Spatial Interpolation of Daily Potential Evapotranspiration for New Zealand Using a Spline Model

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ABSTRACT

Potential evapotranspiration (PET) is an important component of water balance calculations, and these calculations form an equally important role in applications such as irrigation scheduling, pasture productivity forecasts, and groundwater recharge and streamflow modeling. This paper describes a method of interpolating daily PET data calculated at climate stations throughout New Zealand onto a regular 0.05° latitude–longitude grid using a thin-plate smoothing spline model. Maximum use is made of observational data by combining both Penman and Priestley–Taylor PET calculations and raised pan evaporation measurements. An analysis of the interpolation error using 20 validation sites shows that the average root-mean-square error varies between about 1 mm in the summer months to about 0.4 mm in winter. It is advised that interpolated data for areas above 500-m elevation should be used with caution, however, due to the paucity of input data from high-elevation sites.

1. Introduction

Knowledge of potential evapotranspiration (PET) is crucial for water balance studies. A water balance is simply the balance between precipitation coming into a system (such as a soil profile) and water leaving the system through evapotranspiration (ET), drainage, or runoff. Computations of the water balance are included in estimates of irrigation demand, pasture production, groundwater recharge, and streamflows, for example. Thus, there is a significant scientific and economic need for accurate estimates of PET.

Methods of calculating PET, such as the Penman method (Penman 1963), have been used successfully for many years and for many applications. This method requires detailed climatic measurements as input to the calculations. Such measurements are commonly made at climate stations, which are carefully sited to be representative of the general terrain of the surrounding area. Nevertheless, in many instances there will not be a climate station nearby with all the necessary measurements, and use of a distant climate station calculation of PET may be erroneous for an isolated location.

This paper describes a method of spatially interpolating daily calculations and estimates of PET made at climate station locations throughout New Zealand. Daily data from January 1972 to May 2005 are interpolated onto a regular 0.05° latitude–longitude grid (approximately 5-km grid resolution) covering the whole country using a thin-plate smoothing spline model. Time series of the daily PET estimates for each grid point are then generated, which are currently used operationally in water balance calculations and streamflow models for New Zealand.

2. Data

The majority of New Zealand’s climate data are stored in the National Climate Database (CLIDB), an Oracle relational database. This is maintained by the National Institute of Water and Atmospheric Research, Ltd. (NIWA), in Wellington, New Zealand. There is an extensive network of currently open climate stations throughout New Zealand. For example, rainfall is cur-
rently measured at around 680 sites; screen observations (i.e., maximum and minimum air temperature, and dry- and wet-bulb temperature) at around 240 sites; wind speed or wind run at around 140 sites; and solar radiation or sunshine hours at around 120 sites. These numbers have varied significantly since the early 1970s (e.g., solar radiation was only measured at 27 locations in 1972, compared with 96 sites in 2005).

Climate stations with daily records of Penman PET calculations are used here as the primary data source for the daily PET interpolations. The original Penman formulas for estimating PET are used (Burman and Pochop 1994, p. 81). This calculation requires inputs of net radiation or sunshine hours, relative humidity, air temperature, and wind run. In 1972 there were 49 climate stations at which daily Penman PET has been calculated. In 2005 there were 77 stations, but only 6 of these stations had Penman PET data spanning the whole period since 1972.

There are several climate stations around New Zealand that have no wind measurements, meaning that Penman PET cannot be calculated. At many of these stations, however, a calculation of PET is made using the Priestley–Taylor formulas (Priestley and Taylor 1972). This calculation requires the same input variables as the Penman formulas, with the exception of wind. Further, at still more stations where no PET calculation can be made at all, due to no sunshine or solar radiation measurements, for example, there are records of raised pan evaporation measurements.

The number of climate stations with a daily Penman PET calculation, a daily Priestley–Taylor PET calculation, or a daily raised pan evaporation measurement has varied significantly over the period January 1972–May 2005. This is due to several reasons including a lack of some wintertime records in the early part of the period, new installations of automated climate stations and closing of manually operated climate stations, and the introduction of the digital CLIDB database. One of the consequences of the variations in station numbers is that the overall accuracy of the daily PET interpolations developed in this paper will vary depending upon the number of input data sites. This consequence is discussed further in section 3b.

3. Methods

a. Penman versus Priestley–Taylor and raised pan

Mean daily PET derived from both the Penman and Priestley–Taylor formulas were calculated at 133 climate station sites throughout New Zealand. At least 5 yr of coincident Penman and Priestley–Taylor data were necessary for a station to be included. The ratio of the mean daily values at each of these stations was calculated and plotted on a map. This showed a clear trend for the ratio of Penman PET to Priestley–Taylor PET to vary with latitude, from a ratio of 1.1 in the far north of the country to 1.4 in the far south. These ratios fall into the range (1.1–2.0) calculated by McKenney and Rosenberg (1993) for five geographically diverse sites in North America. The latitudinal variation of ratios in New Zealand is thought to be the result of a greater influence of northwesterly winds on Penman PET in the eastern South Island (where winds from this direction flow downslope from the Southern Alps and have a large drying potential) compared with the North Island, where the aerodynamic effects are less marked. The calculation of Priestley–Taylor PET does not include an aerodynamic component, whereas the Penman method does.

