

Acid atmospheric deposition in a forested mountain catchment

Josef Křeček⁽¹⁾,
Ladislav Palán⁽¹⁾,
Evžen Stuchlík⁽²⁾

Acid atmospheric deposition is harmful to both forest and aquatic ecosystems. In mountain catchments, acidification also leads to difficulties in water resource management. In 2010-2012, acid atmospheric deposition was analysed in a small forest catchment located in the upper plain of the Jizera Mountains (Czech Republic). Patch observations included monitoring of the canopy interception in two mature stands of Norway spruce (*Picea abies*) at elevations of 745 and 975 metres a.s.l., and twelve passive fog collectors situated along an elevation gradient between 862 and 994 metres a.s.l. In the studied area, fog (and low cloud) precipitation starts to affect the interception loss of the spruce canopy at elevations above 700 metres. However, fog drip was found to also rise with the canopy area. At the catchment scale, methods of spatial interpolation (ArcGIS 10.2) were used to approximate the aerial atmospheric deposition of water and acidic substances (sulphate, nitrate and ammonia). In the watersheds of two adjacent drinking water reservoirs, Josefův Důl and Souš, the mean annual fog drip from the canopy was between 88 and 106 mm (*i.e.*, 7-8% of the mean annual gross precipitation, or 10-12% of the mean annual runoff). Simultaneously, this load also deposited 658 kg km⁻² of sulphur and 216 kg km⁻² of nitrogen (*i.e.*, 55% and 48% of the “open field” bulk amounts). Therefore, in headwater catchments stressed by acidification, the additional precipitation (measured under the canopy) can increase the water yield, but can also contribute to a decline in water quality, particularly in environments of low buffering capacity.

Keywords: Mountain Watershed, Spruce Forests, Acid Atmospheric Deposition, Water Resources Recharge

Introduction

Acid rain directly affects the chemical and pH balances of surface and ground waters in headwater regions of central Europe (Holen et al. 2013). Low pH values cause the mobilisation of toxic aluminium, which reduces the biota in water courses and reservoirs. Fog and cloud waters have been recognised as important carriers for the deposition of water-borne pollutants in high elevation forests (Kroll & Winkler 1989, Whitman 2000, Wrzesinsky & Klemm 2000). The process of fog condensation on vegetation foliage and dripping to soil surfaces can significantly affect the water balance in mountain watersheds (Vogelmann 1973, Krečmer et al. 1979, Ingwersen 1985, Lovett & Reiners 1986, Dawson 1998). Recently, fog collection technologies (simple

devices based on erected nets facing on-coming winds and trapping water particles in the air) have been developed in many parts of the world to modify the water cycle and to support local water supplies (Ruiz 2005). Fog has also been viewed as an important source of moisture in coastal ecosystems (Dawson 1998); however, effective fog/cloud water trapping by vegetation has been mainly reported in cloud forests (Vogelmann 1973, Holder 2003, Hildebrandt & Eltahir 2008). In general, higher elevation forests show relatively significant additional water yields due to the occurrence of fog (Ingwersen 1985, Walmsley et al. 1996, Igawa et al. 2002), and Holder (2003) has called the conservation of high elevation forests an important tool for water supply engineering.

Considering forests in Central Europe, Brechtel (1989) reported an elevation of 700 m as the threshold of significant fog precipitation. Upland watersheds above 700 m are currently covered mainly by coniferous forests (Andersson 2005). Fog drip in short vegetation types (like grass) has been found to be much smaller than in forests, with deposition intensities of 0.018 - 0.02 mm per hour in grasslands compared with 0.02-0.4 mm per hour in coniferous forests (Lovett & Reiners 1986, Hildebrandt & Eltahir 2008). In addition to canopy structure, however, a number of variables such as wind speed, liquid water content and droplet sizes influence the deposition of fog/cloud precipitation (Whitman 2000).

In regions affected by polluted air (particularly emissions of sulphur and nitrogen) and by consequent acid atmospheric deposition, processes trapping fog from the atmosphere can intensify the decline of water environment and water resources (Verhoeven et al. 1987, Delleur 1989, Schemenauer et al. 1995, Igawa et al. 2002, Schöpp et al. 2003, Kim et al. 2006, Křeček & Hořická 2006). Therefore, land use and watershed management practices might influence the volumes and chemistry of cloud/fog precipitation as well as the recharge, quantity and quality of water resources (Kim et al. 2006, Křeček & Hořická 2010). Increasing inputs of acid substances from fog precipitation may result in lower

□ (1) Department of Hydraulics and Hydrology, Czech Technical University in Prague, Thákurova 7, CZ-166 29 Prague 6 (Czech Republic); (2) Institute of Hydrobiology, Biology Centre CAS, Na Sádkách 7, CZ-37005 České Budějovice (Czech Republic)

@ Ladislav Palán (ladislav.palan@fsv.cvut.cz)

