2.12 Mean Annual Potential Evaporation Depth as Grass Reference Evapotranspiration

Evaporation is the transformation of water into water vapour at temperatures below the boiling point. Even at temperatures below zero water continues to evaporate, for instance from snow surfaces or ice covers. However, not only water surfaces or wet land surfaces contribute to evaporation, even soils that appear dry evaporate as long as the soil capillaries transport water to the surface. This direct release of water vapour from vegetation-free surfaces is called *evaporation*. Plants release water that was taken up by their roots into the air by *transpiration*.

Precipitation and evapotranspiration are the two main components of the global cycle of water. They also play a major role in the energy budget of the atmosphere and are the driving forces of all weather phenomena. Through evapotranspiration a large portion of precipitation is returned into the atmosphere. Evapotranspiration consumes energy; it is associated with cooling, the so-called evaporative cooling. Conversely, the latent heat bound in water vapour is released again through condensation.

Over land surfaces, the amount of evapotranspiration depends on several factors: on climatic conditions, e.g. energy supply or the saturation deficit of the air, on relief, but also on the type and density of vegetation, interception, soil composition and its water-storage.

Evapotranspiration measurements over vegetated surfaces are rather difficult and expensive; only few stations can boast long time series of such data. That is why the evapotranspiration is determined as an approximation from easily measurable meteorological factors or from soil and vegetation parameters. As a first step, the *potential evaporation* is computed from meteorological parameters. It is defined in the German Standard DIN 4049 as: Total evaporation plus transpiration [in mm] from a uniform stand of short vegetation under given meteorological conditions and unlimited supply of water.

Over a short vegetation stand *actual evapotranspiration* is less than the potential value defined above only if the soil dries up below a critical value and the plants have to restrict their transpiration. With a sufficient water supply from precipitation or from the soil, potential and actual evapotranspiration are nearly identical. Thus, as a rule, potential evaporation constitutes the upper limit of the evapotranspiraton, so that it is a reference value for many applications. On taller vegetation stands, e.g. cereals, actual evapotranspiration during the growth phase may be higher than the reference evapotranspiration measured over grass (Fig. 1). An evaporation value is assigned to each day, in winter less than 1 mm and in summer at maximum 6 to 7 mm per day. The sum of these daily amounts yields the annual potential evaporation depth in mm, here averaged over the period 1961 to 1990. This information is essential for many sectors. In water-resources management it signifies the loss component in the water-balance equation, in hydrology it serves as the input in water-balance models and in agriculture it allows an estimation of how much water the crop stocks may take up from the soil.

Determination of evapotranspiration by mathematical modelling

Mathematical modelling is based on the assumption that complex natural processes, such as evapotranspiration, may be described with sufficient accuracy by climate data and other available parameters. This description is usually made by simple or complicated computation procedures, the models. Older, empirical methods for the determination of potential evaporation were developed by Haude, Thornthwaite, Turc, etc. A common procedure is the Penman method. However, these models have only limited regional validity and, moreover, their results differ (Table 1).

Table 1 **Mean annual evapotranspiration totals (potential and actual) determined by different empirical methods from maps for the lower Main river basin between Frankfurt a. M., Offenbach, and Hanau**

Method	ETP depth
Haude-method (DOMMERMUTH et al. 1990)	680 mm/a
Water equivalent of net radiation (KELLER 1979)	670 mm/a
Potential evapotranspiration according to Penman (KELLER 1979)	625 mm/a
Actual evapotranspiration from precipitation and runoff (KELLER 1979)	550 mm/a
Actual evapotranspiration according to Albrecht (KELLER 1979)	440 mm/a
For comparison: Grass reference evapotranspiration (WENDLING 1995)	596 mm/a

The international uniform standard for the computation of potential evaporation is the *grass reference evapotranspiration* ET_0 (ALLEN et al. 1994), which is based on the Penman-Monteith model. It describes the evapotranspiration process in a physically exact way on the basis of the influencing meteorological factors and the various forms of resistance through which soils and plants retain the water. For the computation of the grass reference evapotranspiration ET_0, the above-mentioned resistances to evapotranspiration are taken for a short stand of grass of 12 cm height which has unlimited water available in its root zone. In general, with a soil water storage in the root zone, plants can potentially transpire between 50 and 100 % of the available field capacity.

