

Actual Evapotranspiration from Partially Tile-drained Fields as Influenced by Soil Properties, Terrain and Crop

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Abstract: Physical properties of soils have a significant influence on their water regime and should be considered when selecting suitable agricultural crops for particular sites, taking into account the crop productivity and its water requirements. Mean daily rates of actual evapotranspiration (ETa) were obtained by collation of measured or otherwise estimated 10-min values for the years 2004, 2006 and 2009 for a partially tile-drained agricultural experimental catchment in the Bohemo-Moravian Highland (Czech Republic). ETa was measured using the Bowen ratio (β) and energy balance (BREB) method at four weather stations located on different soil types (Stagnosols, Cambisols) and terrain relief positions (defined with respect to the groundwater recharge and discharge zones) over different crops (cereals, oil rape and permanent grassland). A systematic influence of soil properties on the evapotranspiration rate was more pronounced during the periods of limited transpiration (soil drought, crop maturity), when the average daily ETa was significantly lower and the corresponding β significantly higher over coarser-textured soils (shallow Haplic Cambisols), namely (year–ETa (mm/day)/ β): 2004 – 1.75/1.66; 2006 – 2.44/0.93; 2009 – 2.60/0.81), than over finer-textured soils (Stagnic Cambisols and Haplic Stagnosols), namely: 2004 – 2.92/0.97; 2006 – 3.06/0.44; 2009 – 3.42/0.39). When the transpiration was not limited by soil water deficit, it acted as an equalizing factor smoothing down evapotranspiration from heterogeneous soil areas, whereby the effect of the soil physical properties was masked. With regard to soil water regime and evapotranspiration, the tile-drained Stagnic Cambisol lands behaved similarly as non-drained Haplic Cambisols. The effects of land use and of the terrain relief position could not be tracked independently, because the permanent grassland was situated in the wetter and texturally heavier parts of the catchment and the positions of the recharge/discharge zone coincided with the positions of texturally lighter/heavier soils, respectively.

Keywords: actual evapotranspiration; Bowen ratio; Cambisol; cereals; discharge zone; energy balance; grassland; oil rape; recharge zone; soil physical properties; Stagnosol; tile drainage; transient zone

Actual evapotranspiration rate (ETa) represents a key element of landscape water balance. It plays an active role in the biomass production, establishes the cooling capacity of the region and, depending on soil properties, contributes to runoff formation in the catchment (MONTEITH 1976; WARD & ELLIOT 1995; ALLEN *et al.* 1998). The rate of the process is determined by the gradient of water potential between soil, vegetation, and atmosphere and the prevailing aerodynamic and surface resistances. It integrates the effects of meteorological parameters

(precipitation, radiation energy, water saturation deficit and wind speed), soil water content, soil hydraulic properties, vegetation density, height and roughness and the depth of the root system (DUNN & MACKAY 1995; SERRANO 1997; MENGELKAMP *et al.* 1999; JHORAR *et al.* 2002; BRUTSAERT 2005) on both the spatial and the temporal bases.

The impact of the soil on ETa depends upon the properties of its pore space, which are determined primarily by its grain size distribution and structure. Clay (fine-textured) soils tend to show higher

porosity (LUXMOORE & SHARMA 1984; BRUTSAERT 2005), higher soil water storage and ETa, regardless of the effect of nutrients or aeration (YOKOO *et al.* 2008), but, on the other hand, lower hydraulic conductivity and subsurface runoff (WARD & ELLIOT 1995), compared to sandy (coarse-textured) soils. The highest available moisture-holding capacity is displayed by loamy soils, which, though possessing a somewhat lower field water capacity than the clay soils, exhibit a significantly lower wilting point than the latter. The movement of water in the soil can be extensively altered by the preferential (e.g., macropore) flow, which is 100 to 400 fold faster than water flow in the soil matrix (BRONSTERT & PLATE 1997), depending on rainfall and snowmelt patterns and, if applied, on irrigation management.

Physical properties of soils influence the selection of suitable agricultural crops with respect to their water consumption and their productivity. For example, POPOVA and KERCHEVA (2005) showed that soil types with higher moisture-holding capacity are better suited to crops, such as corn, that are more sensitive to atmospheric drought than to less sensitive crops, such as wheat.

The spatial distribution of soil types and textures, and thus of the soil water storage, is determined by geology, terrain relief, climate and biotic factors. From a hydrogeologic viewpoint, the catchment can be divided into recharge zones, where precipitation infiltrates and then recharges the groundwater store, and discharge zones, where groundwater approaches the land surface or a surface water body (SERRANO 1997). The recharge zones are mainly located in the highest areas of the catchment, close to the catchment divide, peaks and ridges. The soils of these zones are typically shallow and stony, with high sand content and high infiltration capacity. The coarse-textured soils of the recharge zones are, with respect to groundwater resources, well suited to growing grass, which, beside water quality benefits, increases their field capacity and results in virtually complete infiltration of precipitation, including rainstorms (RYCHNOVSKÁ *et al.* 1985; DOLEŽAL & KVÍTEK 2004; LEXA 2006; KVÍTEK *et al.* 2007; FUČÍK *et al.* 2008). The discharge zones can be found in the lowest parts of the slopes and along surface streams and lakes and are prone to surface waterlogging. The dominant soils in the discharge zones are generally deep, with higher clay content and a lower capacity for infiltration. A connection between the recharge zones and the discharge zones is provided by transient zones, where precipitation is mostly transformed to

surface runoff and groundwater flows downslope in a quasi-steady way (DOLEŽAL & KVÍTEK 2004; ZHENG *et al.* 2004). The transient zones are located mainly in the middle sections of slopes. Groundwater in natural catchments flows from the recharge zones to the discharge zones. Actual spatial distribution of these zones depends on local geologic and geomorphologic conditions (BARRETT & CHARBENEAU 1997; MINÁR & EVANS 2008).

The aim of this study is to determine how the soils and their physical properties in the recharge, transient, and discharge zones can influence ETa in a cultivated catchment, where different crops are grown and some fields are tile-drained, in different periods and vegetation development phases.

MATERIAL AND METHODS

Description of the catchment and weather stations

The study was conducted in the experimental catchment Dehtáře, situated in the south-west Bohemo-Moravian Highland (Czech Republic), in the years 2004, 2006 and 2009. The outflow point of the catchment lies at 49°28'N – 15°12'E.

The catchment Dehtáře (Figure 1) has an area of 59.6 ha, with tile drained areas occupying 19 ha (~32%). The catchment area is mainly agricultural land (89.3%). Minor forested areas (3.3%) lie at its north-western and northern borders. Grassland (20.3%) covers the southern part of the catchment, as well as the adjacent lowest lying south-western area, which is tile-drained. The remaining area (69%) is arable land, which is exploited mainly for cereals production. The catchment geomorphology belongs to the erosion-accumulation relief type (DEMEK *et al.* 1987). The altitude ranges between 497.0 and 549.8 m. According to Quitt (TOLASZ *et al.* 2007), the local climate is classified as moderately warm. According to Köppen (TOLASZ *et al.* 2007), it belongs to the temperate broadleaf deciduous forest (Cfb) zone. The average annual total precipitation is 660 mm and the average air temperature is 7.0°C.

