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Measurement and Mapping of Potential Evapotranspiration in a Small Mountainous Watershed

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The potential evapotranspiration *ETP* can be estimated by using Brochet and Gerbier's formula (1972), which is derived from Penman's equation

$$ETP \equiv m\, Rg + n\, Ep \text{ (mm/day)},$$

where *m* and *n* are tabulated coefficients depending on season, latitude and shelter type, and where the variables are the global solar radiation *Rg* and the Piche evaporation under shelter *Ep*.

In the small Ringelbach watershed (36 ha), in the Vosges Mountains (France), maps of daily *ETP* have been calculated with this formula, by mapping these two variables

- maps of daily global radiation have been computed for sunny days from horizontally measured *Rg*, by taking into account slopes, aspects and orographic masks.
- small and cheap Piche shelters, specially designed and calibrated, have been implanted over the whole watershed with *Ep* measured twice a day.

The results obtained for *Rg, Ep* and thus *ETP* reveal important differences within the watershed. Their spatial patterns depend on weather type, topographic structure, and soil surface humidity.

This mapping procedure, which gives a good estimation of *ETP,* enables us to better understand the hydrologic behaviour of any mountainous watershed.

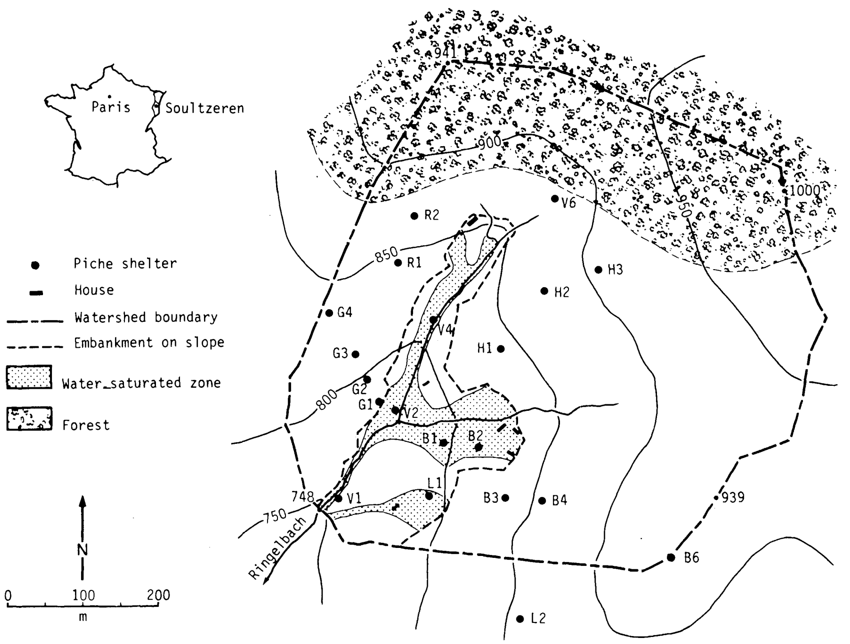

Fig. 1. Topographic map and Piche shelter network in the Ringelbach watershed.

Introduction

Actual evapotranspiration *ETR*, which is a main component of any hydrologic balance, is very difficult to determine directly, even at well-instrumented sites. In most cases *ETR* is estimated by using empirical formulae, where the upper limit of *ETR* must be fixed, corresponding to the climatic evaporative demand.

This limit called potential evapotranspiration *ETP* is also evaluated according to formulae using only climatic data. But most of these formulae are not very well adapted to fine topoclimatic or hydrologic studies: some of them give *ETP* estimates over too long time period (week, decade) for permitting us to get a good insight into the evaporative processes. Other formulae estimate daily *ETP* from climatic data which are not suitable to all cases: in mountains, for instance, where spatial variations of daily temperature amplitude can be very important (Paul 1980), daily mean temperature cannot be a significant climatic data for estimating *ETP*. At daily time level, the best *ETP* formula is Penman's equation or its derivatives.

