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Wind speed regionalization and its influence on areal evapotranspiration prediction

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Abstract Evapotranspiration as one of the basic components in the hydrological cycle plays a major role in determining the water budget of agricultural and forestry catchments. Due to the effects of topography the controlling factors like net radiation, temperature, humidity and wind speed are highly variable in space. In this investigation, we show that spatial differences in wind speed data may result in differences in calculated potential evapotranspiration rates. The Ryan (1977) approach, to extrapolate the wind speed data of an "undisturbed" central meteorological station to any grid point within an agricultural catchment, is introduced and compared to measurements at three different locations in the Weiherbach catchment (Kraichgau, Germany). Although only information from a digital elevation model is used, it is shown that this method provides a much better estimation of the areal windfield, than using the data from the central station alone. Distributed modelling of the water budget for the years 1994 and 1995 demonstrates that neglecting the influence of topography on wind speed will result in over-estimation of the areally averaged potential and actual evapotranspiration rates.

INTRODUCTION

In the context of predicting water and matter budgets of agricultural and forestry catchments, evapotranspiration (*ET*) strongly influences the upper boundary conditions of water and solute transport. Recent research is focussing on determining areally averaged latent heat fluxes using remote sensing data (e.g. Bastiaanssen, 1995) but in general, measurements of *ET* are rarely available, and are unlikely to be sufficient to describe either the spatial variability or the influence of land use and soil characteristics on the evaporation regime.

In the absence of direct *ET* measurements, an alternative solution is the use of mathematical models to predict the spatial variations in *ET*, given meteorological data as well as land use and soil characteristics. One of the most widely used models to calculate the potential *ET* (ET_p) is the Penman formula (Penman, 1948), which describes ET_p as a function of net radiation, temperature, vapour pressure and wind speed. ET_p is converted to give an actual *ET* rate as a function of vegetation type and soil moisture conditions (e.g. Feddes *et al.*, 1978). Within this modelling procedure, for the spatial determination of *ET* it still remains necessary to provide some meteorological data (wind speed etc.) at the regional scale, although they can vary greatly in space due to the influence of topography (Bergold, 1993).

In this paper we focus on the influence of spatial variability of wind speed on the regional ET_p calculation: first showing the location under investigation and the sensitivity of ET_p calculation to wind speed and then giving a regionalization scheme to extrapolate wind speed data from a central meteorological station to other locations and compare measurements within the Weiherbach catchment with predicted values. Finally, the results of actual *ET* calculations for this area using the physically based, distributed water and nitrogen transport model *DYNAMIT* (Schulz & Huwe, 1997) are compared with and without wind speed regionalization.

LOCATION AND MEASUREMENTS

The Weiherbach catchment (area ~6 km^2), is located in the southeast part of Germany, 30 km northeast of Karlsruhe in the Kraichgau region, part of the German "hilly country". Most of the area is under cultivation. Cereals, corn, sunflower and sugar beet are the preferred crops. Due to the dominant loess substrate within the area, loam is the most widespread soil texture class. Altitude ranges 125–250 m a.s.l. Figure 1 shows a digital elevation model of the catchment and "x" denotes the position of the Central Meteorological Station (CMS) within the catchment. It served as a database for the meteorological boundary conditions when determining the water and nitrogen budgets during the period 1989–1997 in the Weiherbach research project (Plate, 1992). The parameters precipitation, global and net radiation, albedo, soil moisture content at five different depths, soil heat fluxes and wind direction as well as temperature, humidity and wind speed at three different levels, were measured at a time resolution of 10 min. To investigate the spatial variability of meteorological data within the catchment, three additional mobile stations (positions 1, 2 and 3 in Fig. 1) were set up for a time period