There is no permanent surface drainage channel within the catchment. The catchment hydrogeology is characterised by shallow aquifers (with groundwater table in the discharge zone lying at 0.2–1.5 m), occurring in Quaternary deposits, in the weathered zone of the bedrock and in its fissures and faults. The bedrock is a partially mig-

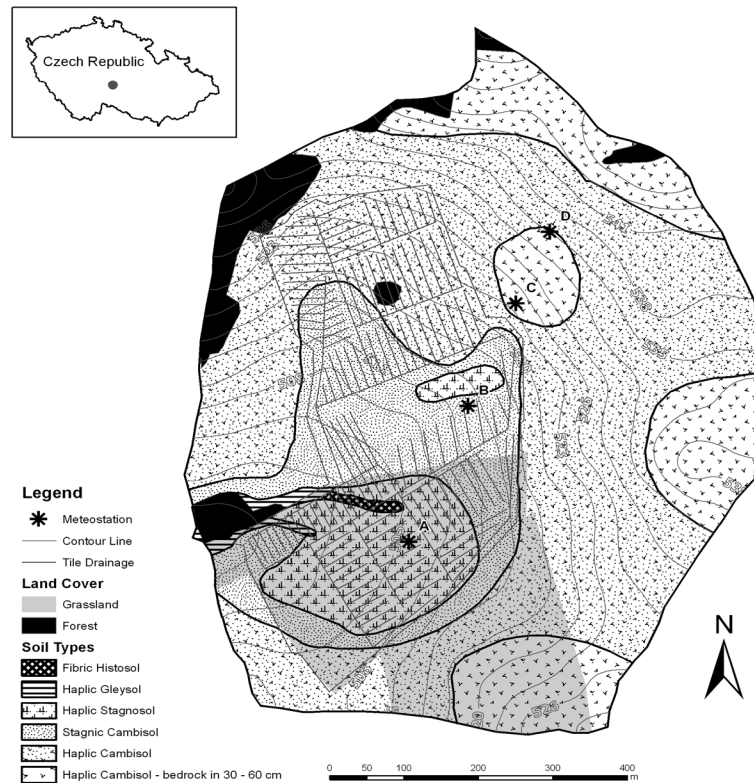


Figure 1. An overview map of the Dehtáře catchment and its soil types

matized paragneiss. Quaternary deposits are slope sands and bottom loams, reaching a thickness of 1–2 m. The bottom loams usually act as aquitards and have their own phreatic groundwater table, partially recharged from the atmosphere, so that the water from below mixes in them with the water from above. The dominant soil types according to World reference base for soil resources 2006 (Figure 1) are Haplic Cambisols (CMha) in the recharge and transient zones. These soils are light, shallow and stony (the thickness of the soil profile being only 30 cm in some parts) sandy loams and loamy sands (according to the USDA soil texture triangle, USDA-NRSC 1999). Haplic Stagnosols (STha), Haplic Gleysols, Fibric Histosols and Stagnic Cambisols (CMst) are typical for the discharge and the discharge/transient zones. Medium-deep sandy loams dominate in the lower parts of the slopes, while deep loams are most typical for the catchment bottom. However, the spatial variability of grain size distribution in the soils of the catchment bottom makes surveying difficult. This variability is due to natural erosion and accumulation processes as well as due to artificial mixing which occurred during the tile drainage installation. The clay (< 0.002 mm)

content in the topsoil and subsoil varies from 10 to 13% and from 9 to 13%, respectively, near the water divide, and from 12 to 15% and from 13 to 25%, respectively, at the catchment bottom. A layer of clay loam was identified by geophysical survey (KAROUS & CHALUPNÍK 2006, 2007) at the catchment bottom at the depth 30 to 200 cm, in some places cropping up to the soil surface.

The tile drainage (still fully functioning) was laid in 1977 in the western, lower part of the catchment. The average slope of the drained land is about 5%. The spacing of lateral drains is either 13 or 20 m. The depth of the laterals is about 1.0 m, while the depth of the mains is about 1.1 m. Circumferential intercepting tile drains, provided with gravel filters, are placed at depths 1.1 to 1.8 m. The tile drainage system empties into a fire water reservoir. Seasonal ascending springs, either point springs or spring lines, emerged in middle parts of the catchment slopes before the tile drainage system installation, causing temporary waterlogging of the lands (HAKEN & KVÍTEK 1982, 1984). Today, the soils in the tile-drained north-western part of the catchment (Figure 1) can be classified as CMha. Before the tile drainage installation they mainly belonged to the STha type.

Four weather stations (A, B, C, D – Figure 1 and Table 1) were placed in the experimental catchment to record conditions on sites with different soil types and textures and in different relief zones. The stations A and B were located in the discharge and the discharge/transient zones, respectively (Table 1) on texturally heavier STha and CMst soils, where the terrain slope was 2–4°. The stations C and D were situated in the transient and the transient/recharge zones, respectively, on the CMha soil and the terrain slope 5–7°. Permeable loamy-sand soils under stations C and D and between them are shallow; weathered bedrock can be found at 15–40 cm below the surface. Each station was equipped with an ETa-measuring system, which comprised a datalogger (MiniCube VV/VX, EMS Brno, CZ), two air temperature and two air relative humidity sensors (EMS 33, EMS Brno, CZ), selected pairwise to have similar characteristics and placed at 0.5–1.5 and 2.0–2.4 m above the ground, depending on the crop growth stage, a net radiometer (Schenk 8110, Philipp Schenk, AT, thermal principle, stability 3% per year), soil temperature sensors (PT 100/8, EMS Brno, CZ) at 0.1 and 0.2 m and a soil heat flux meter (HFP01, Hukseflux, NL). The stations B, C and D were operating during the growing season. The station A, operating year round, was in addition equipped with a pyranometer for measuring global radiation (EMS 11, EMS Brno, CZ, silicone diode sensor, calibration error under daylight condition max. 7%) and a wind sensors measuring wind speed and direction (Met One 034B, Met One, Oregon, U.S.A., 0.28 m/s starting threshold) placed at 2 m height. All stations recorded their data at one-minute intervals, while the dataloggers saved only 10 min averages.

The station A was surrounded by permanent grassland cut three times a year (end of May, second half of July and second half of October). Winter wheat was cultivated in the vicinity of the stations B, C and D in 2004 (sown 20 Sept. 2003, harvested 25 July 2004), winter rape was there in 2006 (sown 22 Aug. 2005, harvested 1 Aug. 2006) and spring barley in 2009 (sown 8 March, harvested 7 Aug. 2009); the latter was a cover crop for red clover.