On the other hand, evapotranspiration varies from one point to another. Such spatial variations cannot be estimated or detected by using most of those formulae which give global *ETP* estimates over a whole area. For many applications we need some practical and reliable procedure for taking into account the topoclimatic structure of the studied region when we determine its evapotranspiration.

This paper presents a method for measuring and mapping *ETP* in any mountainous watershed, where topographic structure influences considerably the evapotranspiration pattern. It has been applied to the Ringelbach watershed, near Soultzeren in the Vosges Mountains (France), where climatologic, hydrologic and geomorphologic processes and their interactions at watershed level have been studied since 1976.

This study catchment (Fig. 1) is a small (36 ha) valley incised in granitic bedrock with a main NNE-SSW direction. Its altitude is varying between 748-1,000 m. It is mostly covered with grass. The valley bottom is water-saturated most of the year.

Brochet and Gerbier's ETP Formula

According to Penman's equation, the potential evapotranspiration *ETP* (mm/day) of a vegetated land surface can be considered as the sum of two terms representing the contribution of both radiative and advective processes

$$ETP \equiv \frac{\Delta}{\Delta+\gamma} Rn + \frac{\gamma}{\Delta+\gamma} Ea \tag{1}$$

where Rn – the net radiation,

Ea – the air evaporating capacity, which depends on mean wind speed and on vapor pressure deficit at air temperature Ta,

Δ – the slope of the saturation vapor pressure curve for water at mean temperature Ta,

γ – the psychrometric constant.

Although rather precise and rigourous, this physically based formula is still not convenient for mapping *ETP* at a watershed level. To measure or compute the involved variables and parameters is difficult and expensive, and is therefore possible on only a very few points of a watershed.

Nevertheless, a good approximation of *ETP* (mm/day) according to Penman is provided by Brochet and Gerbier's formula (1972,75)

$$ETP = m\,Rg + n\ Ep \tag{2}$$

where Rg (J/cm^2/day) – the daily global radiation (radiative term),

Ep (mm/day) – the Piche evaporation under standardized shelter (advective term);

m and n – tabulated coefficients depending on latitude, season and shelter type; for example, by latitude N 48° 05' (Soultzeren), on July 2 and for a small plastic standard shelter their values are $m = 1.477 \times 10^{-3}$ and $n = 0.376$.

This simplified formula has been derived for France from Penman's equation by statistical adjustments and its validity has been confirmed (Seguin 1975). Its main advantages are that the two variables *Rg* and *Ep* are much easier to measure and to map, but also that it keeps the same structure: the two additive terms can be estimated and mapped independently.

Radiative Term

The global radiation *Rg* can vary a great deal accross a mountainous watershed according to slope, aspect and mask effect of relief. Maps of clear-sky global radiation can be performed by computing *Rg* for any chosen point from astronomic and topographic data, provided we have some *Rg* reference measurement. The precision and the validity of the results depend of course on the representativity of this reference for the studied area. The following procedure (Mercier 1980) has been applied to the Ringelbach watershed, where *Rg* measurements (made horizontally and continuously) are available at a meteorologic station 6 km away from the basin.

Global Radiation on Slope

The daily horizontal global radiation Rg_h is the sum of direct S_h and diffuse D_h radiations

$$Rg_h = S_h + D_h \tag{3}$$

For clear-sky conditions, the relation of Liu and Jordan (in Perrin de Brichambaut 1963) permits us to separate these two components in any horizontally measured Rg_h

$$\frac{D_h}{Rg_h} = 1 - 1.13\,\frac{Rg_h}{G_0} \tag{4}$$

where the extraterrestrial daily radiation G_0 can be computed from astronomic relations.

The corresponding values S_i and D_i on any versant are obtained by using the relations (Kondratiev 1960)

$$\frac{D_i}{D_h} = \cos^2\left(\frac{\beta}{2}\right) = 0.5(1+\cos\beta) \tag{5}$$

$$\frac{S_i}{S_h} = \int_{\text{sunrise}}^{\text{sundown}} [\cos\beta + \sin\beta \,\mathrm{tg}z \cos(\alpha-\eta)]\,dt \qquad (6)$$

where ß and η – the slope and aspect of the versant,

α – the solar azimuth,

z – the zenith angle.

