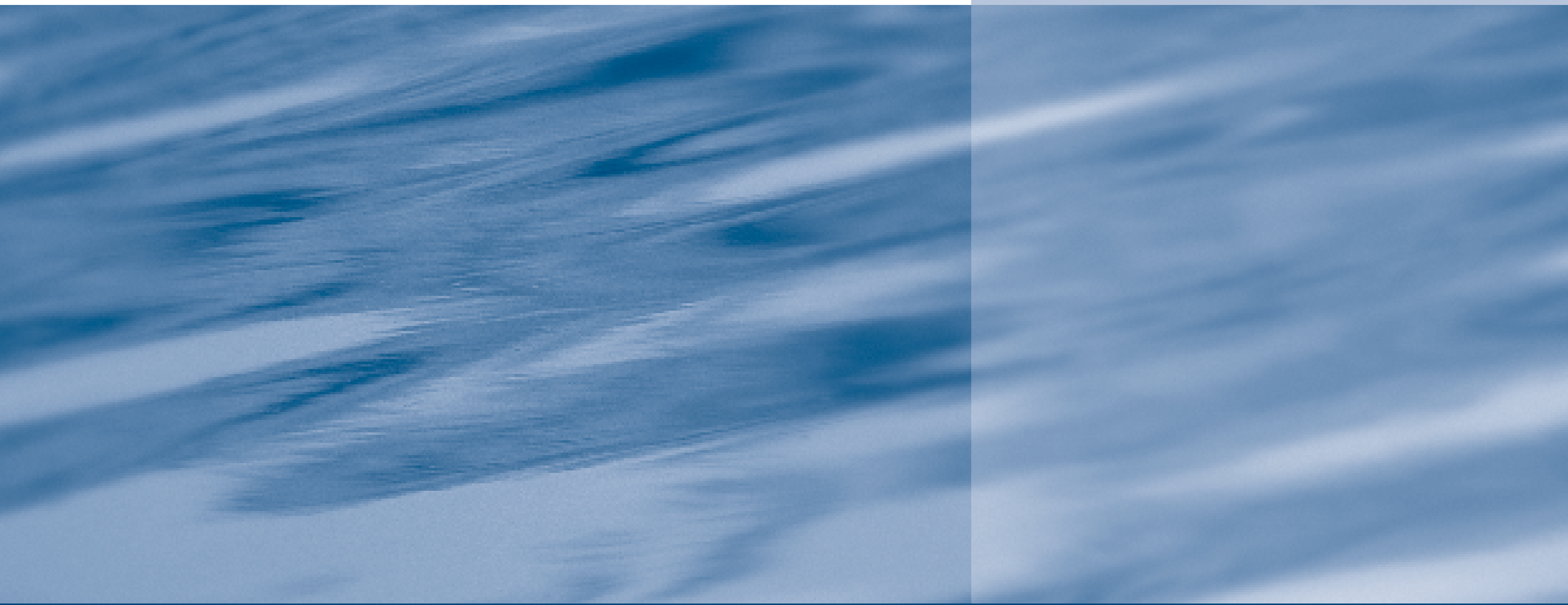

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Estimation of Open Water Evaporation

Guidance for Environment Agency Practitioners

R&D Handbook W6-043/HB

Environment Agency

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This handbook describes how the methods, recommended as a result of the work described in R&D Technical Report W6-043/TR, should be used.

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1 INTRODUCTION

Estimates of evaporation from open water are increasingly required for several Environment Agency functions, particularly Water Resources and Ecology. These estimates are used mainly for water balance studies to support appraisals of applications for abstraction licences, in wetlands and in still waters management. In 1999, the methods of estimating open water evaporation varied between and, in some cases, within Regions; there was no generally adopted best method. In addition, there was often a mismatch between the accuracy of estimates produced by the then current methods (they were generally crude and subject to large uncertainties) and their significance in the calculations that were used as a basis for decision making.

Decisions made by Agency staff must be based upon, and justified by, estimates made using methods that are robust and defensible, both internally and externally. The use of inaccurate estimates may result in resources having to be spent either justifying the basis for the decisions or rectifying the consequences.

Consequences specifically applying to estimates of open water evaporation include:

- A licensee having insufficient water for his purpose (e.g. irrigation from winter storage) if the evaporation estimate is too low.

- The licensee may be allocated more water than is actually required if the evaporation estimate is too high. This will reduce the amount available to other potential license holders, or even in licenses being refused. This has relevance to the Agency's national initiatives for Abstraction Management Strategies and the Abstraction Licensing Review.

- There may be detrimental impacts on the environment due to water being allocated to other uses as a result of either the abstraction licensing being set too high or of open water evaporation losses of wetlands being underestimated. The Agency has a duty to protect and, where possible, enhance the environment. This is particularly relevant to the EU Habitats Directive.

- Inappropriate amounts of water may be allocated for amenity uses, such as navigation on canals.

Therefore there are three benefits to the Agency of robust estimates of open water evaporation:

1. Agency staff can carry out their duties in a consistent and efficient manner.
2. Potential abstractors and amenity users have sufficient resources for their requirements.
3. The Agency can carry out its core duty of protecting and enhancing the environment.

In order to provide improved and consistent estimates of open water evaporation, an R&D project was carried out with the objectives of:

- evaluating the then current methods of estimating open water evaporation;

- recommending the best available practicable methodologies for producing robust estimates;
- assessing the associated uncertainty of these methodologies.

This handbook describes how the recommended methodologies should be used. It is aimed at practising hydrologists, giving a step by step procedure for deriving estimates of open water evaporation and the accuracy associated with those estimates.

The next chapter describes the requirement for estimates of open water evaporation in more detail. It also discusses the methods used by the Agency in 1999 and concludes with a brief summary of the project and its findings. The third chapter describes the fundamental assumptions made by the recommended methods and is followed by a chapter dealing with the criteria for selecting the data which will be used for estimating open water evaporation. A short chapter then describes the procedure for making a correction for the difference in altitude between the site of interest and the site of the meteorological data. The recommended methods are described, along with some worked examples in the sixth chapter whilst the seventh deals with disaggregating time series. The final chapter gives information regarding the accuracy of the estimates of open water evaporation.

2 BACKGROUND

2.1 The requirement for estimates of open water evaporation

A survey of agency staff, carried out in 1999, established that there was a strong consensus that the estimates were required for three purposes: abstraction licensing, water balance studies and management of wetlands.

2.1.1 Abstraction licensing

The abstraction licenses of interest are most often applications by farmers for winter storage, the water from which is used for irrigation during the summer. The size of these water bodies is variable but an ‘average’ case has a diameter of about 100 m and a depth of up to 6 metres. Other types of water body that fall within this category are ornamental and amenity ponds/lakes which require abstractions to maintain their levels during the summer. The size of these varies widely from a diameter of about 10 m to substantial ornamental lakes.

The requirement is to assess the risk of failure of the supply. The approach adopted generally was to estimate the worst case scenario by calculating the evaporation during the year or summer of an exceptionally hot year, e.g. 1976. The accuracy required is commonly agreed to be 10%.

2.1.2 Water balance studies

The water balances of lakes and reservoirs are required for planning and modelling. The size of the water body involved is variable but includes strategic reservoirs.

A more thorough analysis is required for these water bodies as the data are often incorporated in a model. In general, daily values of evaporation are required, as this is the time step of the catchment models. However, it is accepted that accurate daily values are not essential and that weekly values intelligently disaggregated to daily values are acceptable. The time period used is variable but is generally several decades and could extend from 1918 to the present. There is consensus that the accuracy should be the same as other hydrological variables such as runoff and rainfall. An accuracy of 10% is commonly seen as acceptable but 5% is sometimes perceived as preferable.

2.1.3 Wetlands

These were identified particularly by Southern Region but were also commented on by some of the others. Estimates of open water evaporation are required for the wetlands in the context of both abstraction licensing and water balance studies. The abstraction licensing applications are made by farmers who have land within areas designated as Environmentally Sensitive Areas and who are applying for grants to manage the land. The requirement is for at least 20% of the area to be covered with water to a depth of at least 0.1 m during the winter months. The areas involved are typically 40 to 100 ha. Estimates are required as monthly values, either for the fifth driest year in 20 or for the driest year in 20. During the summer months, there may be a need to maintain target water levels in marsh drainage strips.

The requirement in water balance studies is to ensure that flows in streams, some fed by springs, have sufficient volumes to maintain wetlands. Therefore, estimates of losses from the wetlands, due to open water evaporation, are required.

2.1.4 Others

On a few occasions there is a requirement for the estimation of open water evaporation from canals and rivers, the latter in the context of naturalisation and transfer schemes. The Thames Region has an exceptional requirement to estimate open water evaporation from gravel pits. (The estimation of evaporation is complicated by a throughflow of groundwater, which may be very variable, and possible leakage from rivers into the gravel pits.)

2.2 Methods in use by the Agency in 1999

With a few exceptions, estimates of open water evaporation were obtained by applying empirical factors to Potential Evaporation (PE) data. The values of the empirical factors used were generally those given by Penman (1948), i.e. 1.25 May-Aug, 1.67 Nov-Feb, 1.43 Mar, Apr, Sep, Oct. The potential evaporation (PE) data used was generally either the grid form of MORECS grass PE or a form of the Penman (1948) equation.

