WATER RESOURCES RECHARGE IN A MOUNTAIN FOREST ECOSYSTEM

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ABSTRACT

In mountain watersheds, the standard hydrological survey often underestimates components of the water balance. The aim of this study is a detailed water budget analysis of spruce forests (Norway spruce, *Picea abies* (L.) Karst.) in the Jizerka experimental catchment (the Jizera Mountains, Czech Republic). In the investigated mature spruce stand at the elevation of 975 m, the estimated annual evapotranspiration potential is 362 mm and the canopy interception by the absence of fog can reach 224 mm (i.e. 34% of the gross rainfall). But, in 2015-2017, the water budget of that forest stand has been significantly affected by fog/low clouds during 51 foggy days per a summer season. Based on canopy trough-fall observations, the interception loss was reduced to 106 mm (i.e. 16% of the gross precipitation). Thus, the summer fog drip reached 18% of the gross rainfall reducing the canopy interception by 54%. The Slinn model of fog drip was employed to extrapolate the data in both time and catchment scales. In the Jizerka catchment, the mean annual fog drip reached 81 mm (i.e. 7% of the gross precipitation and 11% of the mean annual runoff). Thus, the occurrence of fog/low clouds and the subsequent canopy fog drip represents an important income in the water budget of a forested mountain catchment.

Keywords: *mountain spruce forests, water budget, canopy interception, fog drip.*

INTRODUCTION

In mountainous regions, headwater catchments provide between 40 and 80% of the water resources available to lowland settlements [12]. This role of headwaters has been increasing particularly with the population pressure and impacts of the climate change. Mountain watersheds of central Europe are predominantly covered by forests; therefore, water balance of mountain forest ecosystems seems to be the key factor of the water resources recharge.

In complicated mountain landscapes, the routine hydrological survey leads to underestimating both water budget components: the precipitation income and the evapotranspiration loss [9]. The aim of this study is to analyse the water balance of spruce stands (Norway spruce, *Picea abies* (L.) Karst.) in a small headwater catchment located in the upper plain of the Jizera Mountains (Figure 1). A special attention is paid to the canopy interception and the additional precipitation inputs from the canopy fog by the occurrence of fog or low clouds.

MATERIAL AND METHODS

The Jizerka experimental catchment (50°48’21”- 50°48’59”N, 15°19‘34“-15°20‘48“ E, Elbe river district 1-05-01-004, area of 1 km^2, elevation gradient from 862 to 994 m, covered by spruce forests) operates since 1981. Climate characteristics are available in [11]: North temperate zone, Kőppen Dfc sub-arctic region, mean annual precipitation 1,400 mm, and air temperature 4°C; the snow cover usually lasts from the beginning of November to the end of April. Soils developed on porphyritic granite here (sandy-loamy podzols) are relatively shallow, between 0.5 and 1.2 m.

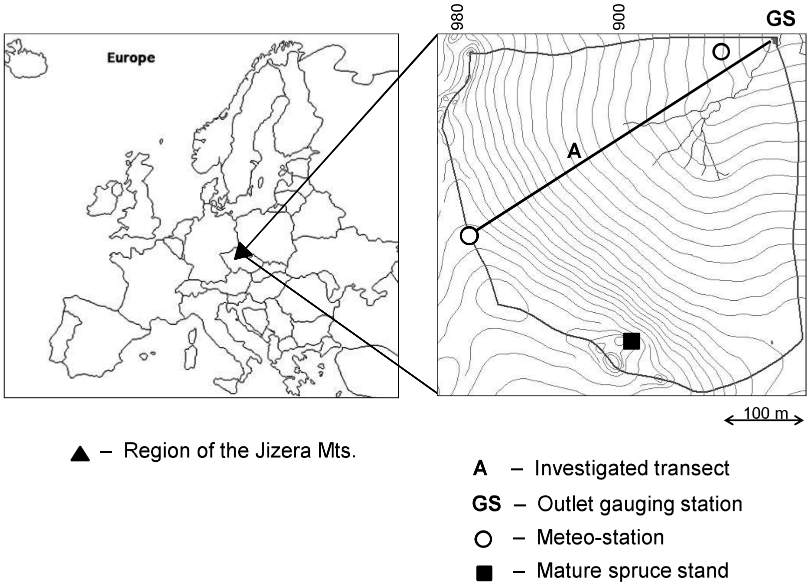

Figure 1. The Jizerka experimental catchment.