Received: Dec 16, 2016 - Accepted: May 08, 2017

Citation: Křeček J, Palán L, Stuchlík E (2017). Acid atmospheric deposition in a forested mountain catchment. *iForest* 10: 680-686. - doi: [10.3832/ifor2319-010](https://doi.org/10.3832/ifor2319-010) [online 2017-07-17]

Communicated by: Elena Paoletti

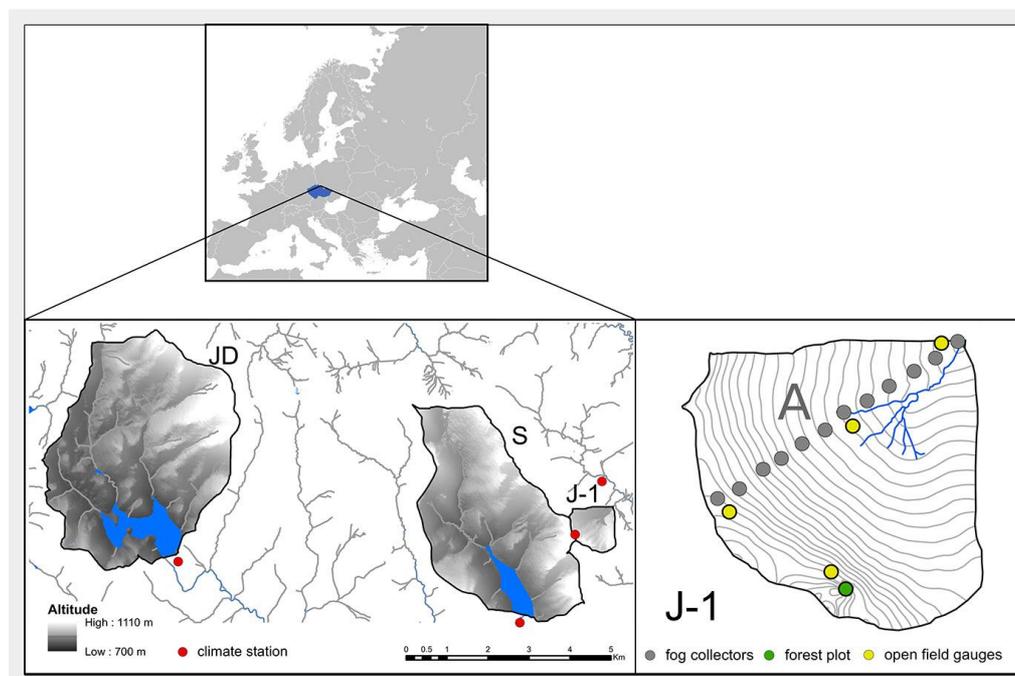


Fig. 1 - Catchments of the drinking water reservoirs (Josefův Důl - JD, Souš - S) and the experimental basin (J-1).

pH, reduced contents of calcium and magnesium (and water hardness), and the mobilisation of aluminium in water environments (Merilehto et al. 1988, Mosello et al. 1995, Kreček & Hořícká 2006). pH is one of the most important operational water quality parameters, with national guidelines for drinking water quality often suggesting an optimum pH in the range 6.5 to 8.5 (WHO 2004). Without air pollution and subsequent acid rain, most lakes and streams would have a pH level close to 6.5 (Merilehto et al. 1988). However, in the headwaters of the European “Black Triangle”, in the late 1980s water pH rose to 4-5 and concentrations of aluminium increased to 1-2 mg per litre (Kreček & Hořícká 2010). The limit of aluminium in drinking water is 0.1 mg per litre for large treatment facilities and 0.2 mg per litre for small facilities (WHO 2004). Therefore, in some water treatment plants, the increased acidity of raw water necessitated several additional investments (Kreček & Palán 2015). The aim of this study was to analyse the genesis of acid atmospheric deposition in forested headwater catchments of the Jizera Mountains (Czech Republic) with special attention on the role of fog/low cloud events, elevation and vegetation canopy.

Material and methods

Study site

This study was performed in the upper plain of the Jizera Mountains (50° 40' - 50° 52' N, 15° 08' - 15° 24' E), which has a humid temperate climate (Fig. 1). This 200 km² headwater area is located above 800 m (subarctic region of the Köppen climate zone, Dfc), the supposed threshold for the occurrence of significant fog/clouds in the Czech Republic (Prošková & Hůnová 2006). The mean annual precipitation ranges from 1290 to 1400 mm, the mean annual air temperature from 4 to 5 °C, and the average maximum snowpack depth is about 120 cm (the snow cover usually lasts from the beginning of November to the end of April – Tolasz & Baštýřová 2007).

The risk of acidification in the Jizera Mountains is enhanced by the granite bedrock and shallow podzolic soils of a low buffering capacity. The upper watersheds are fully forested; however, during the 19th century, the mixed forest of native tree species (Common beech - *Fagus sylvatica*, Norway spruce - *Picea abies*, and Common silver fir - *Abies alba*) was converted to spruce plantations (almost 90% of forest stands) of lower ecological stability (Kreček & Hořícká 2006).