For climatological purposes, the mean monthly grass reference evapotranspiration ET_0 can be determined from the monthly means of air temperature T in °C and the global radiation R_G^*. The necessary calibration gives a correction, which depends on the elevation h (in m above sea level) (WENDLING 1995, see also DIN 19685), so that the relation is

$$ET_0 = g(T)\cdot(0{,}65\cdot R_G^{\ *} + 7{,}6\cdot k)\cdot\frac{1}{1+0{,}00019\cdot h} \qquad (1)$$

with $g(T) = s/(s+\gamma)$ being a temperature function, computed from the gradient of the curve of saturation vapour pressure and the psychrometer constant γ; k is a coastal factor which ranges in coastal areas between 0.5 and 1. The global radiation R_G^* is given as the monthly evapotranspiration equivalent in mm and is determined from the duration of sunshine. For elevations above 600 m, one sets h = 600.

The grass reference evapotranspiration ET_0 is a physically defined potential evaporation value that can be computed uniformly in all countries from the data of climate stations. Information on the respective vegetation cover, the momentary soil-water storage or slope gradient and exposition of the site are not included. These site characteristics find consideration only in a second computation step, which yields the actual evapotranspiration amount (cf. Map 2.13 "Mean Annual Actual Evapotranspiration Depth").

Map Structures

The potential evapotranspiration totals computed by means of Equation (1) may be mapped with the numerical method by MÜLLER-WESTERMEIER (1995), which is described in detail in the cover text of the maps of precipitation depths. Using an elevation database in a 1-km²-grid, first the needed input data, in this case the monthly values of relative duration of sunshine and air temperature, are interpolated over the grid. For both parameters values from all stations with 30-year time series are considered. For reasons of accuracy, the relative duration of sunshine at sun heights >15° are used for mapping to eliminate possible shielding effects of the horizon at the stations. The global radiation R_G^* in Equation (1) is computed from the relative duration of sunshine S_r by means of the following equation (WENDLING, FUCHS & MÜLLER-WESTERMEIER 1997):

$$R_G^{\ *} = R_0^{\ *}\cdot(0{,}20+0{,}46\cdot S_r) \qquad (2)$$

with R_0^* being the extraterrestrial radiation, which is also given as the monthly evapotranspiration equivalent in mm.

In the next step, the monthly grass reference evapotranspiration depths ET_0 are computed and added up for the annual sum. Map 2.12 shows for each grid square the mean annual evapotranspiration total. The colours of the squares stand for certain ranges of ET_0 in mm per year. The assignment code can be seen from the colour column in the map´s legend. As in the maps of precipitation depths, the graduation is in 50-mm steps. Only in the range from 500 to 600 mm/a are intermediate steps of 25 mm used to improve the presentation of regional differences.

The smallest potential evapotranspiration amounts were found in the elevated regions of the uplands and the Alps with 350 to 400 mm/a. The maxima occurred in the Karlsruhe region and in the Upper Rhine Plain near Freiburg/Breisgau with values above 650 mm/a. In those parts of Germany where agricultural land use prevails, the annual ET_0 total ranges between 525 and 600 mm/a. The values rise quite evenly from Schleswig-Holstein towards the south of Brandenburg and Saxony. Similar high values to those in Saxony occur also in the Rhine-Main Plain, in the adjacent Rhine Plain to the south and in smaller areas on the middle course of the River Main.

The map illustrates clearly the changing potential evapotranspiration amounts with increasing elevation, especially in the upland regions. In the north German lowlands, the annual ET_0 total rises by 32 mm/a from sea level towards elevations of 100 m due to the changing influences of the distance to the coast and the terrain height. Between 100 and 700 m above sea level, it decreases on average by 14 mm/a per 100 m difference in altitude.

The computed grass reference evapotranspiration ET_0 is in good agreement with values measured by weighable lysimeters. Figure 1 shows a comparison of the evapotranspiration totals measured in the year 1990 at four lysimeter stations (from the German IHP/OHP Yearbook) and the computed values. Both series are added up in monthly steps as annual sums. In the same manner, the associated precipitation amounts are shown as columns.