The catchment runoff is registered by V-notch weir in the outlet (Figure 1) and standard meteorological parameters (temperature, humidity, gross rainfall, and wind speed) are observed in two spots by the ALA monitoring system. In 2015 – 2017, detailed observations of the canopy through-fall and fog drip were performed in the interception plot (30x30 m, elevation of 975 m) found in the mature spruce forest with the crown density 0.78 and mean tree height 23 m. Ten plastic Hellman-size rain collectors were randomly installed under the forest canopy and sampled in monthly intervals. Twelve passive fog collectors were installed in the vertical transect A of the catchment (along the harvested part of the catchment) to evaluate an elevation effect. At each collector, the drip of fog was generated by 400 metres of Teflon wire (diameter of 0.25 millimetres, thus, surface area index SAI = 5) exposed at the height of 1.7 metres above the ground, and collected in (one-litre) sample bottles at monthly intervals too. Sample bottles were protected against direct rainfall access by a wide-brimmed cover that overlapped the fog collector at an angle of 34°.

Potential evapotranspiration was calculated by the Monteith-Penman equation (1), [7]:

$$\lambda E = \frac{\Delta . R_n + \frac{1}{r_a} c_p \rho_a (e_{sat} - e_{act})}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} \quad (1)$$

Where, R_n – net radiation (W m^{-2}), r_a and r_s – aerodynamic and stomatal resistances (s m^{-1}), e_{sat} and e_{act} – saturated and actual vapour pressures (kPa), c_p – specific heat of the dry air (J kg^{-1} $°C^{-1}$), ρ_a – air density (kg m^{-3}), Δ – the slope of the curve of saturated vapour pressure against temperature (kPa $°C^{-1}$), γ – hygrometric constant (kPa $°C^{-1}$).

Interception loss (I) was estimated from the balance equation (2), [6]:

$$I = P_G + P_F - P' = P_G + P_F - (P_T + P_S) \quad (2)$$

Where, P' – net precipitation (mm), P_G – open field (gross) precipitation (mm), P_F – fog drip (mm), P_T – through-fall under the canopy (mm), P_S – stem-flow (mm).

The analytical model of Gash [2] was applied to simulate interception loss of forest stands in absence of a significant fog drip. This approach considers series discrete events of rainfall, comprising the periods of canopy wetting (when the rainfall P_G is less than the threshold value necessary to saturate the canopy P_G'), canopy saturation, and drying out after rainfall ceases. The forest structure is described in terms of the canopy capacity S, which is defined as the amount of water left on the canopy in zero evaporation conditions when rainfall and through-fall have ceased, the free through-fall coefficient p, which determines the amount of rain which falls directly to the forest floor without touching the canopy, and the proportion of rainfall diverted to stem-flow p_s. The interception components I_1, I_2, I_3, and I_4 were calculated as the interception of m relatively small storm insufficient to saturate the canopy I_1:

$$I_1 = (1 - p - p_s) \sum_{i=1}^{m} P_{G_i} \quad (3)$$

The loss I_2 by wetting the canopy, for n storms that saturate the canopy ($P_G > P_G'$):

$$I_2 = n\,(1 - p - p_s) P_{G'} - nS \quad (4)$$

Evaporation from saturation until rainfall ceases I_3:

$$I_3 = \frac{E}{R} \sum_{i=1}^{n} \left(P_{G_i} - P_{G'}\right) \quad (5)$$

And, evaporation after rainfall ceases I_4:

$$I_4 = nS \quad (6)$$

Then, the total amount of intercepted rainwater (I) in a certain period is:

$$I = I_{1,} + I_2 + I_3 + I_4 \tag{7}$$

In spruce stands, stem-flow as well as the evaporation from trunks are considered negligible, according to [5], [7].

The modified Slinn model [10], [4] was used to calculate the fog drip P_F based on the flux of cloud droplets (8):

$$P_F = 3.6\ LWC\ v_d\ t \tag{8}$$

Where, P_f – fog drip (mm), LWC – liquid water content (g m^{-3}), v_d – settling velocity of droplets (m s^{-1}), t – time of the deposition during a day (hours).