Eq. (6) is integrated with ¼ h time increment over the day. The orographic mask is taken into account by adequately reducing the insolation duration at the rise and down of the sun.

A small approximate term R_i is also introduced for representing the radiation reflected by the other versants

$$R_i = a\,Rg_h \cos^2(\frac{\beta}{2}) \qquad (7)$$

where a – the mean albedo of these versants.

The sum of these 3 terms gives the global radiation on slope Rg_i

$$Rg_i = S_i + D_i + R_i \qquad (8)$$

Topographic Parameters

Available topographic maps at a 1:25,000 scale being not precise enough for such a test study, a more detailed map has been specially surveyed (Fig. 1). From this map have been derived a slope map (5° classes, mean slope of 19°) and an aspect map (45° classes, main WSW aspect) (Humbert et al 1981). Sunrise and sundown angle maps have been also determined for each season (solstices, equinoxes) by systematic topographic cross-sections (0° and ± 23.5° directions). In such a mountainous watershed these angles can rise up to 33° and cannot therefore be neglected.

The daily global radiation *Rg* and the radiative term *mRg* of Brochet and Gerbier's formula are then mapped by sampling the watershed: 90 points have been chosen, most of them at intersections of limits of slope and aspect classes (where these parameters are already known). On each point, *Rg* and *mRg* have been computed. *Rg* class limits have been obtained by linear interpolation between these points.

Example of Results

As an example of map resulting from this procedure, Fig. 2 shows the global radiation computed for July 2, 1981, a sunny anticyclonic day. This map reflects well the main topographic features of the watershed. A maximum radiation arrives on S or SSE versant with heavy slope, minimum on WNW versant. The

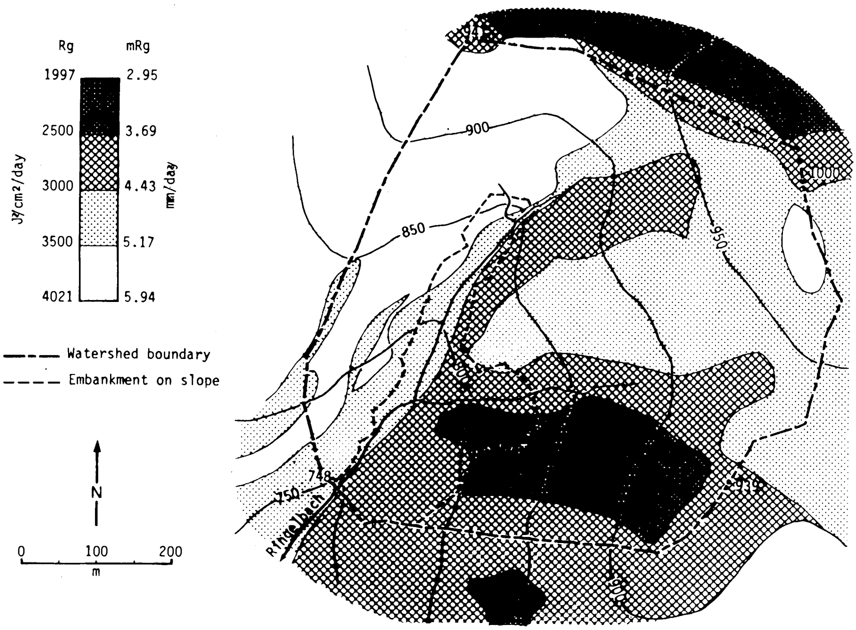

Fig. 2. Map of the global radiation Rg and the radiative term mRg on July 2nd 1981 in the Ringelbach watershed.

bottom of the small valley stands out between the two well-contrasted versants.