Determination of actual evapotranspiration rate and reference evapotranspiration rate

ETa was determined from the latent heat flux (LE) in the simplified energy balance equation (MONTEITH 1973):

$$R_n = G + LE + H \text{ (W/m}^2\text{)} \quad (1)$$

where:

R_n – net radiation

G – soil heat flux

H – turbulent sensible-heat flux

RN and G could be directly measured with a sufficient accuracy and H was calculated from the Bowen ratio (β). The turbulent diffusion theory admits that, under some assumptions, the Bowen ratio can be calculated from the vertical air temperature and vapour pressure gradients. The basic assumptions are the equality of transport coefficients for vertical turbulent transport of heat and water vapour under conditions, the neutral atmosphere stratification and a flat homogenous extensive plant cover over a certain distance upwind of the point of observation (fetch), ensuring that the gradient measurements can be made within the equilibrium sublayer, where the fluxes are assumed to be independent of height (HEILMAN & BRITTIN 1989; TATTARI *et al.* 1995; TODD *et al.* 2000; PAUWELS & SAMSON 2006). The thickness of the equilibrium sublayer for an aerodynamically smooth-to-rough transition is assumed to be 10% of the internal boundary layer thickness δ . The latter can be calculated using the MUNRO and OKE (1975) equation (cited in HEILMAN & BRITTIN 1989):

$$\delta = x^{0.8} z_0^{0.2} \text{ (m)} \quad (2)$$

where:

x – fetch

z_0 – momentum roughness length of the crop surface (it can be taken as 13% of the crop height)

The adequate fetch length for the internal boundary layer to be of sufficient thickness (2.0 to 2.5 m above the ground, depending on the crop height) can be then estimated as:

$$x = (\delta/z_0^{0.2})^{1.25} \text{ (m)} \quad (3)$$

The Bowen ratio β is defined as:

$$\beta = \frac{H}{LE} \quad (4)$$

After substitution from the equations of vertical turbulent heat and mass transport (MONTEITH 1973; GRACE 1983) and after introduction of the psychrometric constant γ (kPa/°C), we obtain:

Table 1. Location, soils, land use, tile-drainage and terrain conditions around the weather stations A to D in the Dehtáře catchment

Weather station	Terrain zone*	Altitude (m)**	Soil type*	Textural class topsoil/subsoil*	Average content*				Maximum capillary water capacity** (% vol) at 20–30 cm	Land use*	Tile-drained area*(%)	Slope(°)*
					< 0.002 mm (%)		0.05–2.0 mm (%)					
					clay	sand	topsoil	subsoil				
					topsoil	subsoil	topsoil	subsoil				
A	discharge zone	506	Haplic Stagnosol (STha)	silt loam or loam or sandy loam/sandy loam or loam or clay loam	12.3	16.1	48.3	48.4	40.8 (topsoil)	grassland	100	2–3
B	discharge /transient zone	513	Stagnic Cambisol (CMst), Haplic Stagnosol (STha)	loam/sandy loam or loam (STha)	12.3 (CMSt)	10.6 (CMSt)	48.5 (CMSt)	62.2 (CMSt)	39.8 (subsoil)	arable land	69	3–4
C	transient zone	523	Haplic Cambisol (CMha)	sandy loam or loamy sand/sandy loam or loamy sand	11.0	11.7	66.9	62.2	30.4 (subsoil)	arable land	29	5–6
D	transient /recharge zone	534	Haplic Cambisol (CMha)	sandy loam or loamy sand/sandy loam or loamy sand	12.6	10.7	62.5	66.2	30.3 (subsoil)	arable land	0	6–7

*within a 100 m radius circle around each weather station; ** samples taken close to weather stations

$$\beta = \gamma \frac{(T_2 - T_1)}{(e_2 - e_1)} \quad (5)$$

where:

$(T_2 - T_1)/(e_2 - e_1)$ – ratio of the air temperature (°C) and vapour pressure (kPa) vertical gradients above the plant canopy

ETa can be calculated by combining Eqs (1) and (4):

$$\text{ETa} = \frac{\text{Rn} - \text{G}}{\text{L}(1 + \beta)} \times 3600 \text{ (mm/h)} \quad (6)$$

where:

L – latent heat of vaporization (J/kg) and 1 mm of water is taken as 1 kg/m²

Conditions needed to fulfil theoretical requirements for using this method usually cannot be achieved in the early morning, evening and night periods and sometimes even on cloudy or rainy days or on days with significant advection. Therefore, the cases when $|\text{Rn} - \text{G}| \leq 10 \text{ W/m}^2$ or $\beta < -0.1$ or $\beta > 4$ or $\text{LE} = 0$ or when simultaneously $\text{LE} < 0$ and $\text{H} > 0$ were excluded from further processing. In this way, it was ensured that the situations when the gradients of air temperature and vapour pressure had opposite or uncertain signs (due to insufficient resolution limits of the sensors or due to advection) or when the stratification was strongly instable (far from neutral) (PEREZ *et al.* 1999; INMAN-BAMBER & MCGLINCHY 2003) were not taken into account. Table 2 shows Bowen ratio data excluded, which comprises $\beta < -0.1$ or $\beta > 4$; Table 3 rejects ETa values with this “unfavourable” Bowen ratios in conjunction with all other cases mentioned above. During the periods of vapour condensation at the surface under conditions of nocturnal inversion and outgoing available energy ($\text{LE} < 0$ and $\text{H} < 0$), the equilibrium evaporation $\Delta (\text{Rn} - \text{G})/(\Delta + \gamma)$, which is negative under these conditions, was set as a lower limit of vapour condensation, i.e., the absolute value of the actual condensation could not be higher than the absolute value of this equilibrium evaporation (PEREZ *et al.* 2008). PAUWELS and SAMSON (2006) and PEREZ *et al.* (1999) suggested that the cases of β in the range -0.7 to -1.3 should be excluded. Our approach is also supported by TODD *et al.* (2000) who found that the greatest differences between the BREB method and lysimeters were observed when β values were less than zero. The missing

ETa values for the periods thus excluded were estimated based on linear regression between the valid ETa values and the equilibrium evaporation. Then the summation of the resulting uninterrupted series of 10-min ETa values gave the average daily ETa rates in mm/h and these were subsequently converted to daily totals of ETa in mm/d.

To allow a better interpretation of the ETa values, the reference crop evapotranspiration ET_0 (ALLLEN *et al.* 1998) was calculated from the station A data as follows:

$$\text{ET}_0 = \frac{0.408\Delta(\text{Rn} - \text{G}) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \text{ (mm/day)} \quad (7)$$

where:

Δ – slope of the vapour pressure curve (kPa/°C)
 T – mean daily air temperature at 2 m height (°C)
 u_2 – wind speed at 2 m height (m/s)
 $e_s - e_a$ – saturation vapour pressure deficit (kPa)
 $\text{Rn} - \text{G}$ – expressed in MJ/m²/d

Measurement of precipitation and maximum capillary water capacity and the soil textural class estimation

A tipping-bucket rain gauge 276 mm in diameter (with the interception surface 0.06 m²) was located near the centre of the catchment. Each tip corresponded to 0.1 mm increment of precipitation. The precipitation totals were recorded at 10-min intervals.