This model of fog deposition does not take into account edge effects of forest stands. In a catchment with fragmented forest stands (i.e. with the forest effect), the equation (9) is recommended [4]:

$$v_d = c\ v_t + v_g \tag{9}$$

Where, c – edge effect factor (greater or equal to one), v_t – turbulent settling velocity (m s^{-1}), v_g – gravitational settling velocity (m s^{-1}).

RESULTS AND DISCUSSION

In the Jizerka catchment, the annual Monteith-Penman evapotranspiration potential ranges between 330 and 450 mm with the elevation and canopy; with 362 mm found for the investigated mature spruce stand (Figure 1). Such a potential could be considered equal to the actual evapotranspiration in a mountain terrain well saturated by frequent and high rainfall events [1], [3].

The dominant loss component of the water budget in mountain forests is the canopy interception [5]. In 2015-2017, by a negligible fog drip, the interception loss of the mature spruce stand calculated by the Gash model (equations 3-7) reached 36, 35 and 31% of the gross precipitation per a season. Parameters of that model were found from the canopy through-falls observed in the absence of fog: the free through-fall coefficient $p = 0.22$ (the horizontal canopy coverage is 0.78), negligible stem-flow in spruce stands ($p_s = 0$), the canopy storage capacity $S = 1.7$ (mm), the evaporation rate from saturated canopy during rainfall $E = 0.21$ (mm $hour^{-1}$), mean rainfall rate $R = 2.18$ (mm $hour^{-1}$) and the threshold rainfall to saturate the canopy $P' = 2.8$ (mm). This analysis included 513 rainfalls with 317 events not sufficient to saturate the canopy and 196 rainstorms saturated the canopy.

The hypsometric relation (10) was found by estimating the fog drip volume P_F:

$$P_F = 0.001\ (aH + a_0)\ A_r\ F_c \tag{10}$$

Where, H - elevation, a_0 – seasonal coefficients of the hypsometric effect, A_r – effective receptor area, and F_c – fog drip coefficient (between 0.18 and 1.0 upon the canopy density).

In the catchment scale, weighted averages of interception and fog drip volumes were identified by respecting four basic canopy groups: 1) mature stands (above 61 years), 2) middle age stands (31 – 60 years), 3) young forests (age below 30 years), and 4) grass dominating (Figure 2).

In real conditions (the interception loss is compensated with the fog input), the mean summer interception varied between 14 and 18% of the gross precipitation (Table 1). Comparatively, in similar mature plantation of Norway spruce (canopy density 0.8-0.9) not affected by the fog or low clouds, the 37% interception loss is reported [5]. In 2015-2017, the canopy through-fall was affected by the fog drip in 51 foggy days a year. Thus, the mean summer fog drip (119 mm) reached 18% of the gross rainfall, reducing the canopy interception by 54 % (from 34 to 16 % of the gross rainfall).

Table 1. Gross precipitation and canopy through-fall observed in the mature spruce stand (May-October, 2015-2017).

Year	Gross precipitation P_G (mm)	Through-fall P_T (mm)	(%)	Interception P_I (mm)	(%)
2015	437	358	82	79	18
2016	772	656	85	116	15
2016	778	654	84	124	16
Mean	662	556	84	106	16

Seasonal (May - October) and annual fog drip estimated by the Slinn model (equations 8-9) and from the observation of gross precipitation and canopy through-fall (equation 1) are presented in Table 2. The two-tailed P value of the Mann-Whitney test resulted in 0.7, thus medians of observed through-falls and the Slinn estimates did not differ significantly, therefore, the Slinn model showed a relatively good agreement with the through-fall based data. In the investigated forest stand, we did not find any significant effect of the forest edge reported in [6], [8], so, the coefficient c (equation 9) was considered equal to one. In the Jizerka catchment, probably, the relatively high forest fragmentation (Figure 4) means that there is a lack of large homogenous forest stands with sharp edges.

Table 2. Seasonal and annual fog drip in the mature spruce stand calculated by the Slinn model (2015-2017).

Year	Summer fog drip (mm) Throughfall	Slinn model	Annual fog drip (mm) Slinn model
2015	79	112	260
2016	154	146	294
2017	117	125	268
Mean	117	128	274

The daily fog occurrence and the fog drip volume V_c sampled by the passive fog collector in the open field in 2015-2017 are presented in Figure 2.