The values of the empirical factors given by Penman (1948) were derived from measurements of evaporation, for two years, at one site (Rothamsted Experimental Station) in southern England using cylinders 0.76 m in diameter and 1.83 m deep. (It will be appreciated that the size of the these cylinders is untypical of the water bodies of interest to the Agency.) The cylinders were filled either with water or soil on which mature grass, which was kept well watered, was growing. This enabled Penman to calculate the average difference between the evaporation from the two different surfaces. At the time, the site was criticised as having poor exposure. In addition, the empirical factor for the winter months is derived from measurements at Fleam Dyke, in Cambridgeshire. Thus these empirical factors were derived from a relatively short period of measurements, on an unrepresentative water body and for a potential evaporation data set rarely used by Agency staff. The result is that there must be considerable concern about the accuracy of estimates of open water evaporation based on this method.

2.3 The project

As well as establishing the purposes for which estimates of open water evaporation were required by the Agency and establishing which methods were used, a literature review was made of methods that could potentially be used. Seven methods of estimating open water evaporation were identified; pan evaporation, mass balance, energy budget models, bulk transfer models, combination models, the equilibrium temperature method and empirical factors. A ranking of the seven methods of estimating open water evaporation against nine criteria (covering accuracy, robustness, ease of use etc.) established that the equilibrium temperature method would best serve the Agency's purposes. The use of empirical factors and the combination models were ranked equal second.

A literature review of the spatial variability of the meteorological variables that drive evaporation showed that they are strongly influenced by proximity to the coast. Inland, the spatial variability of wind speed and air temperature is low whilst for incoming solar radiation and relative humidity it is significantly higher. Topography has a strong effect on the driving variables, either directly, in terms of the lapse rates of air temperature and vapour pressure, or indirectly, through the formation of clouds affecting the amount of incoming solar radiation.

Methods of correcting for the effect of altitude on the driving variables (except for the effect of cloudiness on incoming solar radiation) were documented. Empirical corrections to evaporation estimates for altitude were also found, although these are not as physically rigorous as correcting the driving variables.

A literature review established that the size of the water body affects evaporation rates in two ways. Firstly, there is evidence that, for water surfaces greater than 10 m in diameter, the rate of evaporation over water is enhanced due to increased wind speed resulting from the smoother surface. Secondly, the size of the water body (in England and Wales) affects the development of thermal stratification. This can have a significant effect on open water evaporation, increasing it during autumn and winter and decreasing it during spring and summer. The maximum depth of the warmer surface layer is a function of the surface area of the water body.

The methods recommended for use by Agency staff (equilibrium temperature and empirical factors) were tested against measurements of evaporation made at a reservoir at Kempton Park south-west of London) between 1956 and 1962. The combination models of Penman and Penman-Monteith were included for the purposes of comparison. The results show that the estimates of open water evaporation made by the equilibrium temperature method are in excellent agreement with the measured values.

The sensitivity of the estimates of open water evaporation made using the equilibrium temperature model to the parameters required was investigated. Values for these parameters were recommended.

New empirical factors, for use with MORECS or PENSE (which use the Penman – Monteith equation) grass potential evaporation and PETCALC (which uses the Penman equation) estimates of potential evaporation, were calculated from the measured values at the Kempton Park reservoir.

The project also looked at the validity and accuracy of transposing the new empirical factors to other parts of England and Wales with different climatic characteristics. The accuracies of corrections for differences in altitude between the meteorological station and the site of interest were tested.

3 ASSUMPTIONS MADE BY THE METHODS

Two methods are recommended for estimating open water evaporation, empirical factors and the equilibrium temperature method. The first relies on multiplying estimates of potential evaporation (PE) for grass by empirical factors to obtain estimates of open water evaporation. The equilibrium temperature method is more rigorous in that it estimates the open water evaporation by a combination of the radiation balance and the aerodynamic function.

3.1 Assumptions common to both methods

Both methods are essentially point models, i.e. they assume that the water body is infinite in its lateral extent and of constant depth. Therefore they ignore any effects at the edge of the water body which might modify the evaporation rate, e.g. reducing water depth, decreasing turbulence in the atmosphere etc.

It is assumed that the water can be considered as low salinity. The evaporation rate decreases by about 1 per cent for each 1 percent increase in salinity and so this effect can normally be safely ignored for fresh water bodies in England and Wales.

The assumption is made that changes in the heat content of the water body due to inflows, including rainfall, and outflow are negligible. This means that the inflow and outflow volumes are small compared with the amount of water evaporated from the water body and/or that the temperature of inflows are not significantly different from the temperature of the water body.

It is assumed that vegetation floating on the surface or protruding through the water surface is minimal.

It is assumed that the water temperature does not vary with depth, i.e. that the water body is well mixed. Larger, deeper water bodies become thermally stratified due to heating of the surface layers during summer. As long as the temperature of the water in the surface layers is within a few degrees of the average temperature of the water body throughout the year then the effect can safely be ignored.

The assumption is made that the meteorological conditions above the water body do not differ significantly from those over the land (which is where the meteorological data will have been measured). Both the wind speed and the relative humidity of a parcel of air will change as it passes from land to water. The smoother surface of the water results in an increase in wind speed and there is less ‘resistance’ to evaporation from a water surface resulting in increased relative humidity. However, conditions are generally fairly humid in the UK so there is relatively little scope for significant changes.

It is assumed that the net heat flow between the water body and the underlying substrate is minimal.

3.2 Assumptions additional to the empirical factors method

The empirical factors method is considerably simpler than the equilibrium temperature method with the result that several other assumptions are made. These mainly relate to the type of water body from which the measurements of open water evaporation were made that were used to derive the factors. Failing to fulfil these assumptions does not automatically invalidate estimates of open water evaporation made using this method. However, the more that conditions at the site of interest deviate from these assumptions, the greater the uncertainty in the estimates of open water evaporation. It should be noted that the methods used by Agency staff in the past involved more assumptions and therefore greater uncertainty,

It is assumed that the water depth is roughly 6 m in depth (because this was the water depth of the reservoir at Kempton Park). The water depth can have a significant effect on the temperature of the water which in turn influences the evaporation rates. This is because heat is stored in the water column which may also become thermally stratified.

The assumption is made that the characteristics of the climate, from the perspective of evaporation, do not differ significantly from that found in the area of Kempton Park (south-west of London).

It is assumed that there are no major variations in the monthly evaporation rates (both from grass and water) from year to year.

Finally, it is assumed that the water has a low turbidity and reflection of light from the bottom of the water body is negligible. The latter is unlikely to be true of shallow water (2 metre or less)but the error is unlikely to exceed 10%.

4 DATA SELECTION

The criteria for selecting the meteorological stations, from which data will be used for estimating open water evaporation, are discussed in this chapter. The first section deals with the spatial scales whilst the second deals with the time step and periods to be used for different purposes. A more detailed discussion on these issues can be found in Finch and Hall (2001).

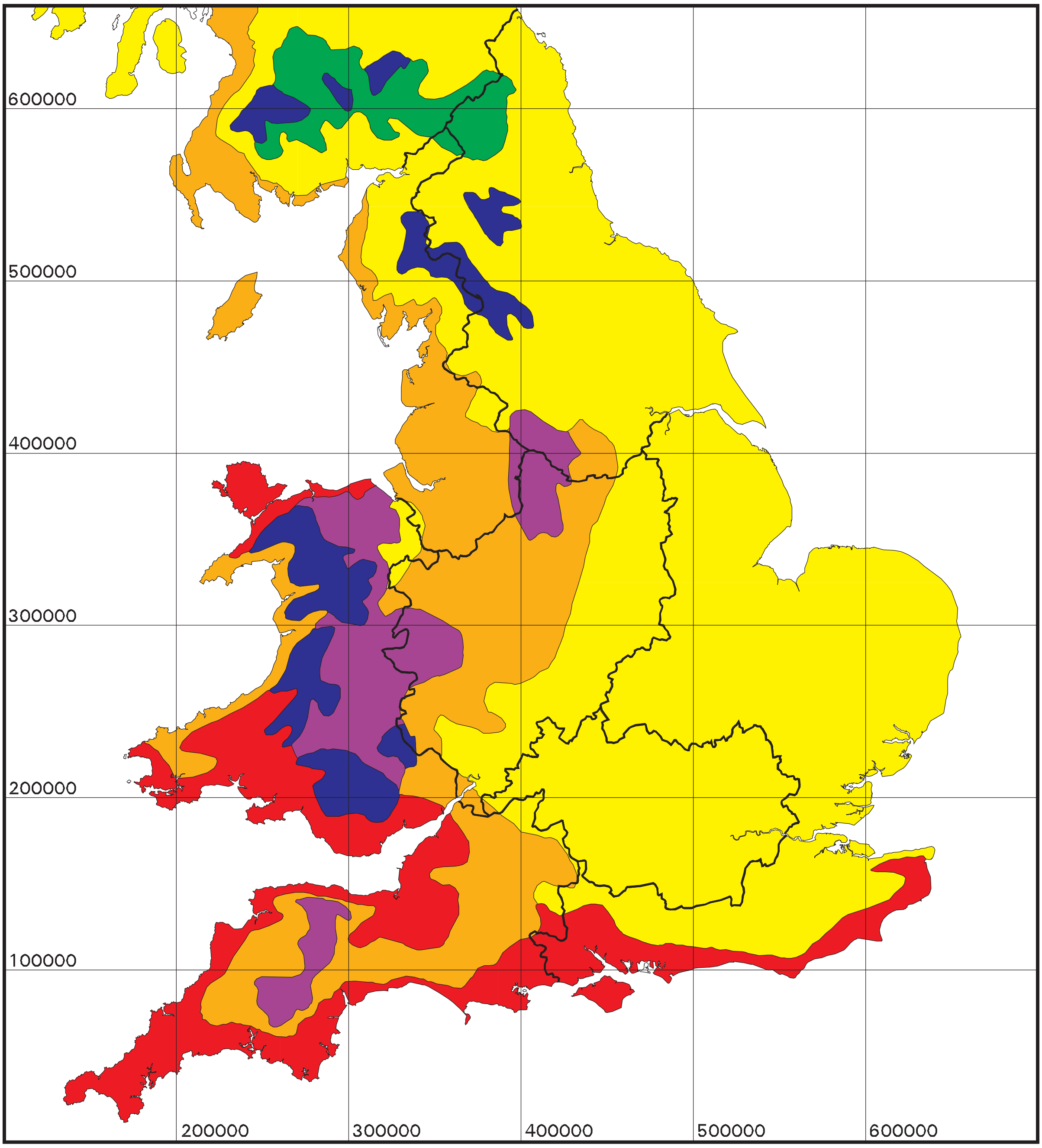
4.1 Locational considerations

This section applies when using the equilibrium temperature method or the empirical factors method with single station MORECS grass PE. It does not apply if empirical factors are being used with MORECS grid grass PE, or if PET-CALC or PENSE are being used (since the latter models produce estimates of grass PE for the site of interest). In selecting the station(s) from which the data are to be used for estimating open water evaporation at the site of interest, it is important to ensure that they are within the same climatic region. Gregory (1976) gives a classification, Figure 4.1, that is relevant to evaporation studies as it considers a combination of rainfall, evaporation and topography. Therefore, this should be used as the basis for selecting stations. Only data from stations within the same climatic region as the site of interest should be used. In the eventuality that no station meets this criterion then data from a station in a climatic region next in the sequence of classes should be used.