A regression analysis was used to predict this ratio from the northing coordinate (New Zealand Map Grid projection; measured in meters). Figure 1a shows a scatterplot of these two variables. The $r^2$ of the regression analysis is 0.36 and the standard deviation of the residuals is 0.1071 mm. The linear relationship is significant at the 99% level. The regression equation is as follows:

$$\text{PET}_p/\text{PET}_T = (-2.6805 \times 10^{-7})\text{Northing} + 2.8356,$$

(1)

where PET$_p$ is the Penman-calculated PET and PET$_T$ is the Priestley–Taylor–calculated PET.

Rearranging Eq. (1) yields

$$\text{PET}_p = \text{PET}_T[-(2.6805 \times 10^{-7})\text{Northing} + 2.8356].$$

(2)

A similar approach to that shown above was used to relate mean daily Penman PET to mean daily (class A) raised pan evaporation. In this case, however, there was no latitudinal trend in the ratios. Figure 1b shows a scatterplot of these two variables. A regression analysis, forced through the origin, produced the following equation, with an $r^2$ value of 0.30, a standard deviation of the residuals of 0.2174 mm (significant at the 95% level):

$$\text{PET}_p = 0.77\text{RP},$$

(3)

where RP is the mean daily raised pan evaporation.

The coefficient 0.77 in Eq. (3) is in the middle of the range of coefficients for raised pans, which are sited (like most of those in New Zealand) in short green cropped areas (Doorenbos and Pruitt 1975). It is possible that the coefficients in Eqs. (2) and (3) may vary with time of the year; however, this was not investigated here.
Equation (2) was applied to all available daily Priestley–Taylor PET values to produce Penman PET estimates at climate stations where no Penman values were calculated. Equation (3) was applied to all available daily raised pan data to produce Penman PET estimates at climate stations where no Penman or Priestley–Taylor values were calculated. These Penman estimate sites were then added to the actual Penman sites to augment the number of input data sites for the daily interpolations.

b. Selection of base stations

For the purposes of interpolation of daily PET data onto a regular grid covering the entire country, the more input data sites there are, the more accurate the interpolated surface is. Thus, if the goal of the interpolations is to strive for the greatest interpolation accuracy for every day, then using all the station data available for each day is the best approach. This approach would result in the most accurate interpolations in October 1985, when the number of input stations peaked at 129, and least accurate in July 1996, when there were only 70 climate stations around New Zealand at which either Penman or Priestley–Taylor PET were calculated or pan evaporation was measured. However, the goal of this study is to produce time series of daily PET at every grid point from January 1972 to May 2005, which will be used to analyze year-to-year variability and trends. Thus, it is important that the interpolated PET values are not significantly influenced by nonclimatic effects.

To remove (or at least minimize) the variability in the time series caused by changing input station numbers and locations, the same set of input data sites...
should be used for every day of the 34-yr period. However, due to some stations closing, others opening, and due to various instrumentation failures over the period, the number of stations in this category is zero. A practical alternative method, which will reduce the effect of varying interpolation accuracy in space and through time, is to choose the 70 stations that were open in July 1996 (i.e., the minimum number for the period) and delegate this set as base climate stations.

For every day from January 1972 to May 2005, data from these base stations are used as input to the interpolation process described below. If some of the base stations had missing data (or indeed were not open at the time or had subsequently closed), then PET values are interpolated to the base station locations from all other stations with available data for that day. Error statistics from the spline model (described in the following section) for this preliminary interpolation step show that daily PET values can be estimated at the base station locations with an average root-mean-square error (RMSE) of 0.41 mm and a mean absolute error (MAE) of 0.15 mm.

This method produces interpolation input data files that have PET data at the same 70 base stations for every day of the period. Using these base station data results in daily interpolations to the 0.05° latitude–longitude grid that are not affected by changing input station numbers and locations. Figure 2 shows the location of the 70 base stations. It can be seen that they are well spread out around New Zealand, although the number of stations above 500-m elevation is limited. Unfortunately, while it is desirable to include as many high-elevation sites as possible to improve the accuracy of the interpolation (as elevation is used as a covariate), there are no stations with long-record PET data above 500 m in New Zealand (although there are a few with short records of raised pan evaporation data). As a result, interpolated PET data above 500 m should be used with caution.