Precipitation analyses

We analysed precipitation using the water balance method under a canopy proposed by Lovett (1988) as the most appropriate approach for measuring fog and cloud water deposition in ecological studies. During the period 2011-2012, precipitation (including fog-drip) under the canopy of two mature spruce stands (plots 1 and 2, at elevations of 745 and 975 metres a.s.l. – Fig. 1) were collected by modified Hellmann rain gauges (area of 200 cm², plastic collectors with a shield against bird contamination). Sets of ten gauges were randomly installed in plots of 30 × 30 metres according to forest characteristics (Tab. 1) and the method proposed by Krečmer & Páv (1982). The amount of fog drip was estimated by comparing the volumes of water collected by these sets of ten gauges with a single rain gauge installed in adjacent forest openings (i.e., “bulk”, located 30 to 50 metres away from the forest edge). According to Krečmer et al. (1979), in spruce stands the stemflow of rainwater can be considered to be negligible. To test this assumption at our stands, stemflow in the investigated plots was collected by plastic tubing installed around the circumference of four selected trunks. Collected volumes of water were recorded at monthly intervals; the interception loss of the canopy (*I*) was calculated as (eqn. 1):

$$I = \sum_{i=1}^n \frac{1}{m} P - \left(\sum_{i=1}^n \frac{1}{m} P_i + \sum_{i=1}^n \frac{1}{m} P_s \right) \quad (1)$$

where *P* is the open field (gross) precipitation (mm), *P_i* is the throughfall under the canopy (mm), *P_s* is the stemflow, *n* is the number of months, *m* is the number of seasons.

To identify the effect of elevation on potential fog drip, twelve passive fog collectors were installed in vertical transect A of

Tab. 1 - Characteristics of the investigated plots 1 and 2 (30 × 30 m).

Parameter	Plots	
	1	2
Elevation (m)	745	975
Tree species	<i>Picea abies</i>	<i>Picea abies</i>
Age (years)	80-100	80-100
Number of trees	54	68
Mean height (m)	24	23
Horizontal canopy density (m ² m ⁻²)	0.92	0.78
Leaf area index (m ² m ⁻²)	7.3	6.7

the Jizerka experimental catchment (J-1, area of 1 km², elevation gradient from 862 to 994 metres – Fig. 1), where mature spruce stands were harvested by clear-cutting. For each collector, the fog drip was generated using 400 metres of Teflon line (diameter of 0.25 millimetres, i.e., surface area index = 5) installed at a height of 1.7 metres above the ground, and collected in one-litre sample bottles at monthly intervals. Sample bottles were protected against direct rainfall access by a wide-brimmed cover that overlapped the fog collector at an angle of 34°.

The collected water samples (fog drip, throughfall and stemflow) were analysed by standard techniques in the Hydrobiological Laboratory Velký Pálenec (Charles University in Prague), including pH, conductivity, and contents of elements related to acid atmospheric deposition – sulphur (S-SO₄) and nitrogen (N-NO₃, N-NH₄). Concentrations of NO₃⁻ and SO₄²⁻ were determined by ion chromatography, and NH₄⁺ by the rubazotic acid method (Kopáček & Procházková 1993). Although bacterial activity may alter the chemical composition of water after collection (especially nitrogen – Golterman 1969), in our case the relatively cold mountain climate (subarctic region), relatively high concentrations of nitrogen, and low values of pH and dissolved organic carbon likely limited bacterial activity (Cape et al. 2001). The potential growth of algae was reduced by using dark sampling bottles and keeping samples in the dark during transport.

Precipitation deposition in watersheds

Findings worldwide (Krečmer et al. 1979, Brechtel 1989, Dawson 1998) have shown that in mountain watersheds, fog drip deposition increases with elevation and canopy density. Therefore, the hypsometric method with spatial interpolation (using ArcGIS 10.2) was employed to approximate the spatial atmospheric deposition of fog water (P_{fd}), sulphur (S-SO₄) and nitrogen (N-NO₃, N-NH₄) in two watersheds containing drinking water reservoirs in the Jizera Mountains, Josefův Důl and Souš (Fig. 1). To identify seasonal relationships between fog drip and elevation, data from the fog collectors was analysed separately for the summer (May-October) and winter (November-April) seasons. The occurrence of fog was also recorded at four nearby climate stations: Josefův Důl (elevation of 745 m a.s.l.), Souš (772 m), and at the highest and lowest points in the Jizerka experimental basin (980 and 850 m – Fig. 1).

Several authors (Krečmer et al. 1979, Lovett & Reiners 1986, Weathers et al. 1995) have observed higher fog drip at the edges of forest stands, sometimes exceeding the fog deposition in a nearby stand by 3 to 15 times. However, in fragmented forest stands such as those in the Jizera Mts. Krečmer et al. (1979) found increases of only up to 10% in border areas 10-20 metres wide. We therefore neglected the edge

effect in this study.