An additional constraint is the latitudinal (northing) difference between the site of interest and any meteorological stations. There is a progressive reduction in the amount of incoming solar radiation with increasing latitude. Therefore any meteorological station, from which data will be used, should be within a radius of 50 km of the site of interest.

Local geographic features can modify the local meteorological conditions and therefore should also be considered when selecting stations. Hills and valleys can experience very different climates from the regional weather conditions. Surrounding hills may shade the water body for part of the day. The air temperature in the valleys can be lower than on the surrounding hills because, during the night and during the winter months, cold air flows down into the bottoms of the valleys due to its greater weight. Also, during the day in summer, the valley gets higher daytime air temperatures than the hills. The winds are stronger on the hills than in the valleys. In long valleys, the winds can only blow along the line of the valley. In winter months high air temperatures can occur in the lee of high ground, when a moist south to south-westerly airflow warms up downwind of mountains. There are also differences between urban and rural areas. Urban areas have minimum air temperatures which are higher than those recorded in the rural areas, whilst cities can also have higher maximum air temperatures. Thus, these factors should be considered when selecting stations and every effort should be made to use data from stations with the same physiographic setting as the site.

In the unusual event that more than one meteorological station meets the criteria then open water evaporation should be estimated using the data from each of the stations in turn and the results averaged to produce a single time series.



A - warm temperate, humid with occasional frost
B - transitional between A and C
C - humid temperate with a cold season
D - transitional from C to cooler summers and colder winters
E - transitional between C and F
F - mountainous climates
— Environment Agency Region boundaries

Figure 4.1 Climatic regions of England and Wales (Gregory, 1976)

4.2 Temporal considerations

The choice of time period and step may be project specific and could also depend on the availability of data. However, the following guidance may be found useful. The time period and time step required depend on the purpose for which an estimate of open water evaporation is required. Therefore, these will be considered for each of the three purposes, identified in Section 2.1, in turn.

4.2.1 Abstraction licensing

The requirement is to assess the risk of failure of supply and so the approach is to adopt a worst case scenario. The period covered should be 1961 to 1990 inclusive, the period recommended by the World Meteorological Organization (WMO). A time series of open water evaporation should be calculated for this period using a time step no greater than one month (to ensure that the seasonal variability is reflected in the final results). Then, select the maximum value for each month of the year (i.e. identify the highest evaporation rate for January, then that for February, then March etc.). Finally sum the maximum monthly evaporation rates to produce the annual total for a worst case year that is composed of the highest evaporation rate for each month.

Agency staff from an Area or Region may wish to perform this calculation for a few (four or five) sites, considered representative of their Area or Region, to establish which months of which year record the highest evaporative losses, and then consistently use data for these months in all subsequent estimates.

4.2.2 Water balance studies

The water balances of lakes and reservoirs are required for planning and modelling. The time period modelled is variable but generally will cover several decades and could extend from, for example, 1918 to the present. If a catchment water balance model is being used then it is likely that a time step of one day is required. If the water balance of a water body alone is being calculated then a longer time step (but no greater than 10 days) may be acceptable for bodies greater than 10 Ha in area.

Availability of meteorological data (or estimates of potential evaporation) may be constraints on both the time step and the time period for which it is possible to estimate open water evaporation. The time step is more easily dealt with. The open water evaporation should be estimated with the time step of the meteorological or PE, data and then disaggregated or aggregated to values with the time step of the study.

It is not possible to be prescriptive in terms of the time period, as this will vary according to the nature of the study. PETCALC and PENSE data is available back to 1918, however, MORECS data does not exist for periods prior to 1960. Therefore, either the meteorological data should be used to drive the equilibrium temperature model or, if this is not possible, some means must be found to extrapolate MORECS grass PE data back by correlating it with some other time series. For example, by using a time series of evaporation calculated using a different system and establishing a regression model from a period when the dataset overlaps the MORECS values.

4.2.3 Wetlands

The requirement for wetlands is generally to estimate losses due to evaporation. In the case of abstraction licenses to maintain a specific water depth during the winter months (October to March) then the procedure used should be the same for abstraction licensing generally but only the winter months should be aggregated when producing totals. Where the requirement is to ensure the flow in streams is sufficient to maintain the wetlands, it is necessary to produce time series that reflect the seasonal changes in evaporation rates and therefore time series should be generated with a time step no greater than monthly. The time period used may be determined by the context of the study but, if there is no other basis for selecting the time period, the period 1961 to 1990 inclusive should be used. (This period is recommended for use as a standard by the World Meteorological Organization).

It should be noted that, with the empirical factors method in particular, there is a risk of overestimating, by about 10-15%, the open water evaporation for wetlands. This will occur when the water is shallow and/or turbid as a significantly higher proportion of the incoming solar radiation will be reflected rather than absorbed.

5 CORRECTION FOR ALTITUDE

Altitude corrections for the driving variables are available except for the effect of cloudiness on incoming solar radiation. Although empirical corrections are not as physically rigorous, analyses in Phase 2 of the R&D Project indicated that the latter performed better. This chapter describes the corrections to make to evaporation rates to correct for the altitudinal difference between the meteorological station (or MORECS grid square), from which the meteorological data were used to estimate evaporation, and the site of interest.

5.1 Empirical factors method

The empirical factors method applies a 'correction' factor to standard evaporation data sets to convert the evaporation rate to that for open water. Before the empirical factor is applied, it is necessary to make a correction for the difference in altitude between the elevation for which the standard evaporation was calculated and that of the site of interest. This is achieved by applying a lapse rate that varies according to the month of the year, Table 5.1. This table was produced by the project "Enhanced low flow estimation at the ungauged site", co-funded by NERC and the Environment Agency. The Agency project leader was Dr. R Grew, Regional Hydrologist, South Western Region.) Note that these values apply to monthly values and may need to be adjusted to the time step being used for the time series of open water evaporation. A detailed description of how to do this is given in Section 6.1.

PETCALC and PENSE automatically make corrections between the altitude of the meteorological stations and the site of interest and so no further correction is required.

5.2 Equilibrium temperature method

The same lapse rates are used as with the empirical factors, i.e. Table 5.1, but they are applied to the estimates of open water evaporation.

Table 5.1 Mean monthly lapse rates for variation of evaporation with altitude

Month	Lapse rate (mm m^{-1} per month)
Jan	-0.0143
Feb	-0.0140
Mar	-0.0180
Apr	-0.0237
May	-0.0344
Jun	-0.0314
Jul	-0.0388
Aug	-0.0411
Sept	-0.0316
Oct	-0.0225
Nov	-0.0177
Dec	-0.0136

6 ESTIMATING OPEN WATER EVAPORATION

This chapter describes how to use the two recommended methods for estimating open water evaporation.

6.1 Empirical factors method

This method is based on applying factors to convert 'standard' evaporation data, for grass, into estimates of open water evaporation. Empirical factors have been produced for two evaporation data sets, MORECS grass potential evaporation (PE) and PETCALC by calculating the average monthly factor between these evaporation data and measured values made, between 1956 and 1962, at a reservoir located at Kempton Park (south-west of London). These empirical factors are given in Table 6.1

Table 6.1 Empirical factors for converting grass PE values to open water evaporation

Month	MORECS grass PE	PETCALC PE
Jan	1.43	1.57
Feb	1.14	0.88
Mar	0.92	0.71
Apr	0.95	0.75
May	0.91	0.78
Jun	1.02	0.81
Jul	1.24	0.99
Aug	1.37	1.08
Sep	1.47	1.25
Oct	1.99	1.98
Nov	2.29	2.63
Dec	1.95	2.68

It should be noted that the only distinction that need be considered between MORECS grid square and MORECS single station data is in the altitude to which the estimate of grass PE is applicable. For MORECS grid square data, it is the average elevation of the square, whilst for single station data it is the elevation of the meteorological station. This is because the model used to calculate the PE, in both cases, is identical. The difference is the meteorological data input to the model. In the case of single station, the data is that for the station. For the grid square, the meteorological data can be thought of as recorded by a hypothetical station at the average topographic elevation within the square and where the meteorological conditions are the spatial average throughout the square.

The PENSE system used by the Southern Region is a simulation of MORECS and so the empirical factors produced for MORECS grass should be used with PE estimates from PENSE.

