiation out at night.

In Table 3 the k values are given for the same sixteen sites as in Table 1. The values show little seasonal variation, so only the average value is given for each site. The site with the highest k value of 0.185°$C^{-1/2}$ is New Plymouth Aerodrome. This is not surprising as it is situated right by the sea, is exposed to the prevailing westerly, and is also the windiest site (Table 3). The lowest k

Table 3 – Average values for k in equation (2), the difference between the dew point and minimum screen temperatures, wind speed at 2 m height, and the constants in equation (5) for a range of New Zealand sites. Means for the 16 sites are also given. 'A' stands for Airport.

Site	k (°C$^{-1/2}$)	$T_{\mathrm{dew}}-T_{\mathrm{min}}$ (°C)	u_2 (m s^{-1})	a_c (mm d^{-1})	b_c (mm d^{-1})
Kaitaia A	0.177	0.9	3.2	2.61	1.50
Whenuapai A	0.170	2.0	2.7	2.42	1.55
Hamilton (Rukuia)	0.158	1.6	2.4	2.45	1.57
Tauranga A	0.172	1.4	3.5	2.35	2.27
Rotorua A	0.167	1.6	2.6	2.52	1.66
Gisborne A	0.150	1.2	2.9	2.70	1.71
New Plymouth A	0.185	1.2	4.1	2.42	1.34
Napier	0.175	-0.2	1.8	2.69	1.82
Masterton (Waingawa)	0.149	2.3	2.0	2.35	1.75
Palmerston North	0.163	0.9	2.3	2.28	1.59
Blenheim	0.170	0.2	3.3	2.96	1.97
Hokitika A	0.155	1.0	2.3	1.99	1.22
Lincoln	0.156	0.9	2.7	2.42	1.78
Alexandra	0.140	-0.3	1.0	2.18	2.04
Dunedin A	0.137	0.9	2.7	2.28	1.49
Invercargill A	0.152	1.2	2.7	2.03	1.37
Mean	0.162	1.0	2.6	2.43	1.66

values of 0.137 and 0.140°C$^{-1/2}$ were found for Dunedin and Alexandra.

To see how much of the day-to-day variation in solar radiation could be explained by the variation in the diurnal temperature range, measured values of R_s/R_a as a function of the square root of the daily temperature range for a year in Palmerston North are shown in Figure 1. While the correlation is significant at the 1% level, only 23% of the day-to-day variation in solar radiation is explained by variation in the square root of the diurnal temperature range, much less than the 72% explained by the variation in the daily ratio of actual to clear-sky sunshine hours. Allen *et al.* (1998) comment that equation (3) is suitable only when daily values are summed for periods of a week or more. They also comment that the equation is not appropriate for islands, due to the moderating effects of the surrounding ocean. It seems that, in this respect, New Zealand tends to behave like a group of islands, making equation (3) of limited use.

Estimating vapour pressure

When reliable vapour pressure data are not available, FAO-56 recommends assuming that the dew point temperature (T_{dew}) is near T_{min} in humid environments. The basis for this assumption is that once the vegetation cools to the dew point it tends to remain at that temperature, as further energy lost as long-wave radiation is then provided by latent heat from condensation, rather than by sensible heat from further cooling.

Table 3 shows that the above assumption is reasonable at the 16 sites, with the dew

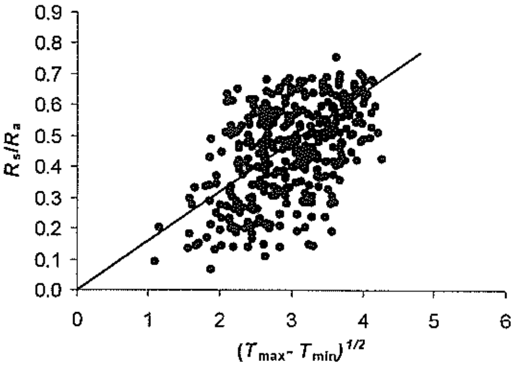

Figure 1 – Daily values from 1 June 2001 to 31 May 2002 for Palmerston North showing the correlation between R_s/R_a and the square root of the daily temperature range. $R^2 = 0.23$. The line is equation (2) with $k = 0.16$.