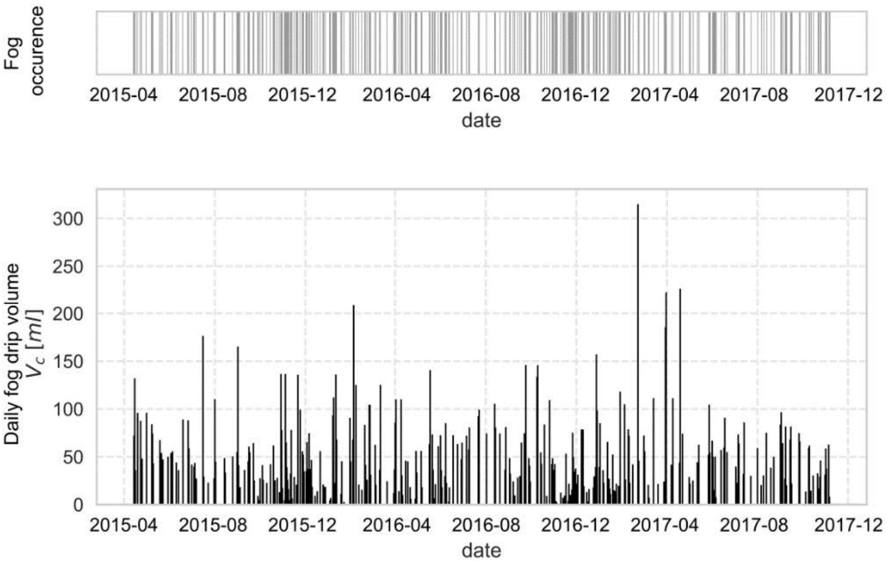

Figure 2. Fog occurrence and fog drip at the Jizerka meteo-station, 975 m a.s.l. (2015-2017).

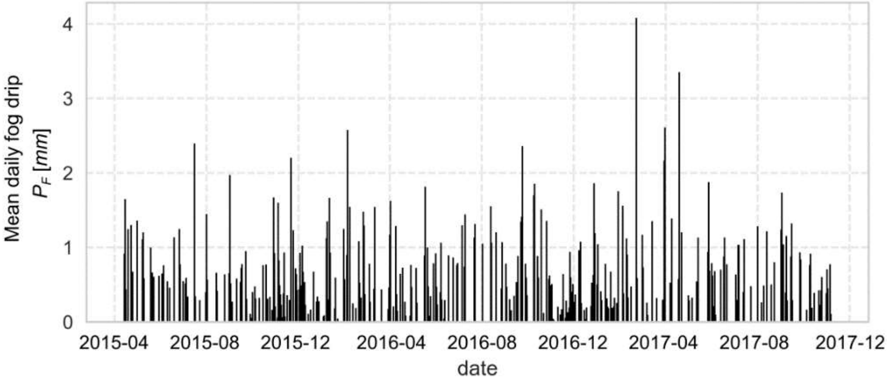

Figure 3. Mean daily fog drip in the Jizerka experimental catchment, 2015-2017.

In 2015-2017, considering the investigated mature spruce stand, the daily fog drip calculated by the Slinn model resulted in the seasonal fog drip contribution: 47% in the summer and 53% in the winter. Finally, the Slinn approach was used to estimate the fog drip in the catchment scale (Figures 3 and 4). In the Jizerka experimental catchment, the mean annual fog drip P_F reached 81 mm (i.e. 7% of the gross precipitation and 11% of the mean annual runoff 736 mm). Respecting the canopy classes (Figure 4), the fog drip and the canopy through-fall are distributed within the catchment area based on the elevation and canopy leaf area (equation

10). In the summer season (May - October), the total fog drip within the focused catchment area was 40 mm (i.e. 6.4 % of the catchment gross precipitation).