Both disturbed and undisturbed soil samples were taken at about 100 m distance from each weather station from both topsoil and subsoil. To assess the moisture-holding capacity of the soil, an empirical characteristic of the soil water retention capacity was determined in the laboratory according to Novák's procedure (KLÍKA *et al.* 1954). It is referred to as the maximum capillary water capacity (MCWC). The procedure consists of allowing an undisturbed soil sample (100 cm³), previously fully soaked with water by capillarity from below, to drain by suction on a layer of filter paper over 2 h. Its moisture content at the end of the period is MCWC. KUTÍLEK (1966) declares that MCWC corresponds approximately to the field capacity of the soil. The grain size distribution of the soil was determined according to ISO 11277 (1998). It was expressed in percent by mass of in-

Table 2. Total number of 10-min Bowen ratio (β) values and the percentage of values excluded in individual periods

Period	Weather station A			Weather station B			Weather station C			Weather station D		
	all β data	all β data excluded (%)	night-time β data excluded (%)	all β data	all β data excluded (%)	night-time β data excluded (%)	all β data	all β data excluded (%)	night-time β data excluded (%)	all β data	all β data excluded (%)	night-time β data excluded (%)
2004 29 May–12 Aug	10 656	18.5	16.1* (87)**	10 944	27.8	17.4* (62.8)**	10 944	33.5	24.5* (73.1)**	10 943	26.6	20.1* (75.6)**
2006 6 May–19 Aug	15 264	16.7	13.6* (81.5)**	15 264	24.2	17.0* (70.4)**	15 264	25.0	19.1* (76.5)**	15 187	25.4	22.7* (89.5)**
2009 1 May–23 Aug	16 560	22.5	13.8* (61.5)**	16 560	13.6	11.9* (87.5)**	16 560	19.6	15.9* (81.0)**	16 556	28.1	24.3* (86.5)**
Average		19.2	14.5* (76.7)**		21.9	15.4* (73.6)**		26.0	19.8* (76.9)**		26.7	22.4* (83.9)**

*related to all β values; **related to all β values excluded

Table 3. Total number of 10-min ETa values and the percentage of values excluded in individual periods

Period	Weather station A			Weather station B			Weather station C			Weather station D		
	all ETa data	all ETa data excluded (%)	night-time ETa data excluded (%)	all ETa data	all ETa data excluded (%)	night-time ETa data excluded (%)	all ETa data	all ETa data excluded (%)	night-time ETa data excluded (%)	all ETa data	all ETa data excluded (%)	night-time ETa data excluded (%)
2004 29 May–12 Aug	10 656	27.6	14.6* (53)**	10 944	36.5	25.4* (69.6)**	10 944	41.7	31.4* (75.4)**	10 943	38.9	30.9* (79.5)**
2006 6 May–19 Aug	15 264	28.1	23.1* (82.3)**	15 264	41.5	33.1* (79.8)**	15 264	32.5	25.2* (77.4)**	15 187	36.8	32.3* (87.8)**
2009 1 May–23 Aug	16 560	41.5	31.8* (76.7)**	16 560	40.6	35.5* (87.5)**	16 560	31.7	25.7* (80.9)**	16 556	38.8	32.7* (84.1)**
Average		32.4	23.2* (70.7)**		39.5	31.3* (79.0)**		35.3	27.4* (77.9)**		38.2	32.0* (83.8)**

*related to all ETa values; **related to all ETa values excluded

dividual particle size fractions (clay: < 0.002 mm, silt: 0.002–0.05 mm, sand: 0.05–2.00 mm). The soil texture was classified according to the USDA (USDA-NRSC 1999) soil texture triangle.

Statistical analysis

To assess the systematic effect of the categorical independent variable “weather station” (including soil type, crop, tile drainage and terrain position) upon the dependent quantitative variable (daily ETa), we used a paired *t*-test, in order to indicate whether or not the expected difference between two matching observations is zero (the null hypothesis), taking the probability of unwarranted rejection of the null hypothesis $P = 0.05$. We separately tested the period of spring and early summer, i.e., from May to mid-July (period 1, up to crop maturity), and the following period of summer from mid-July to mid-August (period 2, after crop maturity). The latter period ended shortly after the crop harvest (in the case of field crops) or in the middle of the interval between the second and the third grass cutting.

RESULTS AND DISCUSSION

Data analysis

Table 2 shows the number of all Bowen ratio (β) values obtained in individual periods and years and the percentage of values excluded. Of all 10-min β values measured at individual weather stations, 19–27% were rejected (these and the following values being taken over the entire period of observation). Seventy-four to 84% of the rejected values were night measurements (between 19:10 and 05:50). PEREZ *et al.* (1999) suggest that 40% of all β data must often be rejected, while INMAN-BAMBER & MCGLINCHY (2003) report a rejection rate 69% for night-time values. Of the night-time β values, 36–43% were rejected, compared with 8–13% rejection rate of daytime β values (not shown in Table 2). These results agree with those by TODD *et al.* (2000) who reported 29% and 9% of β values rejected at night and in daytime, respectively.

Altogether, 32–40% of 10-min ETa measurements were invalid (Table 3), according to the criteria set forth in Materials and Methods. Seventy-one to 84% of the invalid data points occurred at night,

when ETa values tended toward zero (being either very small positive or very small negative). Of the night-time ETa measurements, 62–70% were invalid, as opposed to the daytime ETa pattern, when 11.5–15% were invalid. TATTARI *et al.* (1995) showed that approximately 53% of the daytime evapotranspiration data could be considered valid.

The accuracy of the BREB method of ETa determination, provided that its theoretical assumptions are met, is approximately 10% (TATTARI *et al.* 1995; PEREZ *et al.* 1999). The thickness of the equilibrium sublayer is related to the fetch. It is recommended that the minimum fetch to upper measurement height ratio is at least 10:1 to 200:1, with 100:1 being considered adequate for most measurements. The BREB method is less sensitive to imperfect fetch conditions than other techniques, if the Bowen ratio is small (ca. 0.3–0.4, YEH & BRUTSAERT 1971). According to HEILMAN and BRITTIN (1989), a significant boundary-layer adjustment occurs within the first 15 m of the fetch and, hence, when the Bowen ratio is small, the method can be used successfully at fetch-to-height ratios as low as 20:1, despite the fact that the measurements are not made strictly within the equilibrium sublayer. TODD *et al.* (2000) show fetches ranging from 90 m to 360 m, STEDUTO and HSIAO (1998) mention a sufficient fetch of 148–168 m.