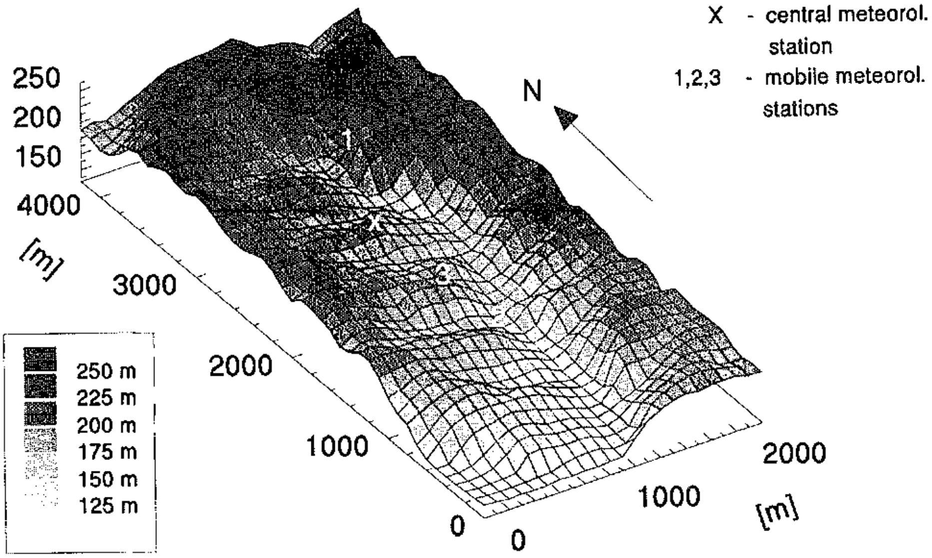

Fig. 1 Digital Elevation Model (DEM) of the Weiherbach catchment showing the positions of the Central Meteorological Station (×) and the three mobile meteorological stations (1, 2, 3).

of 4 months (April–July 1996). Their locations were chosen to represent some typical topographical conditions in the catchment compared to the relatively undisturbed position of the CMS. A very detailed description of the instruments used and their calibration is given by Wöhrlen (1997).

METHODS AND RESULTS

Within this study we wanted to focus on the influence of wind speed data on the prediction of evapotranspiration rates as well as to investigate a relatively simple extrapolation scheme to predict side dependent wind speed data.

Sensitivity of ET_p calculations towards wind speed

We used the Penman formula given by Hillel (1980) to calculate ET_p rates:

$$ET_p = \frac{\Delta / \gamma \cdot R_n / L + E}{\Delta / \gamma + 1} \tag{1}$$

with:

$$E_a = (0.131 + 0.141 \cdot v_{2m} \cdot (e_s - e_a) \tag{2}$$

with ET_p = potential evapotranspiration [mm day^{-1}], R_n = net radiation [J day^{-1} m^{-2}], Δ = slope of the saturation vapour pressure-temperature curve [hPa °K^{-1}], γ = psychrometer constant [hPa °K^{-1}], L = latent heat of vaporization [J kg^{-1}], E_a = ventilation term [mm day^{-1}], v_{2m} = wind speed at 2 m height [m s^{-1}], e_s = saturation vapour pressure [hPa] and e_a = vapour pressure [hPa]. In general, the approach of this investigation is not limited to the Penman equation used; other formulae could be used and analysed in the same way as described below.

For the year 1992, Fig. 2 shows the resulting cumulative ET_p rates using equation (1) based on the data of the CMS (closed line). The dotted line shows the resulting ET_p rates when the wind speed data are reduced to 30% of the measured values. This range corresponds approximately to the measured spatial differences of the wind speed data for a date within the catchment. The results with differences of about 180 mm year^{-1} in the ET_p total already indicate the great influence of the spatially variable wind speed data on the predicted water budget of the catchment.

Regionalization of wind speed

Due to the fact that it is impossible to obtain wind data at every grid point of the model region, the wind field is usually assumed to be homogeneous. Therefore, predictions based on this assumption can only give a rough estimate of reality.