The procedure for using the factors is:

1. Obtain a time series of either MORECS grass PE, PENSE grass PE or PETCALC grass PE (the latter unadjusted for soil heat flux), with a time step of a month or less, covering the period of interest. For MORECS grass PE grid data it should be for the grid square within which the site of interest is located.

2. PETCALC and PENSE PE are automatically adjusted for the difference in altitude between the meteorological station and the site of interest so no correction is necessary. For MORECS grass PE data, obtain the altitude of the site and of the MORECS grid square or station. The altitudes and locations of the latter are shown in Figures C.1 and C.2 respectively. (The OSGB grid references of the MORECS grid squares are also given in Annexe C to assist locating which square the site is located.)

3. Correct each of the PE values for the difference in altitude. Firstly calculate the difference in altitude between the site and the station (or the average height of MORECS grid square) and then multiply by the appropriate lapse rate for the month, from Table 5.1. The resulting value is then added to the PE value. Note that the lapse rates are for monthly evaporation and thus they can only be applied directly to time series with monthly time steps. In order to use them with different time steps it is necessary to divide the lapse rate by the number of days in the month and multiply by the number of days in the time step. Negative values resulting from this calculation should be set to zero.

4. Finally, calculate the open water evaporation by multiplying the PE values, corrected for the altitude difference, by the appropriate empirical factor the month.

The method can be illustrated by an example. Let us suppose that an estimate of open water evaporation is required for a site with the OSGB grid reference of 512100 170500, at an altitude of 155 m, and for June, July and August 1960. The MORECS grass PE time series that will be used is for a station at Heathrow (OSGB grid reference 507700 176700) which is at an altitude of 26 m. The MORECS grass PE for the months of June, July and August in 1960 are 98.7, 74.9 and 61.0 mm respectively.

1. Calculate the altitude correction for each month.
   The altitude correction for June is -0.0314 × (155 – 26) = -4.1 mm per month
   The altitude correction for July is -0.0388 × (155 – 26) = -5.0 mm per month
   The altitude correction for August is -0.0411 × (155 – 26) = -5.3 mm per month

2. These values are then used to correct the MORECS grass PE to the altitude of the site:
   The corrected MORECS grass PE for June 1960 is 98.7 – 4.1 = 94.6 mm
   The corrected MORECS grass PE for July 1960 is 74.9 – 5.0 = 89.9 mm
   The corrected MORECS grass PE for August 1960 is 61.0 - 5.3 = 55.7 mm

3. The appropriate empirical factors are used to convert the altitude corrected MORECS grass PE to monthly estimates of open water evaporation:
   The estimated open water evaporation for June 1960 is 94.6 × 1.02 = 96.7 mm
   The estimated open water evaporation for July 1960 is 89.9 × 1.24 = 111.5 mm
   The estimated open water evaporation for August 1960 is 61.9 × 1.37 = 84.8 mm

6.2 Equilibrium temperature method

Evaporation from land surfaces other than water, e.g. grass, is commonly estimated from meteorological data using a combination model, e.g. MORECS uses the Penman-Monteith model (Hough *et al*., 1998). The challenge in applying such models to open water is in quantifying the heat stored in the water body. Heat storage in the water has a significant influence on the seasonal evaporation rates from a water body, reducing rates during the spring and summer and enhancing them during the autumn and winter.

The equilibrium temperature method addresses the issue of heat storage by calculating a time series of changes in heat storage, which can then be included in a model of evaporation (such as the Penman-Monteith equation). This enables a time series of open water evaporation to be calculated which incorporates an estimate of the heat stored in the water.

The equilibrium temperature method uses the concept of an equilibrium temperature and an associated time constant. The equilibrium temperature is the temperature, towards which the water temperature is driven by the net heat exchange, i.e. when the water is at equilibrium temperature the net rate of heat exchange is zero. It allows the temperature of a well-mixed body of water to be calculated as a function of time and water depth. Thus the change in heat storage can be calculated.

The equilibrium temperature method has been recommended by the R&D study as the best method for estimating open water evaporation, scoring highest overall, compared with other methods according to nine criteria (see Finch and Hall, 2001). However, it does not lend itself to manual calculation and requires a certain amount of coding and data preparation and transformation in order to be used. In the long term, the equilibrium temperature method is likely to be implemented formally for Agency staff to use. However, in the meantime, the following instructions are intended for hydrologists who wish to use the method in a spreadsheet or a computer program developed in-house. The equations that form the model and the Penman-Monteith equation are described in Annexe D. These were coded using FORTRAN-90 as part of Phase 2 of the R&D Project and are listed in Annexe E.

The model requires time series of driving variables (incoming solar and thermal radiations, average wind speed, average air temperature, and average vapour pressure deficit). These can be derived from standard meteorological data (including sunshine hours, wet and dry bulb temperatures etc.) and the methods to achieve this are well described in the literature, e.g. Allen *et al*. (1998). However, the time series must not include any missing periods and must cover the complete period of interest. It is recommended that the time series should include the year prior to the beginning of the period of interest in order to allow the model to stabilise the value of the water temperature, i.e. to 'spin up' the model. The selection of data is covered in Section 4.1.

The model requires three parameters: the albedo, roughness length and water depth. In general, a value of 0.065 should be used for the albedo. This value is appropriate for clear water deeper than 5 m. Using values between 0.033 and 0.097 will result in estimates of open water evaporation varying by about 10%. Situations when a value of 0.065 is likely to be inappropriate are when the water is turbid or reflection of light from the bottom of the water body is likely to be a significant factor. In these situations the albedo will be higher and a value ca 0.13 might be appropriate.

The value for the roughness length used should be 0.001 m. There is currently no information to suggest situations when this value will be inappropriate.

The value used for the water depth should be an estimate of the average depth of water. Once this exceeds 10 m then the estimates of open water evaporation become relatively insensitive to it and so a high degree of accuracy is not warranted. It should be noted that larger water bodies (greater than 50 ha, deeper than 5 m) often become thermally stratified during winter, with the result that one of the fundamental assumptions of this model becomes invalid. This may result in estimates of open water evaporation which should be used with caution, especially if the seasonal variations in evaporation are likely to be important to the purpose for which the estimates are required.

7 DISAGGREGATION OF ESTIMATES

In the following sections it is assumed that the requirement is to disaggregate estimates of monthly evaporation to daily values. The same procedures can be used to disaggregate to other time steps. However, it is not possible to disaggregate annual, or longer, estimates unless there are additional time series available, because the seasonal variability is not present in the annual values.

For most applications, it is recommended that linear interpolation is used because this requires no additional data and is quick and easy to perform. Only if it is essential that the variability of evaporation at the temporal scale of the disaggregated time step is represented should the additional time series method be used.

7.1 Linear interpolation

Linear interpolation is a simple means of representing the seasonal variation in estimates of open water evaporation at a daily time step. However, it should be noted that the true day-to-day variability is not represented. The procedure is:

1. Calculate the daily average evaporation for each month of the time series by dividing the month's total evaporation by the number of days in the month.

2. For each adjacent pair of months in turn, calculate the difference in daily average evaporation and the number of days between the mid-date of each month. (Day numbers for each calendar date are given in Annexe B to assist this). Then calculate the rate of change in the evaporation by dividing the difference in evaporation by the number of days. Note that these rates of change apply from the mid-date of one month to that of the next. Therefore, it is not possible to calculate rates for the first half month of the time series and the last. This limitation can be overcome by generating time series that start one month earlier and finish one month later than the period of interest. If this is not possible then the only recourse is to assume that the rate of change between the mid-dates of the first and second months can also be used for the first half of the first month, and similarly for the last two months of the time series.

3. For each adjacent pair of months in turn, calculate the daily evaporation for each day in turn by multiplying the appropriate rate of change in the evaporation by the number of days between the mid-date of the first month of the pair and the day for which the evaporation is being calculated. The resulting value is then added to the average daily evaporation for the first month of the pair

The procedure can be illustrated by an example of obtaining a daily time series for July 1960 from the monthly estimates of open water evaporation calculated in Section 5.1.

1. Calculate the average daily evaporation for each of the months:
   the average daily evaporation for June is $96.7 \div 30 = 3.22$ mm d^{-1}
   the average daily evaporation for July is $111.5 \div 31 = 3.60$ mm d^{-1}
   the average daily evaporation for August is $84.8 \div 31 = 2.74$ mm d^{-1}

2. The next stage is to calculate the rate of change in evaporation between the mid-dates of June (16^{th} , day number 168 as 1960 is a leap year) and July (16^{th}, day number 198):

   rate of change in evaporation is $(3.22 – 3.60) \div (198\text{-}168) = 0.0127$ mm d^{-2}

   Then calculate the rate of change in evaporation between the mid-dates of July and August rate of change in evaporation is $(3.60 – 2.74) \div (229\text{-}198) = -0.0277$ mm d^{-2}

3. The evaporation can be calculated for each day in turn. Thus for the 1^{st} July (day number 183), the daily evaporation is:

   the evaporation is $0.0127 \times (183\text{-}168) + 3.22 = 3.41$ mm d^{-1}

   and so on for each day up to and including 16^{th} July. Subsequent days through to the end of the month are then calculated using the rate of change in daily evaporation between the mid-date of Jul and the mid-date of August. Thus, for the 31^{st} July (day number 213), the daily evaporation is:

   the evaporation is $-0.0277 \times (213\text{-}198) + 3.60 = 3.18$ mm d^{-1}

7.2 Use of additional time series

A limitation of using linear interpolation is that it cannot quantify the day-to-day variability in evaporation. It is possible to achieve this but it requires that there are daily time series, of open water evaporation and of the meteorological variable, that cover the same period for several years representative of the general climate conditions. The objective of the method is to use the meteorological variable to quantify the day-to-day variability of evaporation around the mean daily evaporation for a given time period, typically a month.