The vegetation canopy was analysed by satellite (Landsat imagery, resolution of 30 × 30 m) and detailed ground investigations (Kreček & Krčmář 2015). Then, the canopy surface was categorised into groups of herbaceous plants and forest stands, and their delineation in watersheds was performed. In the Jizerka experimental catchment, ground-based canopy analyses were carried out for twenty selected plots (30 × 30 m). Twelve of these were instrumented by passive fog collectors (along the harvested transect A – Fig. 1) and two by sets of ten rain gauges installed under the canopy. The forestry characteristics (age, stocking, horizontal canopy density) were estimated by a standard inventory (Kreček & Hořická 2010). The capacity for fog deposition was approximated by the fog-drip coefficient F_c according to the canopy surface estimates (Krečmer et al. 1979). The value of the coefficient F_c ranges from 0 to 1. Equation 2 was used to calculate the seasonal volume of fog precipitation for a specified canopy, elevation and season. The relation is based on a simple linear hypsometric relation between altitude and the precipitation volume (eqn. 2).

$$P_{fd} = 0.001 \cdot (a \cdot E + a_0) \cdot A_{er}^{-1} \cdot F_c \quad (2)$$

where P_{fd} is the seasonal amount of fog drip (mm), a and a_0 are coefficients of the hypsometric relation derived for the individual season, E is the elevation (m), A_{er} is the effective receptor area (m²), and F_c is the fog drip coefficient.

Similarly, the hypsometric method was used to assess the water quality of the deposited fog. Concentrations of the acidic substances (sulphate, nitrate and ammonia) from the fog collectors and rain gauges were used to estimate seasonal amounts of deposited elements (eqn. 3):

$$m = (b \cdot E + b_0) \cdot A_{er}^{-1} \cdot F_c \quad (3)$$

where m is the seasonal amount of deposited elements (kg km⁻²), b and b_0 are coefficients of the hypsometric relation derived for individual season and element, E is the elevation (m), A_{er} is the effective receptor area (m²), and F_c is the fog drip coefficient.

Standard descriptive statistics (including mean, median, maximum and minimum values, standard deviation – SD, standard

error of mean – SEM, upper and lower 95% confidence limits), normality test, and one-way ANOVA were used to analyse the data and to identify relationships between the groups of data (Motulsky & Searle 1998). The paired t-test comparing means of two groups of a variable was used to test differences between groups, and the correlation was tested by the Pearson's coefficient.

Results and discussion

Effects of elevation and canopy

The correlation matrix of elevation E (m), sampled volume of fog drip V (ml), water pH, and contents of N-NO₃, N-NH₄, S-SO₄ (mg l⁻¹) is presented in Tab. 2. Though passive string collectors are limited in their ability to collect cloud/fog water, and their efficiencies depend on the droplet spectra and wind speed (Schell et al. 1992, Avila et al. 2001), these data allow the effects of elevation to be assessed. It is evident that the groups of data are inter-correlated. With rising elevation, there was a significant increase of fog drip, followed by decreasing water pH. Contents of acidic substances (N-NO₃, N-NH₄, S-SO₄) were not well correlated with elevation, but in higher altitudes their deposition did increase with increasing volumes of precipitated water. There was a linear relationship between mean monthly fog drip and elevation in both summer and winter seasons with correlation coefficients $r = 0.93$ and 0.98 , $r_{crit} = 0.73$ ($n = 5$, $\alpha = 0.1$), a slope significantly different from zero ($P = 0.0082$ and 0.0033), and a non-significant departure from linearity ($F = 39.3$ and $73.75 > F_{crit} = 9.78$). During the winter season (November-April), the load of fog precipitation exceeded the summer fog drip (May-October) by 23-50%.

In plot 2 during the warm season (May-October), the observed canopy storage capacity was 2.3 mm. For the seasonal rainfall of 683 mm (Tab. 3) and approx. 100 rainy days saturating the storage capacity, the total interception loss of rainwater by the spruce canopy could be estimated at about 230 mm. Therefore, in plot 2 the interception losses not affected by the fog drip could reach 34 % of the gross precipitation. Similarly, in a dense mature plantation of Norway spruce (canopy density 0.8-0.9) not affected by additional precipitation from fog or low clouds, Krečmer et al. (1979) reported 37 % interception. The vol-

Tab. 2 - The correlation matrix of elevation E (m), sampled volume of fog drip V (ml), water pH (-), and contents of N-NO₃, N-NH₄, S-SO₄ (mg l⁻¹); $r_{crit} = 0.19$ ($n=125$, $p=0.05$).

-	E	V	pH	N-NO ₃	N-NH ₄	S-SO ₄
E	1	0.21	-0.20	0.03	0.03	-0.05
V	0.21	1	-0.72	0.39	0.02	0.07
pH	-0.20	-0.72	1	-0.50	-0.29	-0.23
N-NO ₃	0.03	0.39	-0.50	1	0.08	0.13
N-NH ₄	0.03	0.02	-0.29	0.08	1	0.82
S-SO ₄	-0.05	0.07	-0.23	0.13	0.82	1

Tab. 3 - Rainfall and fog-drip sampled in the plots 1 and 2, May-October, 2011- 2012.