In our case, considering the crop height of 0.4 to 1.5 m (cereals, rape) and an adequate equilibrium sublayer thickness of 2.0–2.5 m, a sufficient minimum fetch, according to Eq. (3), is 80–90 m. The prevailing wind directions observed were 60–120° and 210–300°. The actual wind direction remained within these two directions over 67.0% of the time in 2004, over 59.3% of the time in 2006 and over 64.6% of the time in 2009. The particular weather stations were far enough apart related to the minimum fetch, their mutual distances being 114 m (C–D), 175 m (B–C) and 204 m (A–B). The distances any of A, B, C and D from the up-wind boundary of the crop stand were in most cases greater than 80–90 m. The minimum and maximum fetches were 95–300 m and 180–510 m, respectively, along the prevailing wind directions. Hence, no significant footprint overlapping of the weather stations occurred. The fetch of the station B from the permanent grassland boundary varied between 68 m and 90 m, if the wind direction varied between 125° and 215°. However, only 20–27% of wind directions measured lay within this interval. With the wind direction within this interval and considering only the Bowen ratios

$\beta > 0.4$ (for which we expect greater sensitivity to the perfectness of the fetch), we would have only rejected another 10–14% of β values and 8–9% of ETa values. Based on this analysis, the fetches of all weather stations were considered sufficient and no data were rejected because of “wrong” wind directions. Of all ETa data considered valid and measured by the stations B and C, 70% and 57%, respectively, were influenced by the nearby tile-drained area. This happened when the wind direction was 25° – 250° at station B and 160° – 295° at station C.

Between-stations ETa and β comparison

The soils around the stations A to D are characterized by markedly differing grain size distribution, which influenced their water retention capacity (Table 1). The Haplic Stagnosols and Stagnic Cambisols on which weather stations A and B were located display lower sand content in the topsoil as compared to the Haplic Cambisols around the stations C and D. However, all varieties of Cambisols (around the stations B, C and D) contain more sand in the subsoil than the Stagnosols. The actual soil water retention capacity was influenced not only by the sand and clay content but also by the presence of tile-drainage

systems around the stations A, B, C (see Figure 1 and Table 1). The soils surrounding the station C, with the highest content of sand and partially influenced by the adjacent drainage system, manifested themselves in the lowest ETa values and the highest β over all three years (Table 4, Figures 2–7). In contrast, the fine-textured soils with greater MCWC and affected more by the shallow groundwater table and the shallow lateral flow (STha, CMst, stations A and B), showed in most cases the highest ETa values. The findings by SALVUCCI and ENTEKHABI (1995), WARD and ELLIOT (1995), and YOKOO *et al.* (2008) in this respect are similar. Additionally, the soil water regime of the station A was markedly influenced by the reduction of ETa after grass cutting (i.e. after the above-ground biomass removal).

The reported differences in soil physical properties manifested themselves in the corresponding daily ETa differences during the periods of limited transpiration either due to the onset of crop maturity (when the plant water consumption was already low and the excessive precipitation was absorbed by the soil) and/or due to drought (when the soil water supply to plants was limited). Hence, in some cases (in period 2 but, in 2004, also in the second half of period 1 – from late June to mid-July), the statistical tests signalled systematic ETa differences between

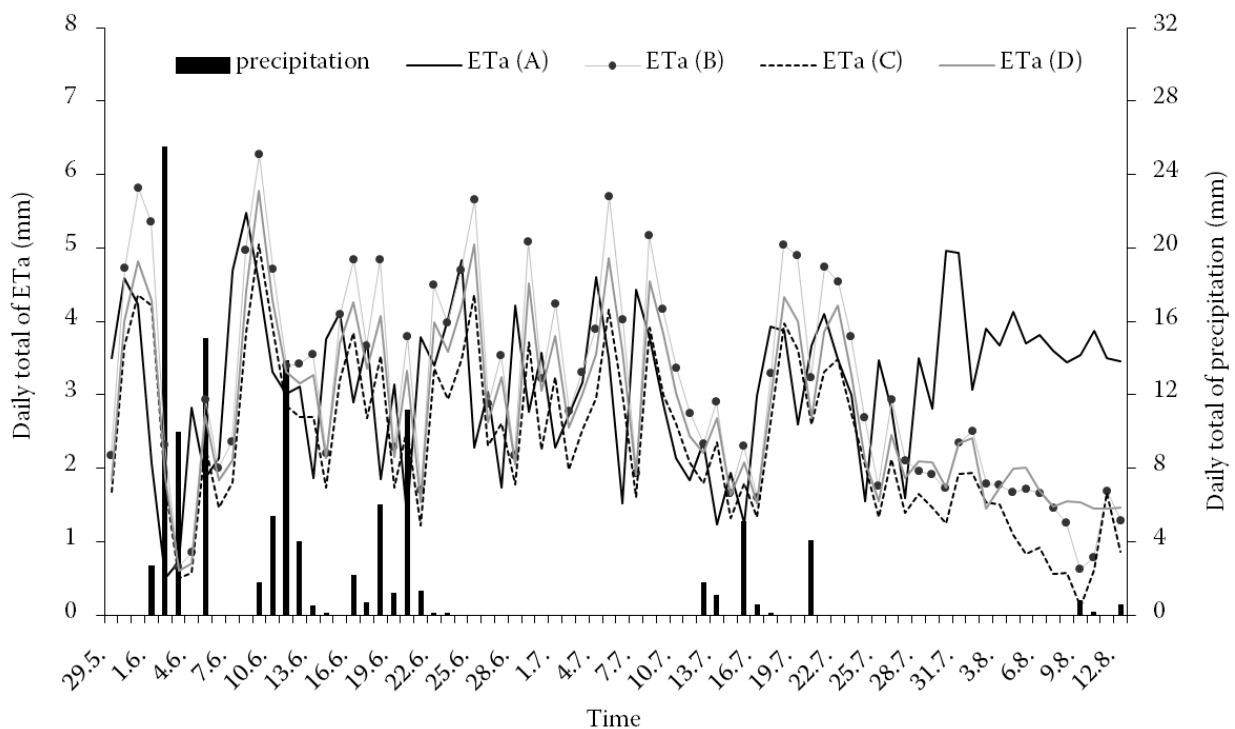


Figure 2. Average daily values of actual evapotranspiration for the Dehtáře catchment, 2004

Table 4. Average actual evapotranspiration (ET_a) and Bowen ratio (β) values $\pm$ their standard deviations, precipitation totals and daily averages and daily averages of reference crop evapotranspiration (ET₀) values for the weather stations A to D in individual years and periods