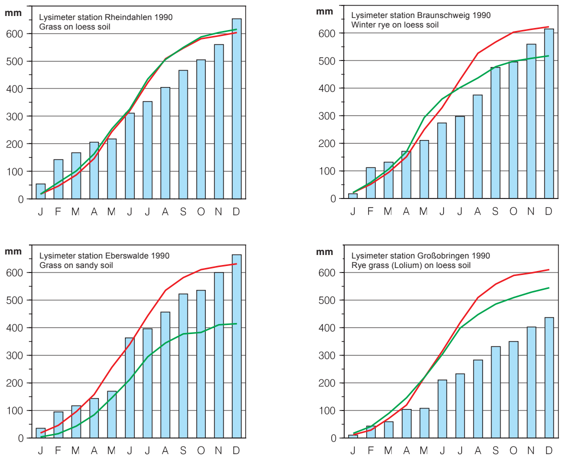

Fig. 1 **Monthly totals of grass reference crop evapotranspiration ET_0 (red lines) in comparison with measured actual evapotranspiration totals (green lines) and precipitation totals (columns) at four lysimeter stations**

At Mönchengladbach-Rheindalen, a site with loess soil and accordingly high water-storage capacity, the grass stock had an unrestricted supply of water during the year 1990 with its even water balance. In all months, actual and potential evapotranspiration depths were nearly identical. At Braunschweig with similar soil and a stand of winter rye, both curves run nearly parallel until June. The taller cereal plants transpire for a time a little bit more than a short grass stand. In August the rye is harvested and the lysimeter records only the much lower evaporation from the bare soil. Also at Großobringen near Weimar, a loess site with little rainfall, the measured actual evapotranspiration of a fodder grass stand coincides with the computed ET_0 until July. Only from August onwards with a beginning water shortage did the actual evapotranspiration drop below the potential one. The difference between precipitation total and evapotranspiration total during the individual year is compensated by the soil storage. Eberswalde, in contrast, has sandy soil with very low storage capacity. The actual evapotranspiration of a grass cover is already from March onwards markedly lower than ET_0, with a difference of about 50 % in the annual evapotranspiration totals.

If the precipitation depths P are included in the interpretation of the map of the grass reference evapotranspiration depth ET_0, then the climatic water balance KWB = P – ET_0 of different regions can be established (cf. Maps 2.5 "Mean Annual Corrected Precipitation Depths" and 2.14 "Climatic Water Balance"). However, the values of precipitation and evapotranspiration read from the map give only rough estimates. More exact data may be obtained from the databases of the Deutscher Wetterdienst (DWD, German Meteorological Service) that served as basis for the maps. Nevertheless, it is possible to identify, for example, where dry regions lie, like those in the lee of the Harz Mountains, or areas where surpluses may be found.

Practical Information

Compared to the grass reference evapotranspiration depths ET_0 shown in Map 2.12, the potential evaporation values obtained by older methods are usually too high. The totals computed by the Haude method are on average 8 % higher. As Table A on Map 2.12 and Figure 1 show, higher crop stands have more intensive evapotranspiration than ET_0 (valid for a grass stand 12 cm high). A cereal stand grown to a height of 80 cm would evaporate and transpire about 22 % more than ET_0. How the factors are to be applied in each case according to the prevailing land use, the height of crop stands and the portion of interception evaporation for computing the actual evapotranspiration from the potential one must be decided in each individual case. Here, only first hints are given for the use of the map of potential evaporation depths for specific forms of land uses.

Besides the mean annual evapotranspiration totals, their distribution over the months is also of interest (Table B on Map 2.12). The regional differences are less pronounced here than in the case of precipitation. For representative stations in areas dominated by different precipitation types (cf. cover text on Maps 2.3 and 2.4 "Mean Precipitation Depths of the Hydrological Half Years") the differences in the portions of the monthly evapotranspiration depths are merely 1 to 2 %. For a rough estimate of the monthly portions of potential evapotranspiration totals the averages given in Table B should be sufficient.

More detailed and use-oriented information is given in the DVWK Bulletin on Water Resources Management Nr 238/1996 "Determination of evaporation from land and water surfaces", which may also be helpful in combination with the map on potential evapotranspiration.