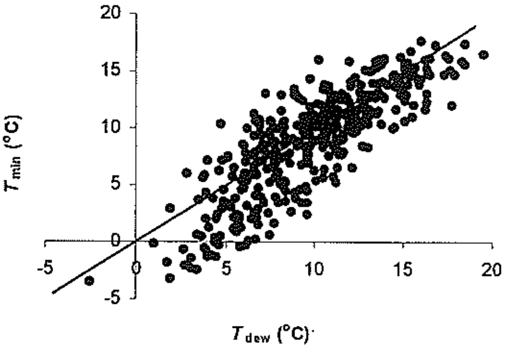

Figure 2 – Daily values from 1 June 2001 to 31 May 2002 for Palmerston North showing the correlation between the dew point temperature and the minimum temperature. $R^2 = 0.68$. Also shown is the 1:1 line.

point being on average one degree higher than the minimum temperature. Alexandra, the most arid of the sites, differs most from the average. There the dew point was on average 0.3°C lower than T_{min}, and 1.4 degrees lower in summer. Apparently the humidity there is often too low for dew point to be reached. Averages can of course be misleading. Figure 2 shows a year's values of T_{dew} and T_{min} for Palmerston North (Grasslands). While the correlation between the two temperatures is strong ($R^2 = 0.68$), and the regression equation of

$$T_{min} = 1.02\ T_{dew} - 1.1 \qquad (4)$$

supports the assumption of the dew point being about a degree above T_{min}, there is considerable scatter in the data.

Estimating wind speed

In places like Palmerston North, which is close to the west coast and the large thermal mass of the Tasman Sea, the prevailing westerly wind has a moderating effect on air temperature. For the period from 1 June 2001 to 31 May 2002 there was in fact a significant negative correlation between daily wind run and $(T_{max} - T_{min})^{1/2}$, with $R^2 = 0.09$. However this correlation is not high enough to make the use of variable daily estimates of u_2 inferred from air temperature data worthwhile in E_0 calculations. So where daily wind data are not available, we suggest using a long-term average value for the month of interest from a nearby site. Alternatively, the average value of 2.6 m s^{-1} from Table 3 could be used, although this will result in a poor description of the day-to-day variation in E_0 in winter.

Estimating E_0 when input data are missing

Three possible strategies come to mind for estimating E_0 when some, or even all, of the required daily weather data are not available for the site and period of interest. The first strategy is to use E_0 from a nearby site with a similar average annual rainfall and air temperature; the second is to calculate E_0 using what limited data are available at the site of interest and to estimate the missing weather data; and the third strategy is to use long-term averages for E_0 at the site of interest or at a similar site.

Examination of Table 1 suggests that the first strategy, of using E_0 calculated for a site subject to the same weather patterns and not too far away, is a sound approach. Examples of such paired sites would be Whenuapai and Hamilton, and Napier and Gisborne, where the corresponding average monthly E_0 values are within a few mm of each other. Where full weather data are available for a suitable adjacent site, this would seem to be the best of the three strategies.

The second strategy, of calculating E_0 using the limited data available and estimating the missing weather data, as suggested in FAO-56, has its limitations. Solar radiation cannot be reliably inferred, and in summer it is the critical input. Thus accurate daily estimates cannot be obtained. But for irrigation scheduling and pasture growth modelling, the cumulative evapotranspiration over a period of about 10 days (a common interval between irrigations) is more important than the individual daily values. Figure 3 shows the relationship between the E_0 values estimated from the full-data FAO-56 approach, and the low-data approach using just T_{max} and T_{min}, for the 36 ten-day periods in the year 2000 for Palmerston North.

The full-data FAO-56 E_0 values in Figure 3 were found using measured sunshine hour, vapour pressure, wind speed and air temperature data. The low-data E_0 solar radiation values were found using equation (3), assuming $k = 0.16$. The vapour pressure was estimated by assuming the dew point was a degree higher than T_{min}. A constant value of 2.5 m/s was assumed for the wind speed. Agreement between the full FAO-56 and the low-data values is close. The maximum discrepancy between the two estimates is 6 mm, and the average discrepancy is 2 mm.

The third strategy is to ignore day-to-day variations in E_0 and to use long-term averages for E_0 at the site of interest. Woodward *et al.* (2001) propose the simple empirical equation

$$E_0 = a_c + b_c \cos(2\pi d / 365) \qquad (5)$$

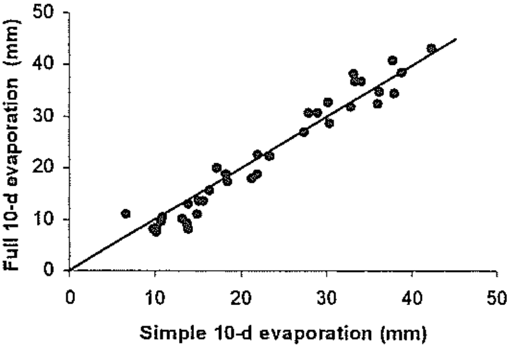

Figure 3 – The correlation between the FAO-56 Penman-Monteith evaporation for Palmerston North in 2000 computed for 10-day periods using a full set of daily weather data, and computed using just air temperature data. Also shown is the 1:1 line. $R^2 = 0.95$.