From this map, it appears that for this special day the gobal radiation can double in size from one point to another within the watershed: the extreme values are 1,997 and 4,021 J/cm^2/day. Further on, the mean global radiation over the watershed (3,064 J/cm^2/day) exceeds largely the horizontally measured global radiation (2,758 J/cm^2/day for this day). Without taking into account the topography, point measurements are not sufficient to understand the function of the watershed.

Advective Term

Piche Evaporometer and Shelter

The Piche evaporometer is a graduated glass tube, which is vertically placed in a shelter; its opening is down. Being filled up with water, it can evaporate through a standardized paper which is closely maintained to the opening. This evaporation is very sensible to shelter, tube and paper type and size. If carefully used, the Piche

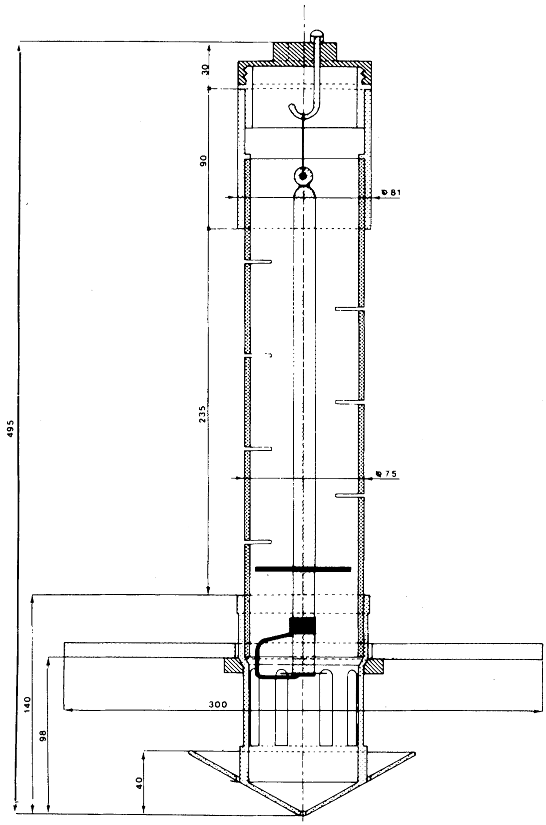

Fig. 3. Simplified Piche shelter – longitudinal cross-section – dimensions in mm.

evaporometer can give very reliable measurements.

The Piche evaporation under shelter *Ep* is easy to measure, but its mapping requires the implantation of shelters at many points of the watershed. The standard meteorological shelters being expensive, a small and cheap simplified shelter for the Piche evaporometer was specially designed with standard PVC components (Fig. 3). It was calibrated by systematic comparisons with a small plastic standard meteorological shelter (Najjar and Ambroise 1981).

Piche Network

From June 23 to July 7, 1981, 20 Piche evaporometers were implanted in the Ringelbach watershed in 3 small plastic standard shelters and 17 simplified PVC shelters. The measurements were made twice a day, at 6 a.m. and 6 p.m. U.T., and all Piche evaporometers were filled every morning. At 13 of these sites, the minimum and the maximum air temperatures were also measured. In the 3 stan-

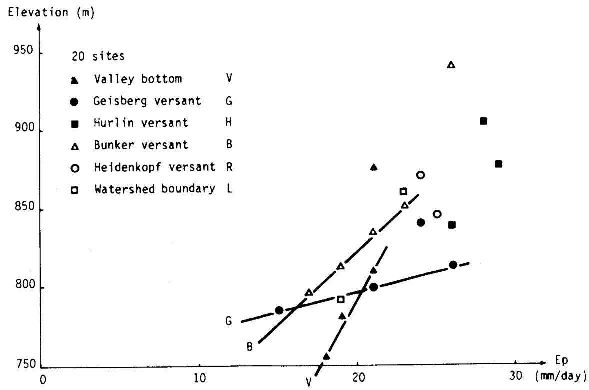

Fig. 4. Daily Piche evaporation Ep measured at 20 sites on July 2nd 1981 (1st, 6 P. M. – 2nd, 6 P. M.) in the Ringelbach watershed

dard shelters the air humidity and temperature were recorded.