Where there is more than one meteorological variable then wind speed should be used in preference to others (it shows the greatest correlation with day to day variability in evaporation) with air temperature being the second choice.

It is recommended that the analysis to establish the relationship between the variability of the daily evaporation and the meteorological variable should be carried out on the basis of months to allow seasonal variations to be catered for. The procedure is:

1. Using the daily time series, calculate the mean daily evaporation and the mean daily value of the meteorological variable for each month.

2. Using the daily time series, calculate the departure from the mean daily value for that month of each daily value of evaporation and the meteorological variable.

3. Carry out a linear regression between the departures from the monthly mean of the evaporation (dependant variable) and the meteorological variable. This should be done for all the values available for each month of the year i.e. use all the available values for January from all the years and repeat for each subsequent month. The result will be 12 values of slopes and intercepts, one pair for each month.

4. Using the aggregated evaporation time series and the daily time series of the meteorological variable for the same period, calculate the mean daily evaporation and the mean daily value of the meteorological variable for each month.

5. Calculate the time series of disaggregated daily values of evaporation. To do this, subtract the mean daily value of the meteorological variable of that month, $\overline{V}_m$, from the value of the meteorological variable, V_i, for each day. Calculate the departure from the mean daily evaporation using the appropriate values from the linear regression for that month for each day (the slope g_j and the intercept c_j for the j^{th} month of the year). Add these to the monthly mean daily evaporation, $\overline{E}_m$, i.e. to estimate the evaporation on day i, E_i:

$$E_i = \overline{E}_m + g_j(V_i - \overline{V}_m) + c_j$$

8 ASSESSING THE ACCURACY OF ESTIMATES OF OPEN WATER EVAPORATION

This chapter gives guidance on the likely accuracy of estimates of open water evaporation and presumes that the assumptions made by the methods, as detailed in Chapter 3, have been adhered to. A more detailed discussion on these issues can be found in Finch and Hall (2001). The analysis of errors was based on a limited number of sites and therefore cannot be considered comprehensive. As a result, the values given should be used for guidance rather than being regarded as rigorous. The PENSE system used by the Southern Region is a simulation of MORECS and so has not been considered separately.

8.1 Measurement errors

Meteorological measurements are the ultimate source of the data used by Agency staff for estimating open water evaporation, whether these are used directly in the equilibrium temperature method or indirectly for generating grass potential evaporation (PE) data sets. It is inevitable that these measurements will not be perfect and thus some degree of error will occur in estimates of open water evaporation as a result. The following discussion assumes a "worst case scenario", i.e. that the errors are systematically above or below by the accuracy stated for an instrument. They are also considered in isolation, whereas in practice, all the meteorological variables will have errors and thus the accuracy in the estimate of open water evaporation will result from the compound of these errors.

Estimates of evaporation are based on measurements of the incoming solar radiation, air temperature, wind speed and vapour pressure deficit. Errors in the measured wind speed result in the smallest errors in the estimated open water evaporation, generally less than ±1 % depending on the location of the meteorological station and the time step of the estimates and the method used. Therefore, it will be appreciated that measurement errors in the wind speed can be considered negligible. The accuracies due to errors in the air temperature and vapour pressure deficit are comparable with this, except when using PETCALC PE (see below). The accuracy is a function of the time step; at a daily or monthly time step it is lower, typically half compared with annual values. It does not vary much with the location of the meteorological station but is dependant on the method used for estimating open water evaporation. With the equilibrium temperature method the accuracy is around ±2 % for a daily time step, whilst it is of the order of ±3% when using empirical factors with MORECS PE. Estimates of open water evaporation produced by using empirical factors with PETCALC PE are very sensitive to errors in the measured air temperature varying being of the order of ±20% for daily values. The sensitivity for annual values is less, around ±12%.

The accuracy of both methods of estimating open water evaporation is dominantly determined by errors in the incoming solar radiation, except in the case of empirical factors applied to PETCALC PE. The equilibrium temperature method is more sensitive than the empirical factors method with errors in the estimated open water evaporation of the order of ±9% for a daily time step. For empirical factors applied to MORECS grass PE the errors are around ±6%. Annual values are less sensitive, typically the error is reduced by one percent. In the case of empirical factors applied to PETCALC PE, the accuracy is dominantly determined by errors in the air temperature and so the accuracy resulting from errors in the incoming solar radiation are about ±4%.

8.2 Altitude correction

The accuracies of the monthly and daily values have a distinct seasonal difference. During the summer months (May to October incl.) the accuracy, expressed as a percentage, is much better than during the winter months. For stations that can be considered climatically similar to the site of interest, the accuracy during the summer months is ±20% on average. During the winter months this falls to ±150% with the highest errors occurring in January and February. The accuracy in the winter months may seem low but it is important to remember that the evaporation rates are much lower than those during summer (the evaporation rate in December is very roughly a fifth of that in June). It should be noted that the accuracy will be a function of the difference in height between the meteorological station and the site of interest. The greater the difference, the greater the error.

Estimates of the annual open water evaporation are less susceptible to errors in the correction for altitude. Accuracies of better than ±12 % can be attained using data from a meteorological station in the same climatic region.

8.3 Effect of regional differences in climate

The accuracy is significantly worse when data from stations that are clearly not in the same climate region are used. During the summer months the accuracy of monthly and daily estimates of open water are around ±50% but during the winter months this decreases to ±250%. For annual estimates the accuracy is better but can still be worse than ±30%.

8.4 Others

A number of other factors can potentially have an impact on the accuracy of estimates of open water evaporation. However, it is not currently possible to provide quantitative assessments of the impact, only qualitative. Most of these factors are deviations from the assumptions described in Chapter 3.

The open water evaporation of water bodies on the scale of a hundred metres across and less may be overestimated if adjacent objects, e.g. trees or buildings, shelter the water body from the wind. Wind speed is normally recorded at sites where there is a fetch of several hundred metres clear of major obstructions. Therefore there is the potential for a significant difference between the measured wind speed and that over the water body with a resulting decrease in the accuracy of the estimated evaporation rates.

Larger water bodies often become thermally stratified during summer but this is not taken into account by either of the recommended methods. The result will be a decrease in the accuracy of estimates. The degree of thermal stratification exhibited by a water body will be a function of the climate and the size (area and depth) of the water body. In general, the larger the surface area of the water body the greater will be the depth to which thermal stratification extends in summer. The depth does have some impact but it is more as a limit, i.e. a shallow water body will not become thermally stratified because the water will always be mixed by wind driven waves. The major impact of thermal stratification is on the changes in the evaporation rate through the seasons, increasing it during autumn and winter and decreasing it during spring and summer. Thus the accuracy will decrease for sub-annual estimates of evaporation more than annual estimates.

Turbid water will reflect more of the incoming solar radiation than clear water, resulting in a decrease in evaporation rates. Thus, increasing turbidity will result in decreasing accuracy in estimates of open water evaporation. However, this can be taken into account by the use of an appropriate value for the shortwave albedo used in the equilibrium temperate model.

If there is a net flow of heat between the water body and the surrounding substrate then the accuracy of estimates of open water evaporation will be reduced. The accuracy of annual estimates is likely to be unaffected (because the net exchange over the year is likely to be close to zero). However sub-annual estimates could be affected. Deep water bodies often show little thermal variation near the bottom so the net heat exchange can be assumed to be zero. However, the effect can be pronounced in shallow water bodies because some of the incoming solar radiation will pass through the water column and be absorbed by the substrate, increasing its temperature and thus resulting in a net heat flow from the substrate into the water.

Inflows and outflows of water could change the heat stored in the water body and thus affect the evaporation rates with a reduction in the accuracy of the estimated open water evaporation. The decrease in the accuracy will be a function of the size of the flows and their temperatures, compared to the volume of the water body and its temperature, i.e. if there are no flows or the temperature of the inflow is that of the water body then there will be no decrease in accuracy.

9 REFERENCES

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ANNEXE A – LIST OF SYMBOLS

c specific heat of water
c_j intercept of the linear regression between departures of the daily evaporation from the mean daily evaporation and the daily meteorological variable and the mean daily meteorological variable for the j^{th} month of the year
c_p specific heat of air at constant pressure
E evaporation rate from a water body
E_i estimated daily evaporation on day i
$\overline{E}_m$ monthly mean daily evaporation of month m
e vapour pressure of the air at the reference height.
e_a^* saturated vapour pressure of the air at air temperature
$f(u)$ wind function of wind speed u
g_j slope of the linear regression between departures of the daily evaporation from the mean daily evaporation and the daily meteorological variable and the mean daily meteorological variable for the j^{th} month of the year
k von Karman's constant
$K\downarrow$ incoming shortwave (solar) radiation
$L\downarrow$ incoming longwave (thermal) radiation
$L\uparrow$ outgoing longwave (thermal) radiation
N change in the energy storage in the water
p cloudiness factor
R_n net input of radiation at the surface of the water body
R_n^* net radiation when the water temperature is equal to the wet bulb temperature
r_a aerodynamic resistance
T_a air temperature at a reference height
T_e equilibrium temperature
T_n wet-bulb temperature
$T_{w,i}$ water temperature at the end of the current day
$T_{w,i-1}$ water temperature at the end of the previous day
t length of the model time step
u_z wind speed at z m above the surface
V_i value of the meteorological variable on day i
$\overline{V}_m$ mean daily value of the meteorological variable of month m
z water depth
z_o roughness length
z_r height of the meteorological observations above the surface
α_S albedo for short wave radiation
Δ slope of the saturated vapour pressure-temperature curve at air temperature
Δ_w slope of the temperature-saturation water vapour curve at the wet bulb temperature (kPa $^o C^{-1}$)