Plot	Precipitation	Amount (mm)	pH (-)		S-SO ₄ (mg l ⁻¹)		N-NO ₃ (mg l ⁻¹)	
			mean	SD	mean	SD	mean	SD
1	Rainfall	630	5.1	0.15	0.40	0.05	0.20	0.04
	Fog drip	27	4.1	0.9	4.60	0.8	1.92	0.69
2	Rainfall	683	4.8	0.11	0.43	0.04	0.22	0.14
	Fog drip	120	3.8	1.1	7.70	1.3	3.21	1.20

Tab. 4 - Fog drip coefficient F_c .

Stand category	Age classes	Horizontal canopy density	Fog-drip coefficient F_c
1	Mature stand	> 0.8	1
2	Mature stand	0.65 - 0.8	0.92
3	Middle age stand	0.25 - 0.65	0.33
4	Young stand, grass	< 0.25	0.18

ume of stemflow was found to be negligible, which is consistent with the findings of Krečmer et al. (1979) and Lovett & Reiners (1986). One possible explanation includes the centrifugal structure of the spruce canopy and rough stem-bark.

The observed mean interception loss in the summer season (May-October) was 196 mm (31 % of the gross precipitation) for plot 1, and 112 mm (16 %) for plot 2. These differences in the interception loss between the two spruce stands could be explained simply by the deposition of fog droplets: 37 and 120 mm per season (i.e., 0.2 and 0.7 mm daily).

In the Jizerka experimental catchment (plot 2), the content of sulphur and nitrogen were analysed separately for rain and fog water (Tab. 3). The passive fog drip collectors at different elevations showed in-

creasing concentrations of sulphur and nitrogen with increasing elevation. In comparison with rainfall the collected fog precipitation had lower pH, likely because of the genesis of fog droplets in an atmosphere polluted by emissions of sulphur and nitrogen. Verhoeven et al. (1987) reported higher acidity in fog versus rain in the Fichtelgebirge Mountains (Bavaria, Germany) due to an excess of strong mineral acids by anthropogenic emissions into the atmosphere.

At transect A (899-975 m a.s.l.) during the period 2010-2012, the average annual value of pH varied with elevation from 3.6 to 4.2, and the average annual concentration values (mg l⁻¹) of S-SO₄, N-NO₃, and N-NH₄ varied with elevation from 7.7 to 7.9, from 2.2 to 2.7, and from 6.2 to 7.2, respectively. These data correspond to the results of

Pahl et al. (1997), who reported higher amounts of dissolved chemicals (e.g., SO₄) at greater distances above the cloud base.

In the watersheds of the drinking water reservoirs (Josefův Důl and Souš – Fig. 1), the estimates of the fog-drip coefficient F_c was consistent with standard forestry mapping (age classes and horizontal canopy density) for existing spruce plantations. As shown in Tab. 4, values of the F_c coefficient reflected the efficiency of the spruce canopy to collect fog droplets with a maximum ($F_c = 1$) in a close mature stand, and decreasing with opening of the canopy.

On the other hand, fog deposition depends on the frequency that fog occurs. The meteorological observation of fog events at elevations of 745, 772, 850 and 980 m a.s.l. (Fig. 1) showed a statistically significant relation between the number of foggy days and elevation (correlation coefficient $r = 0.99$, $r_{crit} = 0.95$, $n = 4$, $\alpha = 0.05$ – eqn. 4).

$$D_f = 0.2178 \cdot E - 153.76 \quad (4)$$

where D is the number of foggy days in the summer (days), and E is the elevation (m).

In the winter, the number of foggy days exceeded summer values by 60 %, corresponding to Tolasz & Baštýřová (2007). During temperatures below zero, the deposition of fog droplets falls to almost one-third of the potential, according to Lovett & Reiners (1986).

Watershed deposition

The observed and approximated loads of fog water and acidic substances were used for deriving the coefficients in the hypsometrically based regression of eqn. 2 and eqn. 3 using the effective receptor area of