According to the results of previous measurement periods (Najjar 1980), 20 places have been chosen along some transects, which are representative of the main topographic features of the watershed (Fig. 1)

- 4 on the bottom of the small NNE-SSW oriented valley, whose surface is mostly saturated with water (V1, V2, V4, V6),
- 4 on the Geisberg versant facing SSE, which is relatively dry (G1, G2, G3, G4),
- 3 on the Hurlin versant facing SW (H1, H2, H3),
- 5 on the Bunker versant facing W (B1, B2, B3, B4, B6),
- 4 on other slopes for having a preciser insight of evaporation spatial variations (R1, R2, L1, L2).

Example of Results

As an example, Fig. 4 shows daily Piche evaporation *Ep* measured on July 2, 1981, in these 20 sites. It reflects well the topoclimatic structure of the watershed. The evident increase of *Ep* with increasing altitude reveals in fact how strong is the influence of the air humidity and wind patterns on the Piche evaporation: *Ep* increases if wind w increases and humidity h decreases.

For instance, a minimum value is observed at G1 which is screened from wind and near the water-saturated zone (h=84%); and for two sites which are well exposed to dominant winds, *Ep* is higher at B6 (w=6.2 km/h, h=63%) than at G4 (w= 5 km/h, h= 72%).

There is also a clear differenciation between the equiped versants. The *Ep* variations are linear along each versant (V1,2,4; G1,2,3; B1,2,3), but variation rates depend on the orientation of the versants: the dry Geisberg versant is much

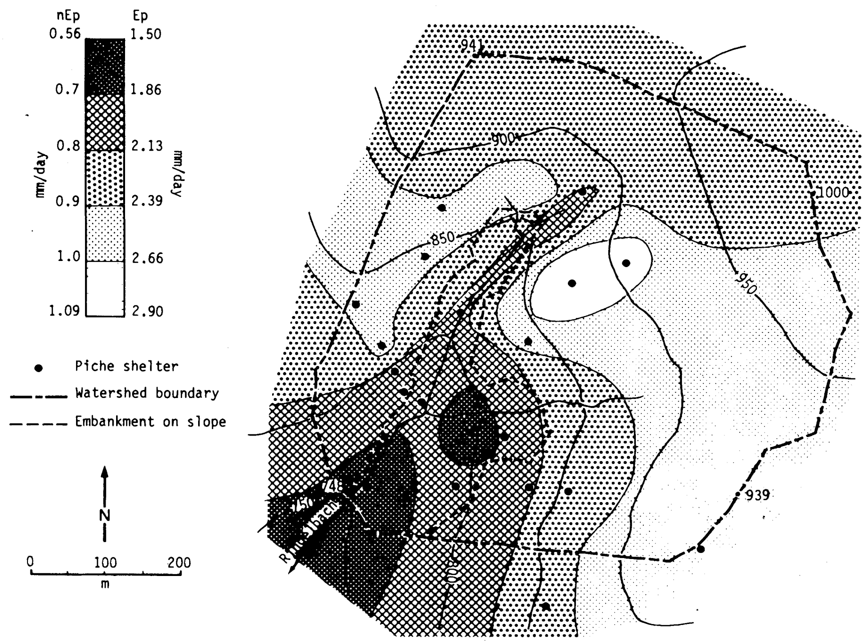

Fig. 5. Map of the Piche evaporation Ep and the advective term nEp on July 2nd 1981 (1st, 6 P. M. – 2nd, 6 P. M.) in the Ringelbach watershed.

more sensible to altitude change than the more humid Bunker versant, and the highest rate is found in the water-saturated valley bottom.

Further on, we can notice the influence of cold and wet air flowing down during that still night from the summital forest: *Ep* measurements at R2, V6 and H3 are smaller than at lower sites.