σ	Stefan-Boltzmann constant
ρ	density of water
ρ_a	density of air
τ	time constant
γ	psychometric constant
λ	latent heat of vaporisation
λE	flux of latent heat (evaporation rate in energy flux units)

ANNEXE B – DAY NUMBERS

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	32	60	91	121	152	182	213	244	274	305	335
2	2	33	61	92	122	153	183	214	245	275	306	336
3	3	34	62	93	123	154	184	215	246	276	307	337
4	4	35	63	94	124	155	185	216	247	277	308	338
5	5	36	64	95	125	156	186	217	248	278	309	339
6	6	37	65	96	126	157	187	218	249	279	310	340
7	7	38	66	97	127	158	188	219	250	280	311	341
8	8	39	67	98	128	159	189	220	251	281	312	342
9	9	40	68	99	129	160	190	221	252	282	313	343
10	10	41	69	100	130	161	191	222	253	283	314	344
11	11	42	70	101	131	162	192	223	254	284	315	345
12	12	43	71	102	132	163	193	224	255	285	316	346
13	13	44	72	103	133	164	194	225	256	286	317	347
14	14	45	73	104	134	165	195	226	257	287	318	348
15	15	46	74	105	135	166	196	227	258	288	319	349
16	16	47	75	106	136	167	197	228	259	289	320	350
17	17	48	76	107	137	168	198	229	260	290	321	351
18	18	49	77	108	138	169	199	230	261	291	322	352
19	19	50	78	109	139	170	200	231	262	292	323	353
20	20	51	79	110	140	171	201	232	263	293	324	354
21	21	52	80	111	141	172	202	233	264	294	325	355
22	22	53	81	112	142	173	203	234	265	295	326	356
23	23	54	82	113	143	174	204	235	266	296	327	357
24	24	55	83	114	144	175	205	236	267	297	328	358
25	25	56	84	115	145	176	206	237	268	298	329	359
26	26	57	85	116	146	177	207	238	269	299	330	360
27	27	58	86	117	147	178	208	239	270	300	331	361
28	28	59	87	118	148	179	209	240	271	301	332	362
29	29	60	88	119	149	180	210	241	272	302	333	363
30	30		89	120	150	181	211	242	273	303	334	364
31	31		90		151		212	243		304		365

Add 1 to shaded values during leap years

ANNEXE C – LOCATIONS AND MEAN ELEVATIONS OF THE MORECS GRID SQUARES

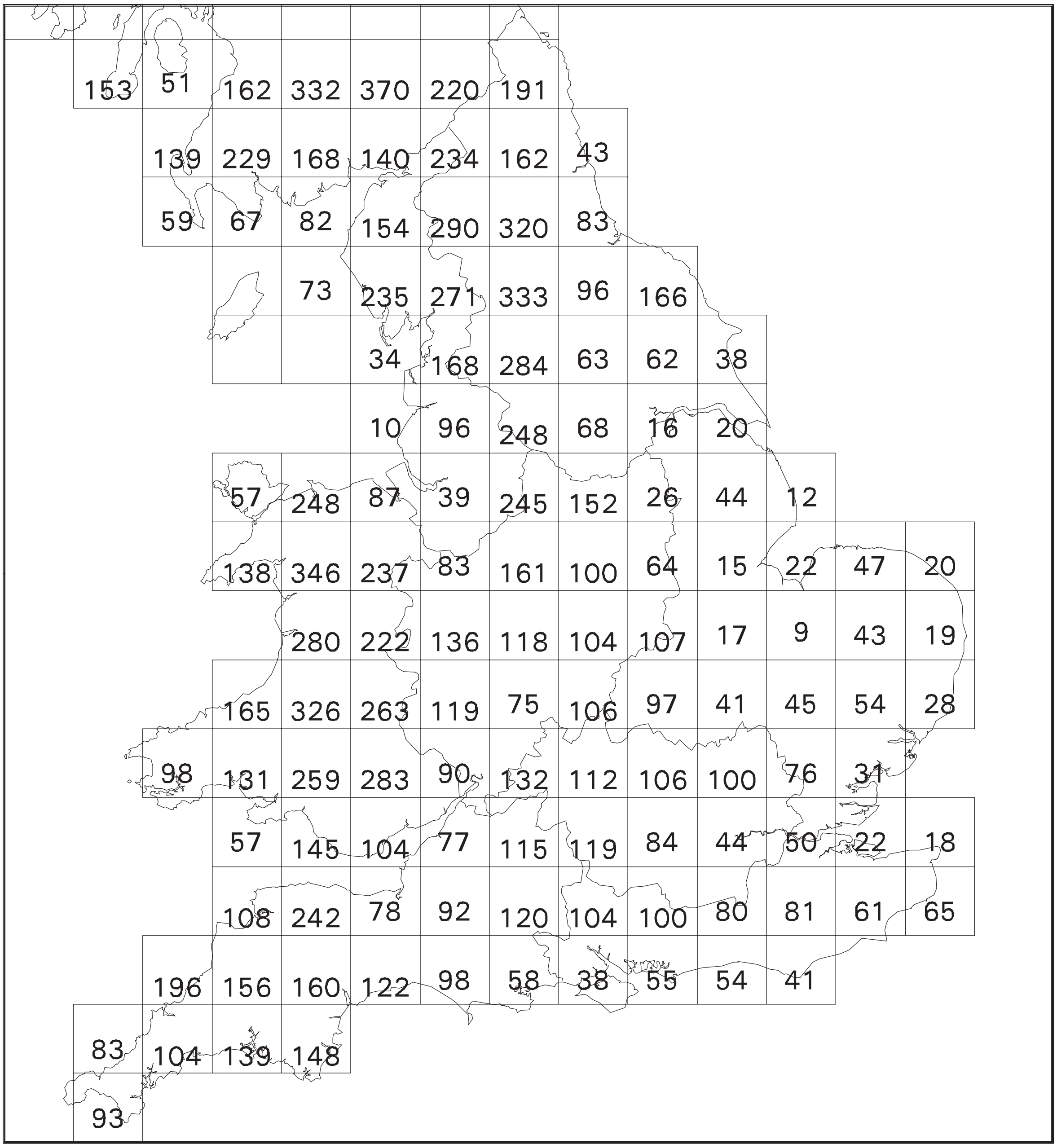

Figure C.1 **Mean elevation of the MORECS squares (m).**

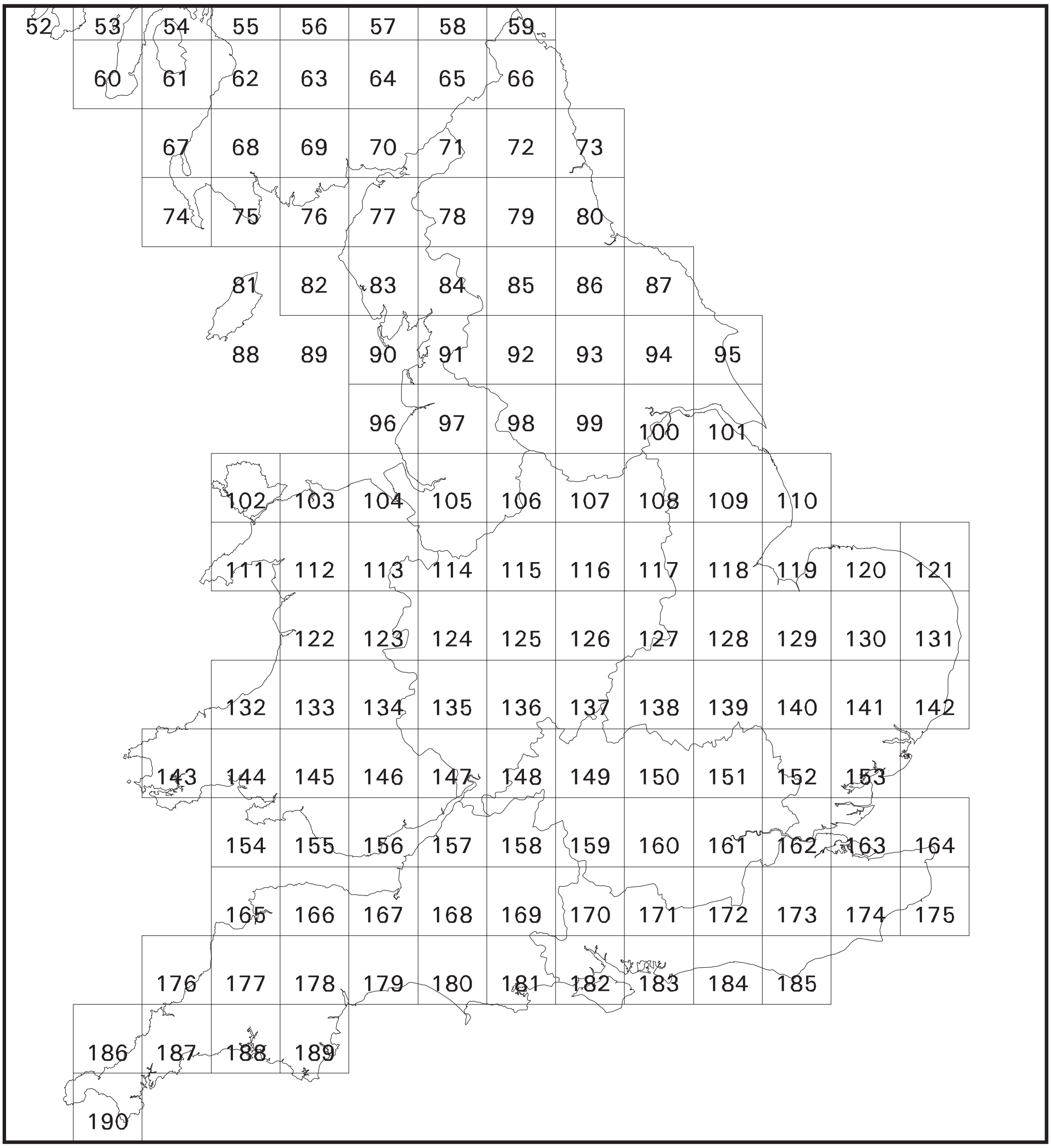

Figure C.2 Locations of the MORECS squares.