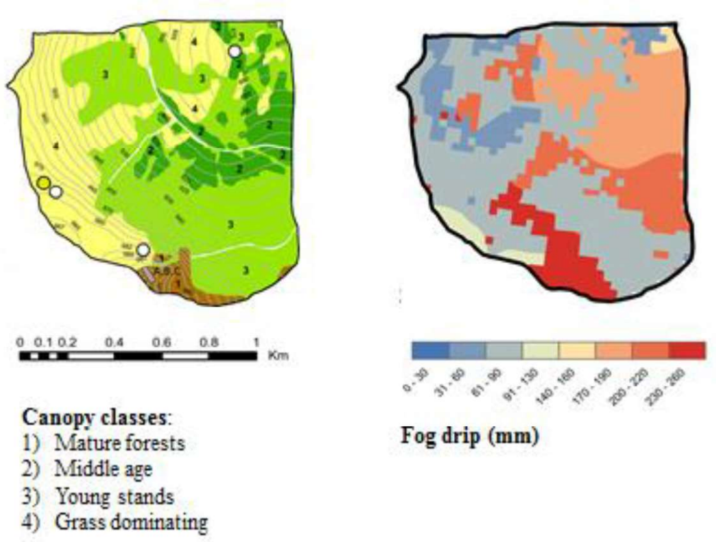

Figure 4. Canopy classes and fog drip in the catchment scale.

CONCLUSIONS

In the investigated mature spruce stand at Jizerka (elevation of 975 m), the mean annual evapotranspiration potential is 362 mm and the canopy interception (wet canopy vaporization) calculated by the Gash analytical model [2] reached 224 mm (i.e. 62% of the evaporation loss and 34% of the gross rainfall). However, the water budget of the forest stand was affected by the occurrence of fog/low clouds during 51 foggy days per season. Based on the trough-fall observation, the interception loss was 106 mm (i.e. 16% of the gross precipitation) only. Thus, in 2015-2017, the summer fog drip (additional precipitation income to the local water budget) reached 18% of the gross rainfall, reducing the canopy interception by 54% (i.e. from 34 to 16% of the gross rainfall).

The Slinn fog drip model [10], [4] showed a satisfactory agreement with the observed data in summer seasons and was applied to extrapolate the data in the annual and catchment scales. Considering the annual cycle, the fog drip in the investigated mature spruce stand was 274 mm (distributed by 47% in the summer and 53% in the winter). In the experimental catchment, the mean annual fog drip reached 81 mm (i.e. 7% of the gross precipitation and 11% of the mean annual runoff). Thus, the occurrence of fog/low clouds and the subsequent canopy fog drip represents an important income in the water budget of a forested mountain catchment.

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REFERENCES

[1] Allen,R.G., Pereira, L.S., Raes, D. and Smith, M. Crop evapotranspiration, guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56, pp. 300, 1998.

[2] Gash, J.H.C., Shuttleworth, W.J. Evaporation, Benchmark Papers in Hydrology, IAHS Press, pp. 521, 2007.

[3] Grismer, M.E., Orang, M., Snyder, R., amd Matyac, R. Pan evaporation and to reference evapotranspiration conversion methods. Journal of Irrigation and Drainage Engineering, vol. 128, pp. 180-184, 2002.

[4] Hildebrandt, A., Eltahir, E.A.B. Using a horizontal precipitation model to investigate the role of turbulent cloud deposition in survival of a seasonal cloud forest in Dhofar, Journal of Geophysical Research, vol. 113: pp. 1-11, 2008..

[5] Křeček, J., Punčochář, P. Design of climate station network in mountain catchments, Hungarian Geographical Bulletin, vol. 61, pp. 19-29, 2012.

[6] Lovett, G.M. Rates and mechanisms of cloud water deposition to a subalpine balsam fir forest, Atmospheric Environment, vol. 18, pp. 361-371, 1984.

[7] Monteith, J.L. Evaporation and environment, In: Proceedings of the 19th Symposium of the Society for Experimental Biology, Cambridge University Press, pp. 205-233, 1965.

[8] Muzylo, A., Llorens, P., Valente, F., Keizer, J.J., Domingo, F., Gash, J.H.C. A review of rainfall interception modelling, Journal of Hydrology, vol. 370, pp. 191–206, 2009.

[9] Palán, L., Křeček, J. Interception and fog drip estimates in fragmented mountain forests, Environmental Processes, vol. 5, pp. 727-742, 2018.

[10] Slinn, W.G.N. Predictions for particle deposition to vegetative canopies, Atmospheric Environment, vol. 16, pp. 1785-1794, 1982.

[11] Tolasz, R. Climate atlas of Czechia. Czech Hydrometeorological Institute, Prague, pp. 256, 2007.

[12] Viviroli, D., Dürr, H.H., Messerli, B., Meybeck, M., Weingartner, R. Mountains of the world, water towers for humanity: typology, mapping, and global significance. Water Resources Research, vol. 43, pp. 1-13, 2007.