where a_c and b_c are constants with units of mm d^{-1}, and d is the Julian day of the year. Table 3 gives values for the empirical constants at each of the 16 sites, found using least-squares optimisation and the data in Table 1. The average values for a_c and b_c of 2.43 mm d^{-1} and 1.66 m d^{-1} respectively are very close to the values of 2.43 and 1.56 mm d^{-1} found by Woodward *et al.* (2001), using just one year of weather data for 8 sites, only two of which were the same as the ones in Tables 1 and 3. It is reassuring that such similar constants are found independently using data for different sites and different years.

Woodward *et al.* (2001) found no significant difference between the empirical constants in equation (5) for their 8 sites with one year of data for each. However we did find some significant differences, for example between the values for Blenheim and Invercargill. This is probably due to the greater consistency in the long-term average values for weather parameters used to derive the E_o values in Table 1, in comparison to the values for just a single year at each site used by Woodward *et al.* in deriving the values of their constants.

Figure 4 shows the success of the third strategy, using long-term averages for E_o, for Palmerston North in 2000. Using equation (5) to find E_o was just as successful as using the much more complex second strategy ($R^2 = 0.95$ in both cases). To check that this result was not just a function of the particular year chosen, the same analysis was made for 1999, and the same result was found, with the same R^2 value. It appears that little useful information about year-to-year variation in E_o can be inferred from just daily air temperature data. So if only air temperature data are available for the site of interest, strategies one or three are the preferred options.

It remains to consider if the estimates of E_o using either estimates of any missing weather data or using long-term averages for E_o at the site of interest, are accurate enough for practical use in water balances and for irrigation scheduling. Differences in catch between plastic and copper rain gauges, and between rain gauges at ground level and 300 mm above it, are about 5% (Scotter *et al.*, 1979), which in Palmerston North translates to an average uncertainty of 1.4 mm in the 10-day rainfall. If irrigation is applied, its spatial non-uniformity will induce even greater uncertainty. Thus the uncertainty inherent in rainfall and irrigation data is similar or greater in magnitude to the uncertainty in the estimates of E_o obtained using the second and third strategies and shown in Figures 3 and 4. So based on the above analysis, estimates of E_o obtained from equation (5) will be accurate enough for most water balance and irrigation scheduling applications.

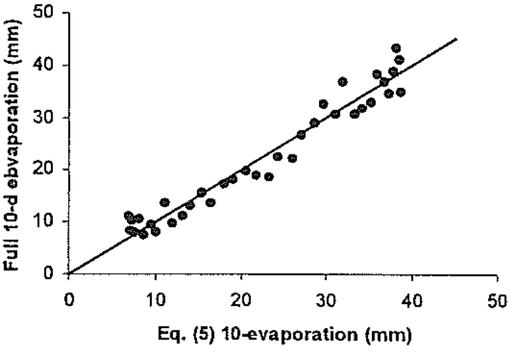

Figure 4 – The correlation between the FAO-56 Penman-Monteith evaporation for Palmerston North in 2000 computed for 10-day periods using a full set of daily weather data, and computed using equation (5) and the constants for Palmerston North in Table 3. Also shown is the 1:1 line. $R^2 = 0.95$.

Conclusions

In summary the recommendations for estimating the reference evapotranspiration (E_o) at a particular site for a particular period are as follows:

1. Where at least air temperature and daily solar radiation or sunshine hour data are available for the site of interest, or for a nearby site (say within 100 km north or south or within 1° latitude – otherwise the solar radiation will be different) and in a similar climate zone, FAO-56 calculations using these data for the period in question will give the most accurate estimates.
2. If daily vapour pressure data are not available, they can be estimated from the minimum screen temperature.
3. In summer in humid areas, good daily E_o estimates can be obtained without daily wind run data.
4. If no suitable solar radiation or sunshine hour data are available from nearby, for periods of 10 days or more, equation (5) with constants from Table 3 will probably give E_o values that are accurate enough for most water balance applications, and for

irrigation scheduling. This is a simpler approach, and just as accurate, as estimating daily solar radiation from air temperature data and using equation (1).

5. The estimates of E_0 (New Zealand Meteorological Service, 1986) calculated using an earlier version of Penman's equation mostly differ by less than 0.3 mm/day from the values in Table 1. So the water balance calculations in New Zealand Meteorological Service (1986) remain valuable.

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