To get better estimates of the wind speed data at the grid points, the Ryan (1977) approach was used to extrapolate the wind speed measurements from one meteorological station to other locations within the catchment. This approach fits a trigonometrical function to measurements of the effect of different kinds of

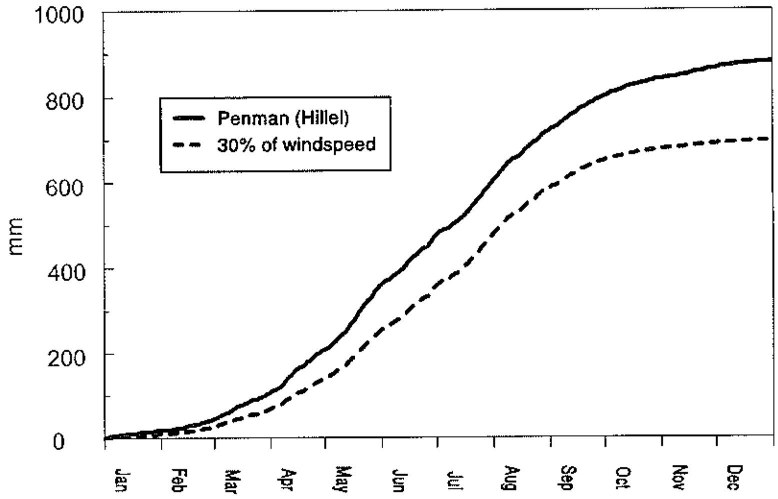

Fig. 2 Cumulative ET_p rates of 1992 with measured and reduced (to 30%) wind speed data.

windshelters and is based mainly on investigations by Kaiser (1959), who analysed the effect of windshield hedges on the wind field. Their influence could be described as a reduction of the wind speed dependent on the ratio of the height of the hedge and the distance to it. Ryan (1977) transferred these results to the influence of topography, which led to a "windshelter factor" correcting the wind speed data of the Central Meteorological Station according to the slope of the horizon upwind in the wind direction. This slope could easily be computed from the DEM.

$$f_{shelter} = 1 - \arctan(0.17 \cdot S)/100 \tag{3}$$

$$v_{2m}^{grid} = f_{shelter} \cdot v_{2m}^{CMS} \tag{4}$$

with S = slope to the horizon upwind in the wind direction [%], v_{2m}^{grid} = predicted wind speed at any grid point [m s^{-1}] and v_{2m}^{CMS} = measured wind speed at the Central Meteorological Station.

In Fig. 3 as an example, measured wind speed data for station 1 (Fig. 1) are plotted on a daily basis and are compared to calculated data using the extrapolation scheme described in equations (3) and (4). This station was positioned on a south-facing slope almost unprotected from southerly winds (horizon slope ~5°) but sheltered from northerly winds (horizon slope 20°–30°). The results show highly reduced wind speed data for northerlies, with only a slight underestimation compared to measured data. The results for southerly wind directions are even better, where the horizon is elevated less than 5%. These results indicate that there are still some minor deficiencies in this extrapolation scheme. The extrapolated data represent a much better estimation of the local wind speed data compared to the assumption that the CMS measured data are valid at every grid point. The mean square of the residuals between measured wind speed data at the mobile stations 1, 2 and 3, and the predicted wind speed data generally, decreases more than one order of magnitude when using the Ryan-approach instead of using the CMS data. Table 1 summarizes this result for all three stations.