Year and the crop around stations B to D	Station	Average daily ET _a (mm)				Average daily Bowen ratio β (–)			Precipitation (mm): total over period/ reference crop evapotranspiration ET ₀ (mm): daily average	
		May–mid-July (up to crop maturity)	mid-July–mid- August (after crop maturity)	Entire growing season	May–mid-July (up to crop maturity)	mid-July–mid- August (after crop maturity)	Entire growing season	May–mid-July (up to crop maturity)	mid-July–mid-August (after crop maturity)	
2004	A*	2.97 $\pm$ 1.18	3.46 $\pm$ 0.76	3.15 $\pm$ 1.06	0.32 $\pm$ 0.11	0.40 $\pm$ 0.15	0.35 $\pm$ 0.13			
	B	3.52 $\pm$ 1.34	2.38 $\pm$ 1.24	3.10 $\pm$ 1.41	0.26 $\pm$ 0.12	1.53 $\pm$ 1.02	0.71 $\pm$ 0.86	109.8/2.29	6.4/0.22	
	C	2.68 $\pm$ 1.04	1.75 $\pm$ 1.00	2.34 $\pm$ 1.11	0.46 $\pm$ 0.17	1.66 $\pm$ 1.09	0.83 $\pm$ 0.82	2.83	4.01	
	D	3.15 $\pm$ 1.15	2.26 $\pm$ 0.90	2.83 $\pm$ 1.15	0.41 $\pm$ 0.15	1.98 $\pm$ 1.15	0.99 $\pm$ 1.04			
2006	A*	3.43 $\pm$ 1.39	2.96 $\pm$ 1.58	3.27 $\pm$ 1.47	0.47 $\pm$ 0.25	0.47 $\pm$ 0.27	0.47 $\pm$ 0.25			
	B	3.37 $\pm$ 1.39	3.15 $\pm$ 1.39	3.29 $\pm$ 1.38	0.53 $\pm$ 0.32	0.40 $\pm$ 0.21	0.49 $\pm$ 0.30	222.3/3.18	126.3/3.41	
	C	3.20 $\pm$ 1.37	2.44 $\pm$ 1.29	2.94 $\pm$ 1.39	0.61 $\pm$ 0.29	0.93 $\pm$ 0.51	0.72 $\pm$ 0.41	3.67	3.43	
	D	3.28 $\pm$ 1.24	2.66 $\pm$ 1.27	3.07 $\pm$ 1.28	0.66 $\pm$ 0.27	0.85 $\pm$ 0.31	0.73 $\pm$ 0.30			
2009	A*	3.06 $\pm$ 1.31	3.65 $\pm$ 1.33	3.26 $\pm$ 1.34	0.35 $\pm$ 0.27	0.27 $\pm$ 0.30	0.32 $\pm$ 0.28			
	B	3.09 $\pm$ 1.44	3.19 $\pm$ 1.06	3.13 $\pm$ 1.32	0.40 $\pm$ 0.16	0.50 $\pm$ 0.17	0.43 $\pm$ 0.17	207.2/2.73	109.1/2.73	
	C	2.67 $\pm$ 1.12	2.60 $\pm$ 0.74	2.65 $\pm$ 1.00	0.59 $\pm$ 0.23	0.81 $\pm$ 0.38	0.67 $\pm$ 0.31	2.85	3.58	
	D	3.05 $\pm$ 1.29	3.47 $\pm$ 1.12	3.20 $\pm$ 1.25	0.36 $\pm$ 0.16	0.30 $\pm$ 0.14	0.34 $\pm$ 0.15			

*Station A is surrounded by grassland

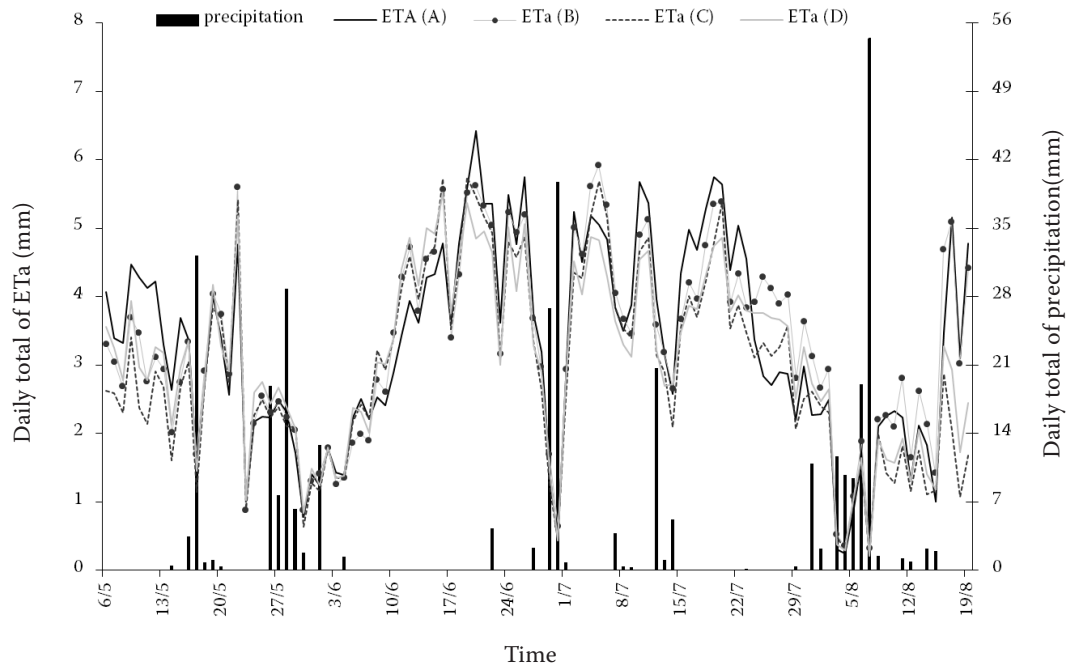


Figure 3. Average daily values of actual evapotranspiration for the Dehtáře catchment, 2006

different soil types under different land use (mostly A vs. C) and even between different soil types under the same land use (always B vs. C, mostly D vs. C, Table 5). However, no such differences were found between the station B (CMst or STha influenced by the tile-drainage system) vs. D (CMha without

a drainage system). With regard to the soil water regime and ETA, the Stagnic Cambisol with a drainage system acted similarly to the Haplic Cambisol. Under extremely dry conditions (period 2, 2004), there were significant differences between the station A and the other stations, because of the dried-out