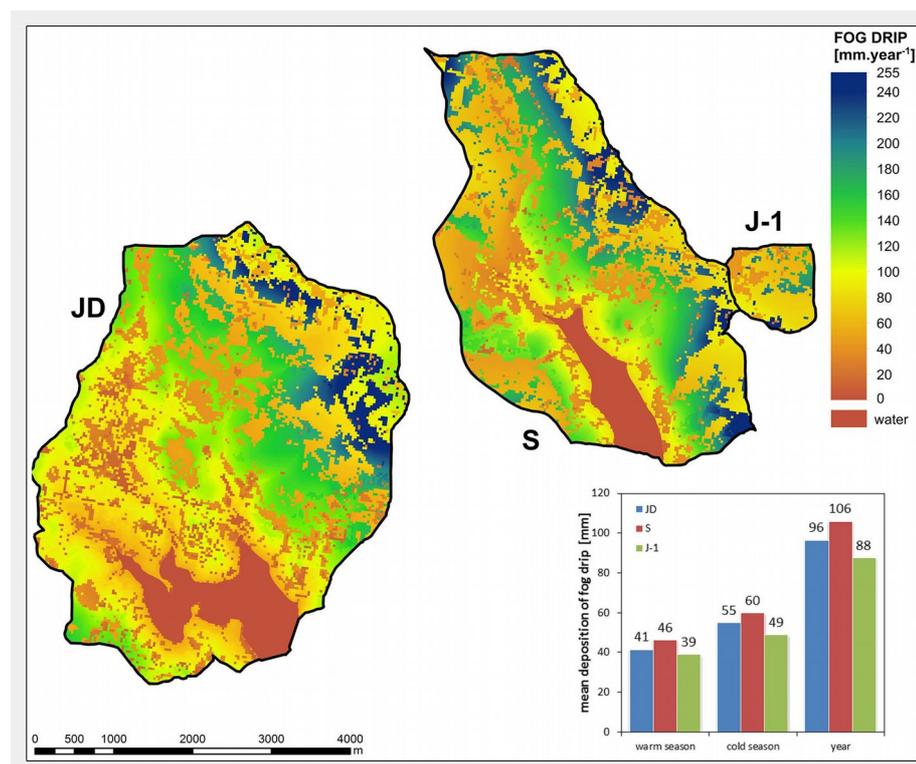
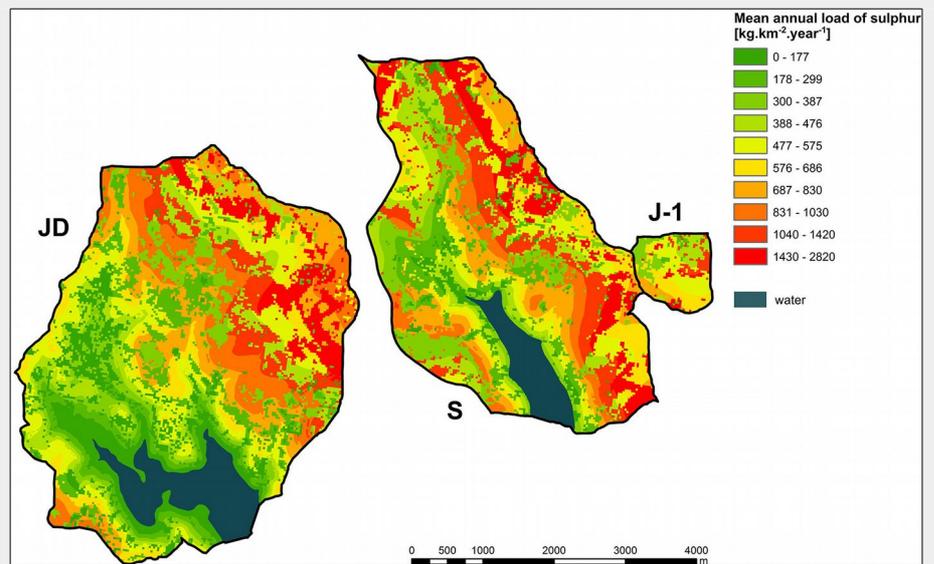
**Fig. 2** - Mean annual fog drip in the investigated watersheds (2011-2012).

Fig. 3 - Mean annual load of sulphur by fog drip (2011-2012).



the fog collector $A_{er} = 0.022 \text{ m}^2$ and the fog drip coefficient F_c depending on the vegetation cover. All relations (Tab. S1, Tab. S2, and Tab. S3 in Supplementary material) were statistically significant, with correlation coefficients varying in absolute value from 0.87 to 0.98 ($r_{crit} = 0.8114$, $n = 6$, $\alpha = 0.05$), slope different from zero (P from 0.01 to 0.0015), and a non-significant departure from linearity (F from 17.34 to 66.66, $F_{crit} = 7.39$).

In the catchments of Jizerka (J-1), Josefův Důl (JD) and Souš (S), approximations of the data using eqn. 2 and eqn. 3 allowed to determinate the spatial distribution of values within catchments respecting local conditions such as the altitude and vegetation cover, resulting in spatial maps of the mean annual load of fog water (Fig. 2), sulphur (Fig. 3) and nitrogen (Fig. 4), and mean annual pH of fog water (Fig. 5).