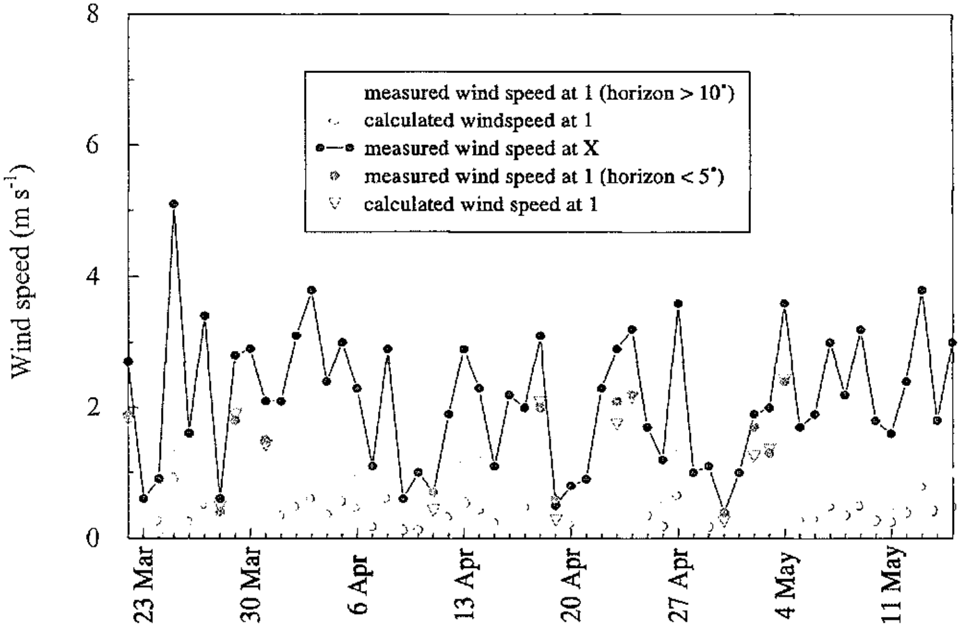

Fig. 3 Comparison between measured data and simulation results classified on horizon slope upwind. Data for horizon slope upwind >10° correspond to north or east wind directions, <5° to south wind directions.

Table 1 Comparison of the estimation variances for the daily averaged wind speed data of the mobile stations 1 to 3 when (a) the wind speed is estimated with the value of the Central Meteorological Station and (b) when it is estimated with the Ryan approach.

	x_{est} = wind speed at CMS	x_{est} = Ryan estimation
Station 1: $1/n\ \Sigma\ (x_{est}-x_i)^2$	1.99	0.13
Station 2: $1/n\ \Sigma\ (x_{est}-x_i)^2$	3.41	0.14
Station 3: $1/n\ \Sigma\ (x_{est}-x_i)^2$	2.39	0.22

Results of areal ET predictions

The water and nitrogen transport model DYNAMIT (Schulz & Huwe, 1997) was used to calculate the water regime of the Weiherbach catchment. The model solves numerically the one-dimensional Richards equation to describe unsaturated/saturated water transport in the vadose zone and uses the approach of Beese *et al.* (1977) to reduce potential evaporation to actual evaporation (EP_a) as a function of soil water pressure at 5 cm depth:

$$EP_a = (1.78 - 0.58 \cdot \lg\psi_{5cm}) \cdot ET_p \qquad (5)$$

EP_a = actual evaporation [cm day^{-1}], ψ_{5cm} = soil water pressure at 5 cm soil depth [cm].

Water balance calculations are carried out on a 50 m × 50 m grid for a bare soil surface. As a consequence in this scenario the influence of the vegetation (transpiration and interception) is neglected. Wind speed regionalization as described above is implemented on a daily basis using the meteorological data of the CMS (×, Fig. 1) for the years 1994 and 1995.

Figures 4 and 5 show the calculated areal distribution of potential *ET* and actual *ET* for the year 1994. Further results for both years are given in Table 2. The areal differences in both ET_p and ET_a show clearly the sheltering effect of the topography in the Weiherbach catchment due to mainly west and northeasterly wind directions. Resulting absolute areal differences in ET_a are of course much smaller than the differences for ET_p due to the drying effect of the bare soil during periods without rainfall and high net radiation. Differences would be much closer to those of ET_p when considering the influence of the vegetation, but this will be a subject of further investigations. Under the conditions and assumptions described with equation (1) to calculate ET_p, the areally averaged ET_p and ET_a rates are about 7–9% lower, when using the Ryan-approach compared to the maximum rates derived using only the CMS data.