Last, it is acknowledged that by selecting data from the base station sites only, compared with using all the available data for any day, the resulting interpolation accuracy of the gridded data is reduced for some areas. However, this is traded off against reducing the influence of varying input station numbers and locations on the gridded PET values, which is seen as more important for the intended use (time series analysis) of these data.

c. Daily PET interpolations

There are several spatial interpolation models that have been used to interpolate climate data from surface observations covering large areas and encompassing complex terrain. The most common models are inverse distance weighting, Gaussian weighting, trend surface analysis (including linear and polynomial regression), kriging (including cokriging), and splines (Borga and Vizzaccaro 1997; Daly et al. 2002; Hutchinson and Bischof 1983; Hutchinson and Gessler 1994; Laslett et al. 1987, Matheron 1981; Phillips et al. 1992; Saveliev et al. 1998; Seaman and Hutchinson 1985; Thornton et al. 1997). In this study, we have chosen a thin-plate smoothing spline model, which has been shown to perform well for the interpolation of New Zealand climate data (Sansom and Thompson 2003; Tait et al. 2006; Tait and Turner 2005; Zheng and Bashier 1995).

A thin-plate smoothing spline works by fitting a surface to the data with some error allowed at each data point, so the surface can be smoother than if the data were fitted exactly. Each station is omitted in turn from the estimation of the fitted surface and the mean square error is found. This is repeated for a range of values of a smoothing parameter; then the value that minimizes the mean square error is taken to give the optimum smoothing. This process is called minimizing the generalized cross validation (GCV). It can be automated once the order of the derivative, which controls the surface roughness, has been chosen.

The spline computation also runs quickly, taking approximately 3 s to interpolate one day’s PET data from the 70 base climate stations onto a 0.05° latitude–longitude grid covering all of New Zealand (11 491 grid points) on a UNIX machine with 2 GB of RAM. The software used was ANUSPLIN version 4.2 (Hutchinson 2005).

As most meteorological variables, including PET, are affected by topography it makes sense to interpolate PET using a spline model with two position variables and a topographic variable such as elevation. The broad spatial pattern is determined by the two position variables, while the inclusion of elevation modifies the broad pattern to give more precise representations of the higher-resolution variability. Hutchinson (1989, 95–104) used a trivariate thin-plate smoothing spline (latitude, longitude, and elevation) to interpolate several meteorological variables across Australia. A trivariate spline, which allows the relationship between the climate variable and elevation to vary spatially, was deemed more appropriate for a continent-wide interpolation, compared with a trivariate partial spline (includes a single linear dependence upon elevation), which is more suited to small-scale applications. Thus, it was decided that for the present study a second-order derivative trivariate (latitude, longitude, and elevation) thin-plate spline (minimizing the GCV) should be used to interpolate daily PET.
Fig. 2. A map of New Zealand showing areas above 500 and 1000 m, the location of the 70 base climate stations, and the location of the 20 validation sites.
As a final step before the interpolations were initiated, the daily input data at the 70 base climate stations were given a weighting (or a relative variance, as it is referred to in the ANUSPLIN program). The relative variance is used to place an emphasis on some stations over others in the interpolation (the smaller the relative variance the greater the weight). Often the inverse of the length of the data record is used when interpolating long-term mean surfaces, which gives more weight to stations with longer records. For the daily PET interpolations, each station has the same period (one day), but some stations are Penman estimates while others are actual Penman calculations. Thus, it was decided to assign the actual Penman PET stations with a relative variance of zero, while the Priestley–Taylor and raised pan evaporation stations were weighted with the squares of the standard deviation of the residuals (from the regression relationships described in section 3a), equal to 0.011 and 0.047, respectively. No modifications to these relative variances were made based on interpolated versus actual base station data.

4. Comparison of mean annual PET surfaces

Figure 3a shows a map of the mean annual PET, based on the period 1972–2004. The map is produced from interpolated mean annual Penman PET values calculated at 111 climate stations using a second-order derivative trivariate (latitude, longitude, and elevation) thin-plate spline (minimizing the GCV) model. Stations were included in the input dataset if they had a minimum of three years of Penman PET data during the period (see Fig. 3a for the locations of these stations), and the inverse of the number of years of data at each station was used as a relative variance for the interpolation. This is the same methodology as that used by Hutchinson (1989, 95–104) for the interpolation of long-term mean climate data for Australia.

Figure 3b shows the percent difference from Fig. 3a of the mean annual PET derived from averaging all the daily PET interpolations over the same period, 1972–2004. It can be seen that for most of New Zealand the difference is ±10%, with some low-elevation areas having a positive difference of up to 20% (indicating the mean of the daily interpolations is greater than the interpolated mean values). Much of the high-elevation areas show a negative difference of 30%–50%.