A map of the Piche evaporation *Ep* and the advective term *nEp* has been obtained by interpolating these measures (Fig. 5). It illustrates well the structure of the watershed: *nEp* is minimal in the wettest zone, near the streams; it increases regularly on the Bunker versant, more rapidly on the dry Geisberg versant; and the maximal values are observed on the Hurlin versant which is facing SW and therefore well exposed to the SW wind of that day.

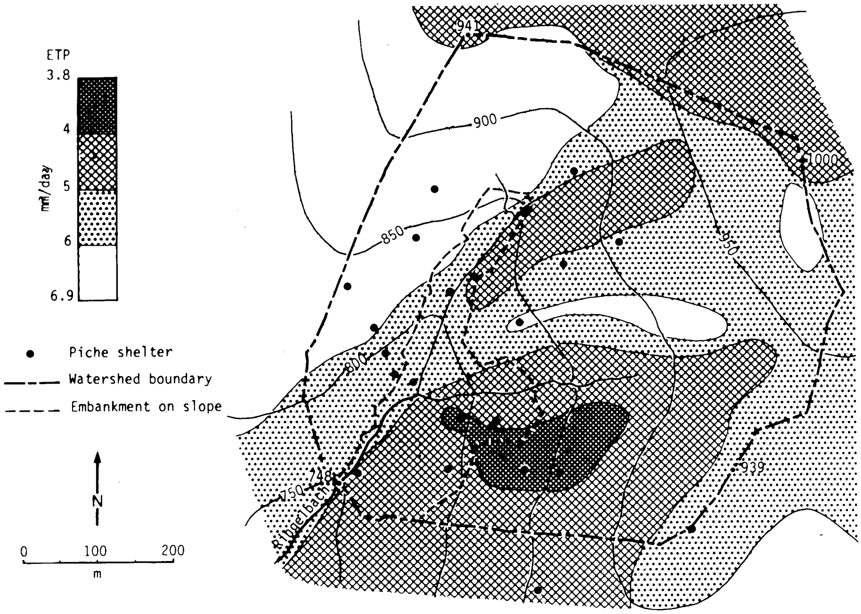

Fig. 6. Map of ETP according to Brochet and Gerbier's formula on July 2nd 1981 (1st. 6 P. M. – 2nd, 6 P.M.) in the Ringelbach watershed.

Potential Evapotranspiration

An *ETP* map is then easily obtained by adding *mRg* and *nEp* on each point according to Brochet and Gerbier's formula. As an example, Fig. 6 shows the *ETP* map determined for July 2, 1981, which is rather similar to the *Rg* map: the radiative term is indeed always much more important than the advective one.

Minimal *ETP* is observed on the Bunker versant and also on the Hurlin versant (in spite of high *Ep* measurement); maximal *ETP* is found on the Geisberg versant which has a high *Rg* (facing S and SSE) and a high *Ep* (dry slope). The wet valley (low *Ep*) has an intermediate *ETP* because of an intermediate *Rg*. Moreover, the relative contribution of advective processes to *ETP* appears to be very variable into the watershed. On this particular day, the rate *nEp*/*ETP* varies from 11% at G1 (confined and humid site facing SSE) to 22% at B4 (high altitude, open site facing W).

Mean *ETP* over the whole watershed can easily be obtained by planimetring this *ETP* map. For July 2, 1981, mean *ETP* is 5.32 mm/day. This value is somewhat different from *ETP* computed with Brochet and Gerbier's formula at G4 and B6 (respectively 4.96 and 5.05 mm/day with $Rg = Rg_h$), which both were considered as representative climatic stations for the watershed.

Conclusions

This mapping procedure, which is physically based and easy to apply, provides us a good tool for estimating *ETP* at different scales of space and time from a few point measurements. It presents also several advantages for topoclimatic and hydrologic studies at watershed level in mountainous area

- it helps us for choosing climatic station truely representative of the watershed climate,
- it gives us reliable information to use in spatially-distributed hydrologic models,
- it permits us a very good insight of the topoclimatic structure of the watershed, of the spatial patterns of climatic variables which also control the actual evapotranspiration.

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