MORECS	Bottom left corner		Top right corner	
grid square	Easting	Northing	Easting	Northing
59	3800	6400	4200	6800
66	3800	6000	4200	6400
71	3400	5600	3800	6000
72	3800	5600	4200	6000
73	4200	5600	4600	6000
77	3000	5200	3400	5600
78	3400	5200	3800	5600
79	3800	5200	4200	5600
80	4200	5200	4600	5600
81	2200	4800	2600	5200
82	2600	4800	3000	5200
83	3000	4800	3400	5200
84	3400	4800	3800	5200
85	3800	4800	4200	5200
86	4200	4800	4600	5200
87	4600	4800	5000	5200
88	2200	4400	2600	4800
89	2600	4400	3000	4800
90	3000	4400	3400	4800
91	3400	4400	3800	4800
92	3800	4400	4200	4800
93	4200	4400	4600	4800
94	4600	4400	5000	4800
95	5000	4400	5400	4800
96	3000	4000	3400	4400
97	3400	4000	3800	4400
98	3800	4000	4200	4400
99	4200	4000	4600	4400
100	4600	4000	5000	4400
101	5000	4000	5400	4400
102	2200	3600	2600	4000
103	2600	3600	3000	4000
104	3000	3600	3400	4000
105	3400	3600	3800	4000
106	3800	3600	4200	4000
107	4200	3600	4600	4000
108	4600	3600	5000	4000
109	5000	3600	5400	4000
110	5400	3600	5800	4000
111	2200	3200	2600	3600
112	2600	3200	3000	3600
113	3000	3200	3400	3600
114	3400	3200	3800	3600
115	3800	3200	4200	3600
116	4200	3200	4600	3600
117	4600	3200	5000	3600
118	5000	3200	5400	3600

MORECS	Bottom left corner		Top right corner	
grid square	Easting	Northing	Easting	Northing
119	5400	3200	5800	3600
120	5800	3200	6200	3600
121	6200	3200	6600	3600
122	2600	2800	3000	3200
123	3000	2800	3400	3200
124	3400	2800	3800	3200
125	3800	2800	4200	3200
126	4200	2800	4600	3200
127	4600	2800	5000	3200
128	5000	2800	5400	3200
129	5400	2800	5800	3200
130	5800	2800	6200	3200
131	6200	2800	6600	3200
132	2200	2400	2600	2800
133	2600	2400	3000	2800
134	3000	2400	3400	2800
135	3400	2400	3800	2800
136	3800	2400	4200	2800
137	4200	2400	4600	2800
138	4600	2400	5000	2800
139	5000	2400	5400	2800
140	5400	2400	5800	2800
141	5800	2400	6200	2800
142	6200	2400	6600	2800
143	1800	2000	2200	2400
144	2200	2000	2600	2400
145	2600	2000	3000	2400
146	3000	2000	3400	2400
147	3400	2000	3800	2400
148	3800	2000	4200	2400
149	4200	2000	4600	2400
150	4600	2000	5000	2400
151	5000	2000	5400	2400
152	5400	2000	5800	2400
153	5800	2000	6200	2400
154	2200	1600	2600	2000
155	2600	1600	3000	2000
156	3000	1600	3400	2000
157	3400	1600	3800	2000
158	3800	1600	4200	2000
159	4200	1600	4600	2000
160	4600	1600	5000	2000
161	5000	1600	5400	2000
162	5400	1600	5800	2000
163	5800	1600	6200	2000
164	6200	1600	6600	2000
165	2200	1200	2600	1600
166	2600	1200	3000	1600

MORECS grid square	Bottom left corner Easting	Northing	Top right corner Easting	Northing
167	3000	1200	3400	1600
168	3400	1200	3800	1600
169	3800	1200	4200	1600
170	4200	1200	4600	1600
171	4600	1200	5000	1600
172	5000	1200	5400	1600
173	5400	1200	5800	1600
174	5800	1200	6200	1600
175	6200	1200	6600	1600
176	1800	800	2200	1200
177	2200	800	2600	1200
178	2600	800	3000	1200
179	3000	800	3400	1200
180	3400	800	3800	1200
181	3800	800	4200	1200
182	4200	800	4600	1200
183	4600	800	5000	1200
184	5000	800	5400	1200
185	5400	800	5800	1200
186	1400	400	1800	800
187	1800	400	2200	800
188	2200	400	2600	800
189	2600	400	3000	800
190	1400	0	1800	400

ANNEXE D – THE EQUILIBRIUM TEMPERATURE METHOD

The equilibrium temperature method is implemented in the form of a model, in which the time constant, τ, is defined as:

$$\tau = \frac{\rho c z}{4\sigma(T_n + 273.13)^3 + \lambda f(u)(\Delta_w + \gamma)}$$

and the equilibrium temperature, T_e, as:

$$T_e = T_n + \frac{R_n^*}{4\sigma(T_n + 273.13)^3 + \lambda f(u)(\Delta_w + \gamma)}$$

where ρ is the density of water = 1000 (kg m^{-3}), c the specific heat of water = 0.0042 (MJ kg^{-1} ºC^{-1}), z the depth of the water, T_n the wet bulb temperature (ºC) and Δ_w the slope of the temperature-saturation water vapour curve at the wet bulb temperature (kPa ºC^{-1}). The wind function, $\lambda f(u)$, is:

$$\lambda f(u) = 0.864(4.4 + 1.82u_z)$$

where u_z is the wind speed at height z_r (m s^{-1}), the height of the measurement above the water surface. The net radiation, if the surface were at the wet bulb temperature, is calculated using:

$$R_n^* = K^{\downarrow}(1-\alpha_s) + L^{\downarrow} - p(\sigma(T_a + 273.13)^4 + 4\sigma(T_a + 273.13)^3(T_n - T_a))$$

where $K^{\downarrow}$ is the incoming short-wave radiation (MJ m^{-2} d^{-1}), α_s the shortwave albedo of the water surface, $L^{\downarrow}$ the incoming long-wave radiation (MJ m^{-2} d^{-1}), p the cloudiness factor, σ the Stefan-Boltzman constant = 4.9 x 10^{-9} (MJ m^{-2} ºC^{-4} d^{-1}) and T_a the air temperature at the screen height (ºC). The water temperature on day j, $T_{w,j}$, is calculated as:

$$T_{w,j} = T_e + (T_{w,j-1} - T_e)e^{t/\tau}$$

where t is the model time step (and also of the input driving variables) in days. Thus the change in heat storage, N (MJ m^{-2} d^{-1}), is given by:

$$N = \rho c z(T_{w,j} - T_{w,j-1})$$

Estimates of the heat storage made in this manner can then be used in the Penman-Monteith combination model. The net radiation, R_n (MJ m^{-2} d^{-1}), is then:

$$R_n = K^{\downarrow}(1-\alpha_s) + L^{\downarrow} - p(\sigma(T_a + 273.13)^4 + 4\sigma(T_a + 273.13)^3(T_{w,j-1} - T_a))$$

and the evaporation can be estimated using the Penman-Monteith model in the form:

$$\lambda E = \frac{\Delta(R_n - N) + 86400\rho_a c_p (e_a^* - e)/r_a}{\Delta + \gamma}$$

where λ is the latent heat of vaporization ≈ 2.45 (MJ kg^{-1}), E the evaporation rate (mm d^{-1}), Δ the slope of the temperature-saturation water vapour curve at air temperature (kPa $^oC^{-1}$, γ the psychrometric constant (kPa $^oC^{-1}$), e_a^* the saturated vapour pressure at screen height (kPa) and e the vapour pressure at screen height (kPa). The aerodynamic resistance, r_a (s m^{-1}), is defined as:

$$r_a = \frac{\log(z_r / z_0)^2}{k^2 u_z}$$

where k is von Karman's constant = 0.41, z_r the height of the measurements above the surface (m) and z_0 is the roughness length for momentum and water vapour (m). The roughness lengths are assumed to have the same value because water is a comparatively smooth surface.