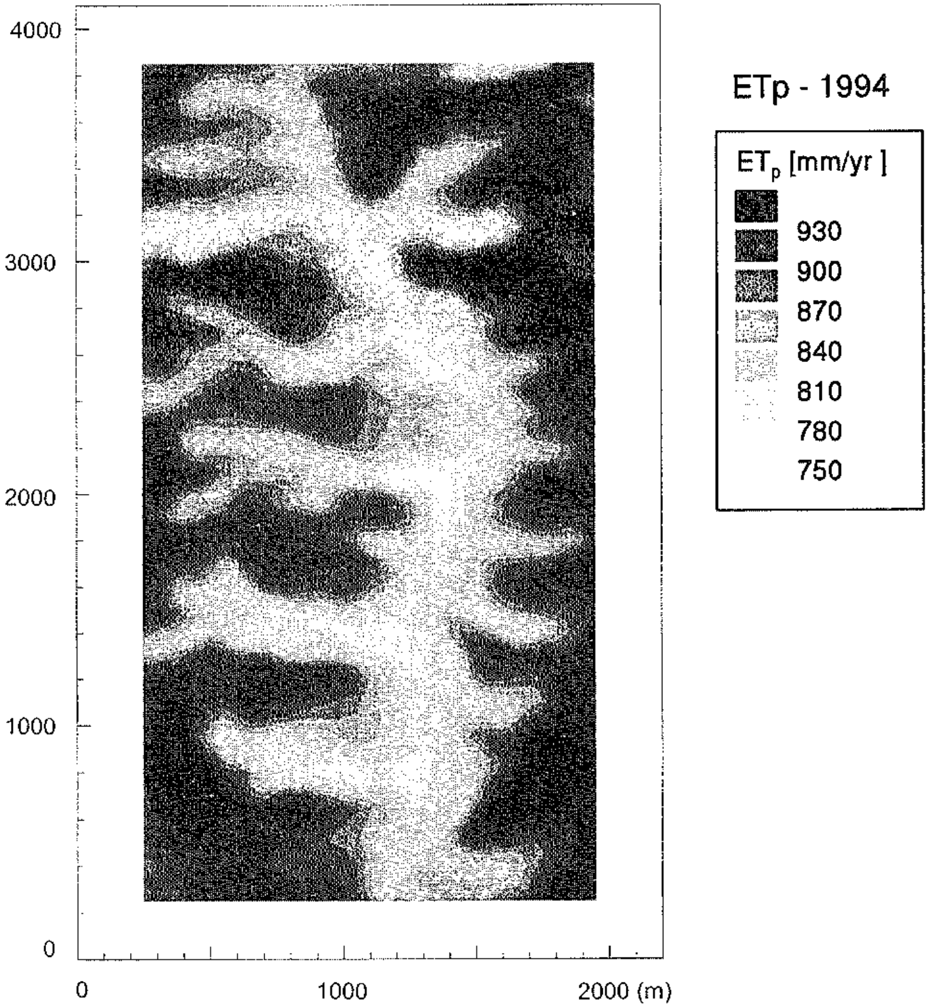

Fig. 4 Areally distributed potential evapotranspiration within the Weiherbach catchment for 1994 with regionalization of wind speed data. A homogeneous soil texture and a bare soil surface are assumed in this calculation scenario.

Table 2 Summary of the results of ET_p and ET_a calculations within the Weiherbach catchment. Maximum ET_p and ET_a values correspond to areal calculations without wind speed regionalization. All units in mm.