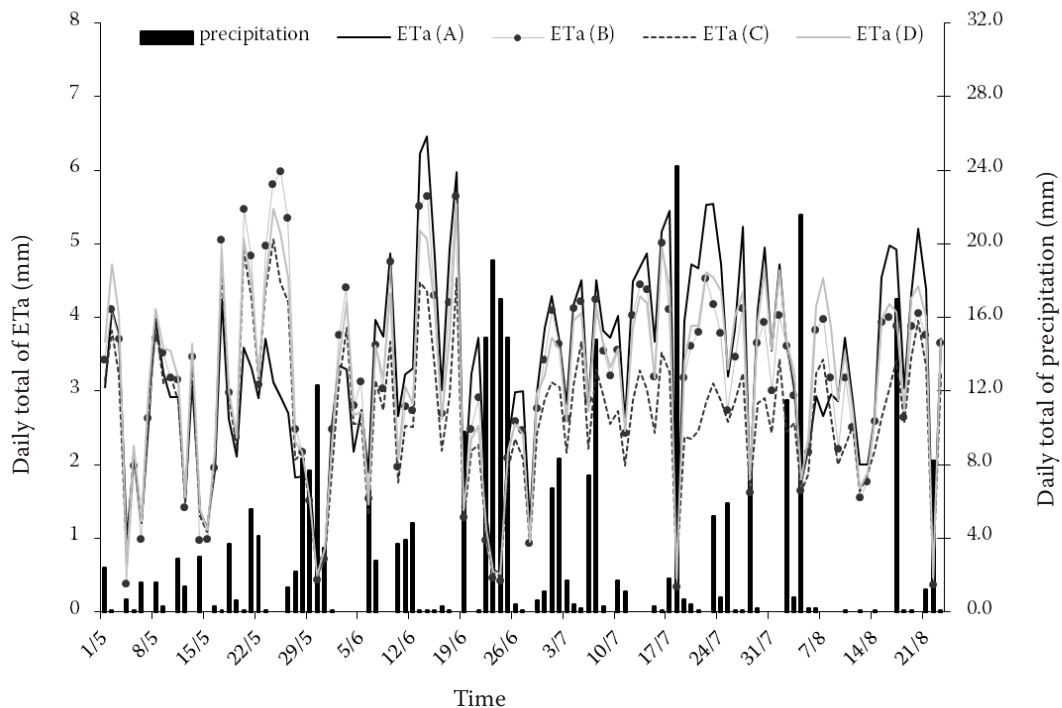


Figure 4. Average daily values of actual evapotranspiration for the Dehtáře catchment, 2009

Table 5. The significance levels (*P*) for paired *t*-tests comparing average daily ETa values

Subjects of comparison	Compared pair of stations	Year	<i>P</i>	
			May–mid-July	mid-July–mid-August
Soils affected by hydromorphism (STha, CMst) under different land use (A – permanent grassland vs. B – field crops) and also the discharge zone vs. the discharge/transient zone, both being tile-drained	A × B	2004	0.03448*	0.00024*
		2006	NS	NS
		2009	NS	NS
Different Cambisol varieties in different terrain zones under the same land use and different intensity of tile-drainage: B (CMst/CMha, discharge/transient zone, tile-drained) C (CMha, transient zone, partially tile-drained) D (CMha, transient/recharge zone, not tile-drained)	B × C	2004	0.00096*	0.03982*
		2006	NS	0.02649*
		2009	0.04805*	0.00546*
	B × D	2004	NS	NS
		2006	NS	NS
		2009	NS	NS
	C × D	2004	0.03808*	NS
		2006	NS	NS
		2009	NS	0.00011*
Permanent grass cover on Stagnosol, discharge zone, tile-drained (A) vs. field crops on Haplic Cambisol, transient (C) or recharge/transient (D) zone, partially tile-drained (C) or not tile-drained (D)	A × C	2004	NS	< 10 ⁻⁵ *
		2006	NS	NS
		2009	NS	0.00004*
	A × D	2004	NS	< 10 ⁻⁵ *
		2006	NS	NS
		2009	NS	NS

*the null hypothesis rejected; NS = not significant

soil profile under arable land (stations B to D), while the lowest part of the catchment around the station A was still relatively wet. The differences in terms of Bowen ratios (the average values between 10:00 and 18:00 of each day when $R_n > 70 \text{ W/m}^2$) were also visible. The β values pertaining to the stations B to D rose in July and August 2004 very sharply while those measured at A remained low (Figure 5). Taken separately over the periods 1 and 2 as well as over the entire growing seasons in particular years, the stations C and D typically gave the highest Bowen ratios (Figures 6 and 7).

In the period 1 the crop transpiration, a critical component of evapotranspiration, was in most cases not limited by the (non-existing) soil water deficit. The water supply to plants was sufficient and uninterrupted, while the crop stand was already fully developed. Under these conditions, both soil

evaporation and plant transpiration were affected by weather factors in a similar way. The uplift of water through the plant tissues is markedly more efficient than the soil water upward movement during physical evaporation only (NOVÁK 1995). After precipitation, the water that has infiltrated into the soil is mainly utilized for transpiration of the fully developed stand, that is, the soil physical properties have only a limited effect on its upward movement. Thus, the prevalence of the transpiration component of evapotranspiration acted as an equalizing factor on ETa from heterogeneous soil areas. The effect of physical properties of the soil was thereby masked. As a result, the daily ETa values were statistically the same across various soil types and crop species (a similar conclusion was made by MAHMOOD & HUBBARD 2003), except in the dry period of 2004. KOZAK *et al.* (2005) arrived at similar conclusions,

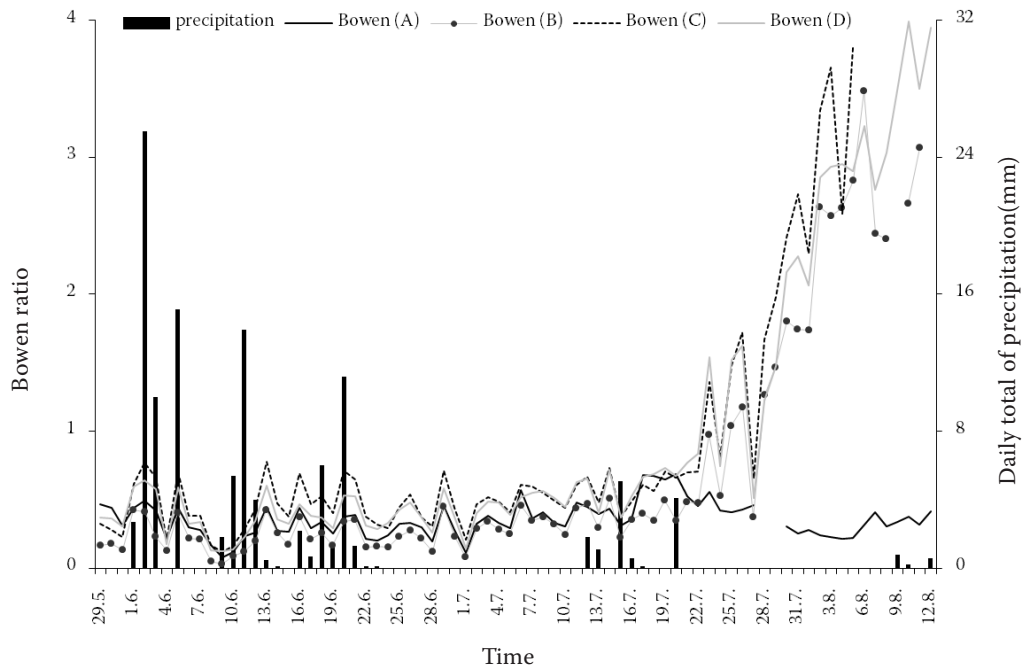


Figure 5. Average daily values of the Bowen ratio for the Dehtáře catchment, 2004

stating that the values of cumulative physical evaporation showed a more pronounced change with alterations in soil texture than did the values of cumulative transpiration. Figures 3–4 and 6–7 support this conclusion by showing that, in the period 1, the differences in ET_a and β among individual weather stations were negligible.