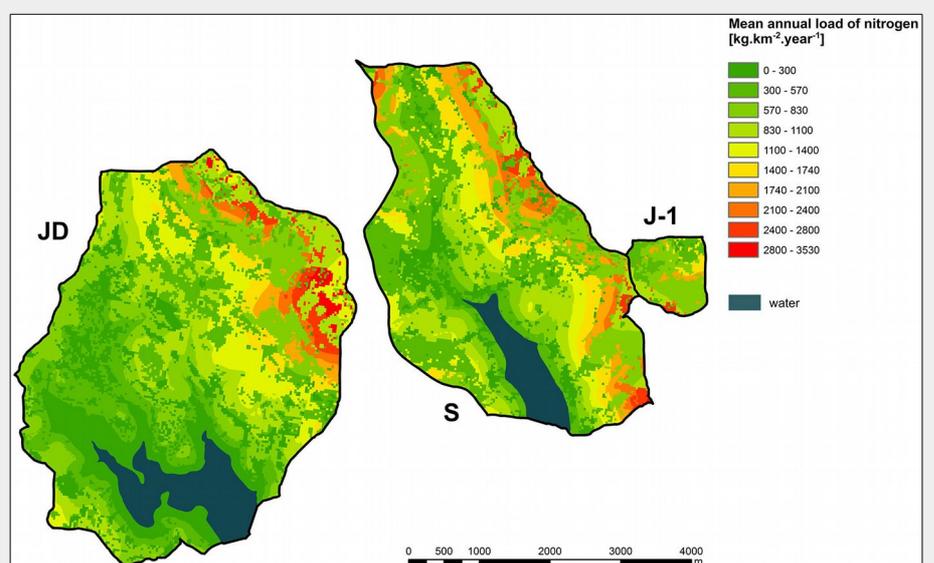
The annual load of fog water varied from 7% to 8% of the mean annual gross precipitation (1324 mm, estimated by the hypsometric interpolation of the standard point

rain gauges). Therefore, the input of fog precipitation in the annual water budget increased the water yield from 10% to 12% (by 867 mm mean annual runoff). On the other hand, the mean annual loads of sulphate and nitrate from fog deposition were 1975 and 1080 kg km⁻² in the watersheds of Josefův Důl and Souš, i.e., 55% and 48% of the amounts of sulphur and nitrogen, respectively, registered in the bulk. Likewise, in the Fichtelberg Mountains (Bavaria, Germany), Wrzesinsky & Klemm (2000) reported a significant role of fog precipitation in the water balance of forest stands at elevations above 800 m a.s.l. At a comparable elevation in the White Mountains (New York, USA), Miller et al. (1993) reported that cloud deposition contributed 32% and 37% of the total atmospheric load of nitrogen and sulphur.

The spatial maps can also be used to indicate locations in the investigated watersheds vulnerable to higher inputs of fog water, which may in turn affect the trees and water quality within the watersheds.

Generally, based on the spatial distribution of pH, nitrogen and sulphur, the higher altitudes of catchments are at higher risk, especially in combination with the occurrence of a mature coniferous forest. From the spatial distribution of the vegetation cover, it was possible to estimate the total inputs of fog water, sulphur and nitrogen, as well as water pH into the catchments, providing us with important information on the acidification of water courses and reservoirs in the water supply catchments Josefův Důl and Souš (Fig. 3, Fig. 4, Fig. 5). Because of the very low buffering capacity of the soil and bedrock in these catchments, these acid atmospheric loads directly affect the quality of surface waters (Kreček & Hořická 2006), and may require investments in water treatment (Kreček & Palán 2015). Those investments could be reduced, however, using forest management practices that respect conditions for the formation of fog precipitation and its negative role in mountain catchments stressed by acidification.

Fig. 4 - Mean annual load of nitrogen by fog drip (2011-2012).



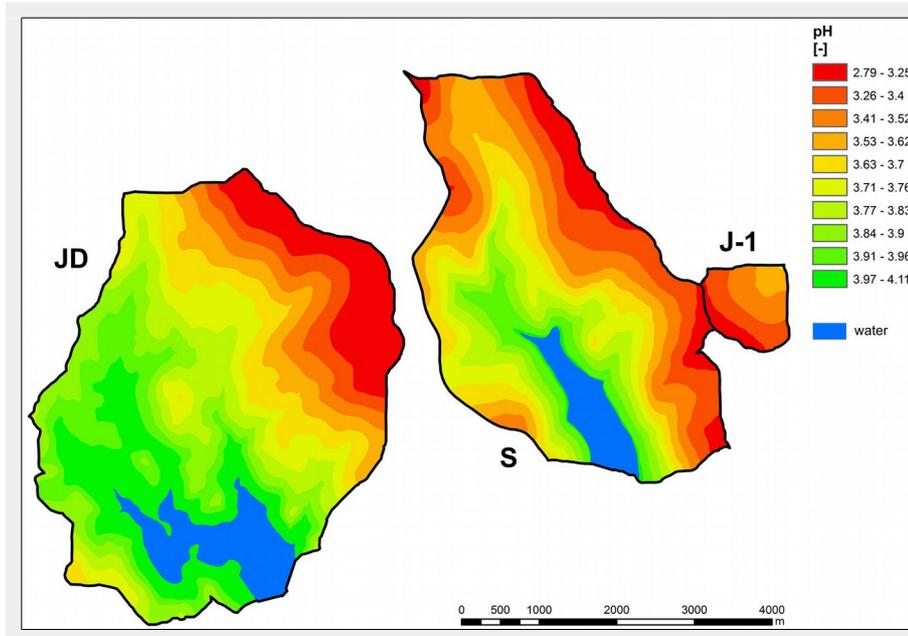


Fig. 5 - Annual pH values of fog drip (2011-2012).