These differences are caused by a combination of factors. First, there are fewer input climate stations used for the daily interpolations (70) compared with the mean annual PET interpolation (111); thus, the mean

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annual surface has a higher overall interpolation accuracy. Second, only actual Penman PET data are used for the mean annual interpolation, compared with a combination of actual and estimated Penman values for the daily interpolations. Last, the interpolation of mean annual climate data is generally more robust and hence accurate than the interpolation of daily values, due to the greater spatial variability exhibited in daily PET values associated with the passage of short-duration weather events.

Despite these potential sources of difference between the two surfaces, it is argued that the percent difference shown in Fig. 3b is relatively low and indicates that the interpolation of daily PET data produces reasonable values for the majority of the grid points covering New Zealand, particularly those in the lower elevations. High-elevation areas showed a larger difference, however, due to the paucity of climate stations at high elevations in New Zealand (affecting both the daily and the long-term mean interpolations). As a result, it is advised that the interpolated PET data for areas above 500-m elevation should be used with caution.

5. Error estimation

The accuracy of the daily PET interpolations was further examined by selecting 20 validation sites that were not included in the set of 70 base stations. In addition, for the validation run, the data from these 20 sites were not used in the initial interpolations to fill in any missing data at the base station locations. The validation sites are all Penman PET sites with at least 5 yr of data during the period January 1972–May 2005 (the average record length for the 20 sites is 16 yr). Figure 2 shows the location of the validation sites, which are well spread around the country.

At each validation site, the interpolated daily PET was compared with the actual daily PET, and the RMSE and MAE for every month were calculated. These error values were then averaged over the 20 sites. Figure 4 shows the average RMSE for each month, as well as the average daily PET for each month at the validation sites (calculated from the actual Penman PET data). The line on Fig. 4 shows the relative error for each month, calculated as the average RMSE divided by the average daily PET, and expressed as a percentage. The average monthly MAE (not shown on Fig. 4) is consistently equal to 0.35 of the average monthly RMSE.

It can be seen that the average RMSE varies between around 1 mm in the summer months to around 0.4 mm in winter. These values are similar to the average RMSE values from the initial interpolation of PET data to the 70 base station locations, indicating that the two-stage approach does not significantly increase the ultimate interpolation accuracy. The average daily PET also varies seasonally, from a maximum in summer of around 4 mm to a minimum in winter of around 0.6 mm. Thus, the relative error varies from 22%–24% in summer to 60%–70% in winter.

Two important results should be emphasized here. First, the relative error throughout the primary growing
season (October–March) is between 22% and 26%, which is acceptable for many applications of these data. This is the period when estimating water loss through PET is most crucial as it directly influences irrigation and water supply decisions, which have a direct impact on productivity and groundwater and low streamflow management. Second, the removal of the 20 validation sites from the daily interpolations has significantly reduced the overall interpolation accuracy, as these sites all have long-term Penman PET data. The actual daily interpolations (i.e., not the validation run) include these data; thus the true error is likely to be less than that shown in Fig. 4.

6. Summary and conclusions

The interpolation of daily PET onto a regular 0.05° latitude–longitude grid for all of New Zealand from January 1972 to May 2005 (which can easily be updated to the present) has yielded a valuable dataset that has many potential applications. The interpolation methodology involves the selection of a set of 70 base climate stations from which the gridded daily PET data are interpolated. These base stations were selected to minimize the effect of varying station numbers and locations over time on the interpolated values.

A regression-based method is used to extend the number of stations at which Penman PET calculations are made to those sites at which Priestley–Taylor PET is calculated and raised pan evaporation is measured. The Penman PET estimates are then weighted lower than the actual Penman PET values in the interpolation procedure, which places more emphasis on the actual Penman values while still making use of the estimated values.

A comparison of mean annual PET surfaces—one derived from interpolated mean PET values and the other from averaging all the daily PET interpolations—showed that for the majority of low-elevation areas throughout New Zealand the difference is between ±10%. High-elevation areas showed a larger difference; hence caution should be taken when analyzing these interpolated data.

An error analysis at 20 validation sites has shown that the average RMSE of the daily PET interpolations for the validation sites varies between about 1 mm in summer and 0.4 mm in winter. The average relative error (the RMSE divided by the average daily PET) is between 22% and 26% throughout the important growing season months (October–April), but increases to 60%–70% over winter when the average daily PET at the validation sites is only around 0.6 mm.

In conclusion, the interpolated daily PET dataset is regarded as a new and valuable resource for New Zealand. Together with daily rainfall estimates, the data are already being used operationally for water balance and streamflow modeling. Further applications, such as water quality modeling, are currently being tested. Readers of this paper may contact the authors for more information regarding the acquisition of these data for their own purposes, if desired.

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