CONCLUSIONS

Different soil physical properties of the catchment, interacting with the tile-drainage system effects, manifested themselves in corresponding daily evapotranspiration differences during the periods of limited transpiration, either at the onset of crop

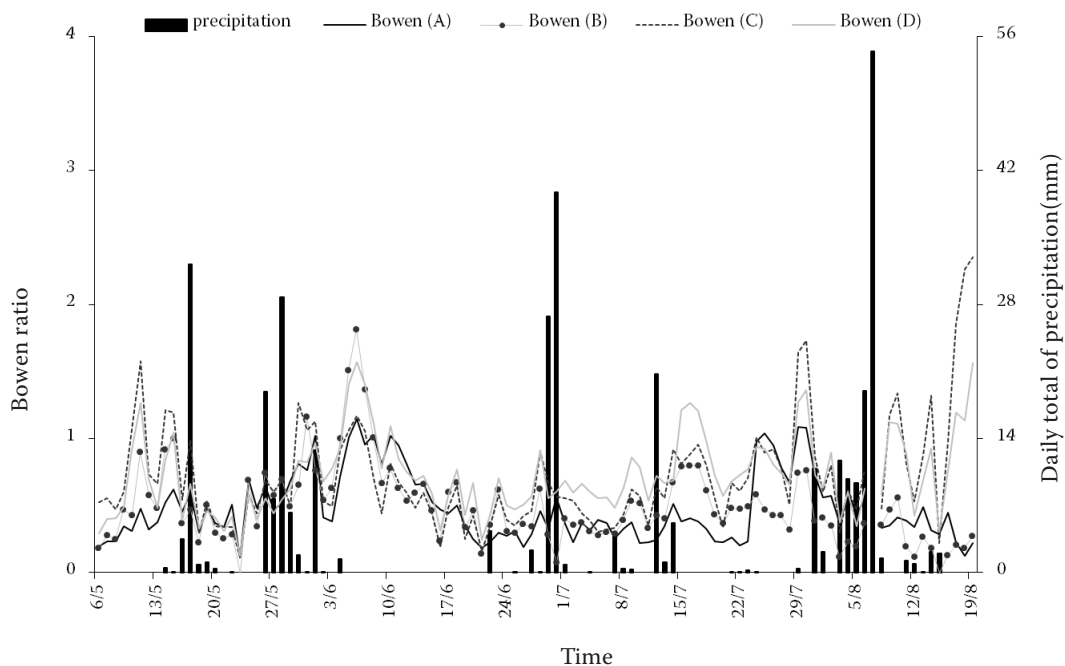


Figure 6. Average daily values of the Bowen ratio for the Dehtáře catchment, 2006

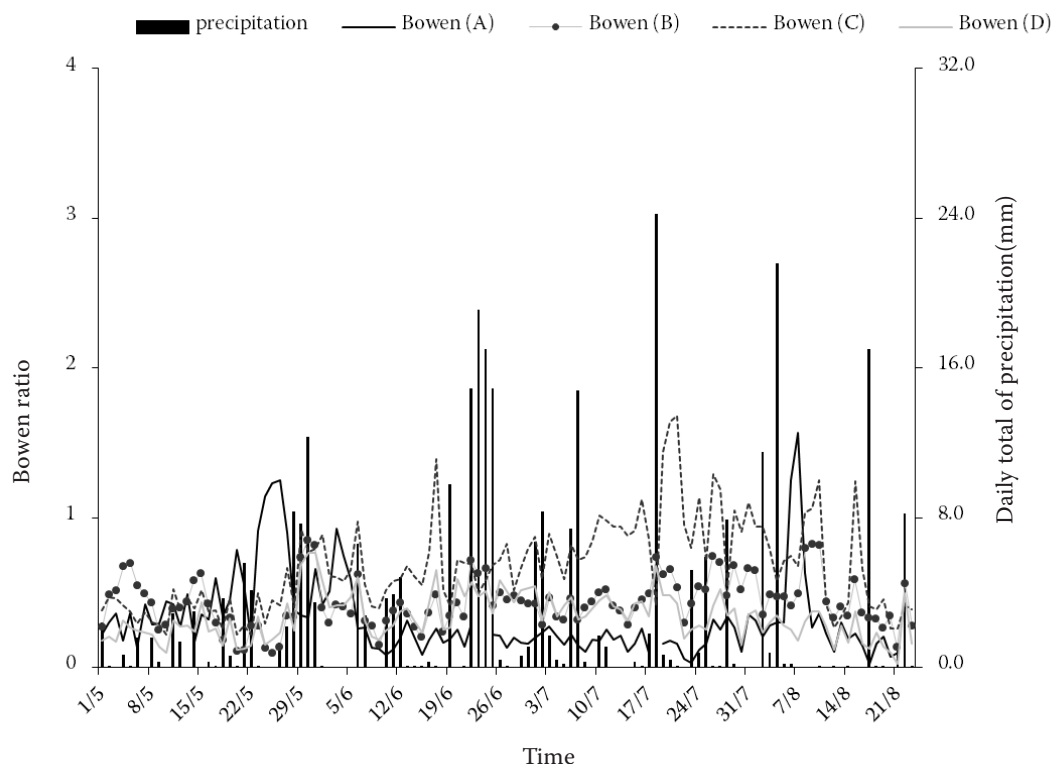


Figure 7. Average daily values of the Bowen ratio for the Dehtáře catchment, 2009

maturity and/or during the soil drought. The fine-textured soils in the discharge and discharge/transient zones, having higher MCWC and affected more by shallow groundwater table and shallow subsurface flow (STha, CMst, stations A and B) were marked in most cases by the highest ETa and the lowest Bowen ratio values. The daily averages of ETa at the station C on soils with the highest content of sand, shallow and stony (Haplic Cambisols), were always the lowest ones and differed significantly from those measured at the station B, which was surrounded by medium-deep sandy loams (Stagnic Cambisols or Haplic Stagnosols). With regard to the soil water regime and evapotranspiration, the Stagnic Cambisols with a drainage system (station B) behaved similarly to the Haplic Cambisols without a drainage system (station D). The discharge zone (station A) did not exhibit a soil water deficit even when extremely dry conditions were recorded on arable lands around the stations B to D.

The transpiration of a green plant cover, which took up a major portion of the soil water storage through its root suction force and was not, in most cases, limited by the soil water deficit, acted as an equalizing factor of evapotranspiration from heterogeneous soil areas. The transpiration also mitigated

the differences in evapotranspiration among different soils, even when these were carrying different crops. The vegetation canopy thus minimized runoff in any form and reduced the infiltration and the groundwater recharge in the recharge zones.

With regard to data consistency, 19–27 % of 10-min β values were considered invalid and therefore were excluded. Most of rejected values (74–84 %) were night-time measurements. Accordingly, 32–40 % of 10-min ETa values were invalid, mostly at night (71 to 84 %). Most of them occurred when ETa values tended towards zero. Considering the average crop height in the range 0.4 to 1.5 m and the adequate equilibrium sublayer thickness 2.0–2.4 m, the minimum upwind fetch needed for the measurements to be relevant (80–90 m) was complied with.

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