	1994	1995
$\sum ET_p$	866	807
max. ET_p	931	873
min. ET_p	770	718
$\sum ET_a$	303	287
max. ET_a	331	313
min. ET_a	271	261

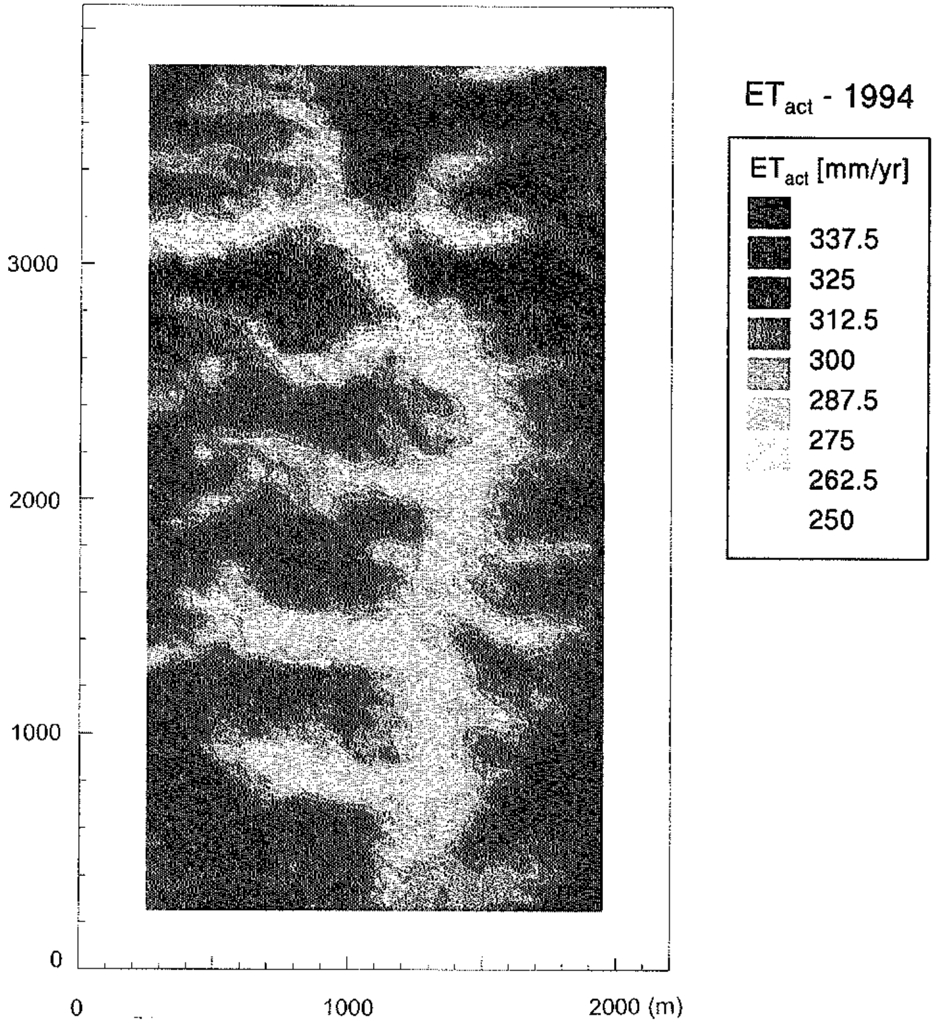

Fig. 5 Areally distributed actual evapotranspiration within the Weiherbach catchment for 1994, calculated with *DYNAMIT* using the regionalization of wind speed data.

CONCLUSIONS

The results of areal *ET* predictions clearly show that neglecting the influence of topography on wind speed data will result in overestimation of areally averaged *ET* rates. The results presented here may vary when using formulae other than the Penman formula to calculate ET_p, or when investigating catchments with quite different characteristics (e.g. vegetation, topography, position of the meteorological station, DEM resolution).

But in general the extrapolation scheme introduced in this paper to regionalize wind speed data from a central meteorological station using topographical parameters is easy to implement in hydrological modelling and needs less computational demands.

However, wind speed is only one of several factors influencing *ET*. Temperature, net radiation and vapour pressure also vary in space and it is still necessary to provide simple schemes to regionalize this data and to examine their impact on areal estimates of *ET*.

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