ANNEXE E – FORTRAN-90 SUBROUTINE CODE OF THE EQUILIBRIUM TEMPERATURE MODEL

```
!***********************************************************************
   subroutine equibtemp(albedo,depth,tstep,vpd,u,ta,tn,solrad,
   & longrad,fc,tw0,z0,rn,le,deltas,tw,evap,ierr)
!***********************************************************************
!  SUBROUTINE TO CALCULATE THE EVAPORATION, USING DAILY DATA, FROM A
!  WATER BODY USING THE EQUILIBRIUM TEMPERATURE MODEL OF de Bruin,
!  H.A.R., 1982, J.Hydrol, 59, 261-274
!  INPUT:
!    ALBEDO - ALBEDO OF THE WATER BODY
!            DEPTH - DEPTH OF THE WATER BODY (m)
!    TSTEP - THE TIME STEP FOR THE MODEL TO USE (days)
!    VPD - VAPOUR PRESSURE DEFICIT (mb)
!    U - WIND SPEED (m s-1)
!    TA - AIR TEMPERATURE (deg.C)
!    TN - WET BULB TEMPERATURE (deg.C)
!    SOLRAD - DOWNWELLING SOLAR RADIATION (W m-2 per day)
!    LONGRAD - DOWNWELLING LONG WAVE RADIATION (W m-2 per day)
!    FC - CLOUDINESS FACTOR
!    TW0 - TEMPERATURE OF THE WATER ON THE PREVIOUS TIME STEP (deg.C)
!  OUTPUT:
!    RN - NET RADIATION (W m-2 per day)
!    LE - LATENT HEAT FLUX (W m-2 per day)
!    DELTAS - CHANGE IN HEAT STORAGE (W m-2 per day)
!    TW - TEMPERATURE OF THE WATER AT THE END OF THE TIME PERIOD
!      (deg.C)
!    EVAP - EVAPORATION CALCULATED USING THE PENMAN-MONTEITH FORMULA
!       (mm per day)
!    IERR - ERROR FLAG
!        0 = OK
!        1 = ALBEDO =< 0 OR => 1
!        2 = DEPTH =< 0
!        3 = AIR TEMPERATURE < WET BULB TEMPERATURE
!        4 = DOWNWELLING SOLAR RADIATION =< 0
!        5 = WIND SPEED < 0.01 m/s
!        6 = VPD =< 0
!  CONSTANTS
!    LAMBDA - LATENT HEAT OF VAPORISATION (MJ kg-1)
!    GAMMA - PSCHROMETRIC CONSTANT (kPa deg.C-1)
!    RHOW - DENSITY OF WATER (kg m-3)
!    CW - SPECIFIC HEAT OF WATER (MJ kg-1 deg.C-1)
!    RHO - DENSITY OF AIR (kg m-3)
!    CP - SPECIFIC HEAT OF AIR (KJ kg-1 deg.C-1
!    SIGMA - STEFAN-BOLTZMANN CONSTANT (MJ m-2 deg.C-4 d-1)
!    K - VON KARMAN CONSTANT
!    DEGABS - DIFFERENCE BETWEEN DEGREES KELVIN AND DEGREES CELSIUS
!    ZR - HEIGHT OF MEASUREMENTS ABOVE WATER SURFACE (m) ASSUMED TO BE
!       SCREEN HEIGHT
!  OTHERS
!    DELTAW - SLOPE OF THE TEMPERATURE-SATUARTION WATER VAPOUR CURVE
!        AT WET BULB TEMPERATURE
!        (kPa deg C-1)
!    DELTAA - SLOPE OF THE TEMPERATURE-SATUARTION WATER VAPOUR CURVE
!        AT AIR TEMPERATURE
!        (kPa deg C-1)
!    TAU - TIME CONSTANT OF THE WATER BODY (days)
!    TE - EQUILIBRIUM TEMPERATURE (deg. C)
```

```
!    WINDF - SWEER'S WIND FUNCTION
!
      implicit none
      integer ierr
      real albedo,cp,cw,degabs,depth,deltaa,deltas,deltaw,evap,
     & evappm,fc,gamma,k,lambda,le,lepm,longrad,lradj,ra,rho,rhow,rn,
     & rns,sigma,solrad,sradj,ta,tau,te,tn,tstep,tw,tw0,u,ut,vpd,vpdp,
     & windf,z0,zr
      real alambdat,delcalc,psyconst
!
!   SETUP CONSTANTS
!
      lambda=alambdat(ta)
      gamma=psyconst(100.0,lambda)
      rhow=1000.0
      cw=0.0042
      rho=1.0
      cp=1.013
      sigma=4.9e-9
      k=0.41
      degabs=273.13
      zr=10.0
!
!   INITIALISE OUTPUT VARIABLES
!
      ierr=0
      deltas=0.0
      evap=0.0
      evappm=0.0
      le=0.0
      lepm=0.0
      rn=0.0
      tw=0.0
!
!   CHECK FOR SIMPLE ERRORS
!
      if (albedo.le.0.0.or.albedo.ge.1.0) then
        ierr=1
        return
      endif
      if (depth.le.0) then
        ierr=2
        return
      endif
      if (tn.gt.ta) ierr=3
      if (solrad.le.0.) ierr=4
      ut=u
      if (ut.le.0.01) then
        ierr=5
        ut=0.01
      endif
      if (vpd.le.0.0) then
        ierr=6
        vpd=0.0001
      endif
!
!   CONVERT FROM W m-2 TO MJ m-2 d-1
!
      sradj=solrad*0.0864
      lradj=longrad*0.0864
```

```
!
!  CONVERT FROM mbar TO kPa
!
     vpdp=vpd*0.1
!
! CALCULATE THE SLOPE OF THE TEMPERATURE-SATURATION WATER VAPOUR CURVE
! AT THE WET BULB TEMPERATURE (kPa deg C-1)
!
     deltaw=delcalc(tn)
!
! CALCULATE THE SLOPE OF THE TEMPERATURE-SATURATION WATER VAPOUR CURVE
! AT THE AIR TEMPERATURE (kPa deg C-1)
!
     deltaa=delcalc(ta)
!
!  CALCULATE THE NET RADIATION FOR THE WATER TEMPERATURE (MJ m-2 d-1)
!
     lradj=fc*sigma*(ta+degabs)**4*(0.53+0.067*sqrt(vpd))
     rn=sradj*(1.-albedo)+lradj-fc*(sigma*(ta+degabs)**4+
    &  4.*sigma*(ta+degabs)**3*(tw0-ta))
!
!  CALCULATE THE NET RADIATION WHEN THE WATER TEMPERATURE EQUALS THE WET
!          BULB TEMPERATURE. ASSUMES THE EMISSIVITY OF WATER IS 1 (MJ m-2 d-1)
!
     rns=sradj*(1.-albedo)+lradj-fc*(sigma*(ta+degabs)**4+
    &  4.*sigma*(ta+degabs)**3*(tn-ta))
!
!  CALCULATE THE WIND FUNCTION (MJ m-2 d-1 kPa-1) USING THE METHOD OF
!          Sweers, H.E., 1976, J.Hydrol., 30, 375-401, NOTE THIS IS FOR
!          MEASUREMENTS FROM A LAND BASED MET. STATION AT A HEIGHT OF 10 m
!  BUT WE CAN ASSUME THAT THE DIFFERENCE BETWEEN 2 m AND 10 m IS
!  NEGLIGIBLE
!
     windf=(4.4+1.82*ut)*0.864
!
!  CALCULATE THE TIME CONSTANT (d)
!
     tau=(rhow*cw*depth)/
    &  (4.0*sigma*(tn+degabs)**3+windf*(deltaw+gamma))
!
!  CALCULATE THE EQUILIBRIUM TEMPERATURE (deg. C)
!
     te=tn+rns/(4.0*sigma*(tn+degabs)**3+windf*(deltaw+gamma))
!
!  CALCULATE THE TEMPERATURE OF THE WATER (deg. C)
!
     tw=te+(tw0-te)*exp(-tstep/tau)
!
!  CALCULATE THE CHANGE IN HEAT STORAGE (MJ m-2 d-1)
!
     deltas=rhow*cw*depth*(tw-tw0)/tstep
!
!  z0 - ROUGHNESS LENGTH
!  DUE TO SMOOTHNESS OF THE SURFACE THE ROUGHNESS LENGTHS OF MOMENTUM
!  AND WATER VAPOUR CAN BE ASSUMED TO BE THE SAME
!
     z0=0.001
!
!  CALCULATE THE AERODYNAMIC RESISTANCE ra (s m-1)
!
```

```
      ra=alog(zr/z0)**2/(k*k*ut)
!
!  CALCULATE THE PENMAN-MONTEITH EVAPORATION
!
      le=((deltaa*(rn-deltas)+86.4*rho*cp*vpdp/ra)/(deltaa+
     &   gamma))
      evap=le/lambda
!
!  CONVERT THE FLUXES TO W m-2
!
      rn=rn/0.0864
      le=le/0.0864
      deltas=deltas/0.0864
      return
      end
!**********************************************************************
      function delcalc(ta)
!**********************************************************************
!  FUNCTION TO CALCULATE THE SLOPE OF THE VAPOUR PRESSURE CURVE
!  SEE ALLEN ET AL (1994) ICID BULL. 43(2) PP 35-92
!  INPUT
!    TA - AIR TEMPERATURE (deg. C)
!  OUTPUT
!    DELCALC - SLOPE OF THE VAPOUR PRESSURE CURVE (kPa deg. C-1)
!
      implicit none
      real delcalc,ta,ea
      ea=0.611*exp(17.27*ta/(ta+237.3))
      delcalc=4099*ea/(ta+237.3)**2
      return
      end
!**********************************************************************
      function alambdat(t)
!**********************************************************************
!
!  FUNCTION TO CORRECT THE LATENT HEAT OF VAPORISATION FOR TEMPERATURE
!
!  INPUT:
!    T = TEMPERATURE (deg. C)
!  OUTPUT:
!    ALAMBDAT = LATENT HEAT OF VAPORISATION (MJ kg-1)
!
      implicit none
      real alambdat,t
      alambdat=2.501-t*2.2361e-3
      return
      end
!**********************************************************************
      function psyconst(p,alambda)
!**********************************************************************
!  FUNCTION TO CALCULATE THE PSYCHROMETRIC CONSTANT FROM ATMOSPHERIC
!  PRESSURE AND LATENT HEAT OF VAPORISATION
!  INPUT:
!     P = ATMOSPHERIC PRESSURE (kPa)
!     ALAMBDA = LATENT HEAT OF VAPORISATION (MJ kg-1)
!  OUTPUT:
!     PSYCONST = PSYCHROMETRIC CONSTANT (kPa deg. C-1)
!
      implicit none
      real psyconst,p,alambda,cp,eta
```

```
cp=1.013
eta=0.622
psyconst=(cp*p)/(eta*alambda)*1.0e-3
return
end
```