Uncertainties in estimates of atmospheric deposition

The estimated loads of fog water and acidic substances (sulphate, nitrate, ammonia) to the watersheds investigated here are affected by several uncertainties. Generally, in mountainous terrain the accuracy of measured precipitation amounts decreases with increasing wind velocity (Shaw et al. 2010), with significant errors (above 5 %) when wind velocities are above 2 m s^{-1} . For the rain gauges installed in spruce stands (plots 1 and 2), the effect of wind was assumed to be negligible. Generally, errors in chemical analyses are considered to be on the order of 10%. The month-long storage of rain/fog water in gauges also introduces the risk of error, namely for nitrogen that can be altered by bacterial activity. Nevertheless, Cape et al. (2001) reported negligible changes of NO_3 contents in longer sampled rainwater in cold mountain environments, finding that significant errors might occur only in high summer months (July, August), but not exceeding 20%.

The efficiency of passive fog collectors is on the order of 10-20% of the actual liquid water content in a cloud; the collection efficiency of a single string depends on the size spectrum of the cloud droplets and wind velocities (Schell et al. 1992, Avila et al. 2001). However, our use of passive fog collectors was intended to just indicate the effects of elevation in the upper plain of the Jizera Mountains, assuming comparable wind speeds in the investigated transect (Fig. 1). The collected volumes of fog might also have been affected by the input of surrounding rainfall. However, the passive collectors at the Jizerka transect were protected against inputs of rainfall up to wind speeds of 2 m s^{-1} . At higher velocities (based on hourly means) and rainfall intensities above 5 mm day^{-1} , the sampled volumes of fog water were possibly increased

by rainfall up to 10%. Considering the collection techniques used, estimates of the canopy structure, and data interpolation, we believe the accuracy of the estimated long-term loads of fog water and acidic substances presented here to be in the range of $\pm 20\%$. Further research is needed to evaluate the effects of particular meteorological situations (particularly wind speed and direction) on episodic loads of fog drip. However, this study provides initial data for evaluating the effects of possible scenarios of forestry practices on atmospheric loads to the water supply catchments of Josefův Důl and Souš.

Conclusions

In the Jizera Mountains, the fog water deposition decreases the interception loss in spruce stands (*Picea abies*) at elevations above 700 m. However, measurable volumes of fog water sampled by passive collectors were detected at elevations above 900 m. Fog drip from the forest canopy was found to increase with elevation and canopy extent. In two mature spruce stands, located at elevations of 745 and 975 m, the observed summer interception losses were 196 mm (31%) and 112 mm (16%), respectively, and were significantly affected by fog drip at the higher elevation. The volumes of fog drip sampled by the passive collectors demonstrated the effects of elevation and seasonal variations. In the winter season (November-April), the fog deposition exceeded the summer values (May-October) by 23-50%.

In the catchments of the drinking water reservoirs Josefův Důl and Souš, loads of fog water varied from 88 to 106 mm (i.e., from 7% to 8% of gross precipitation). Therefore, for the mean annual precipitation of 1324 mm (867 mm runoff), the additional input of fog to the annual water budget could have increased the mean annual water yield from 10% to 12%. The negative

effect of fog precipitation on increasing acid deposition in the investigated watersheds was also demonstrated. The mean annual loads of sulphur and nitrogen from fog drip were 658 kg km^{-2} and 216 kg km^{-2} (i.e., 55% and 48% of the bulk amounts of sulphur and nitrogen, respectively).

Therefore, in headwater catchments stressed by acidification, the deposition of fog water can enhance the water yield and the recharge of water resources. At the same time, however, it can also affect the quality of surface waters, particularly in environments of a relatively low buffering capacity. Both these effects are related to the elevation and canopy structure, and could therefore be altered by forestry practices modifying the above-ground canopy.

Acknowledgements

This research was supported by the Earthwatch Institute (Oxford, UK), Project on Mountain Waters of Bohemia), the Grant Agency of the Czech Republic (GAČR 526-09-0567 - CLIMHED), by the Czech Technical University in Prague (SGS 16/140/OHK1/2T/11), and the Ministry of Education of the Czech Republic (INTER-EXCELLENCE: INTER-COST LTC 17006, 2017).

References

- Andersson F (2005). Coniferous forests. Series "Ecosystems of the world" no. 6, Elsevier, Amsterdam, The Netherlands, pp. 646. [online] URL: http://books.google.com/books?id=_YoO8xKYSJAC
- Avila EE, Pereyra RG, Castellano NE, Saunders CPR (2001). Ventilation coefficients for cylindrical collectors growing by riming as a function of the cloud droplet spectra. Atmospheric Research 57: 139-150. - doi: [10.1016/S0169-8095\(01\)00067-9](https://doi.org/10.1016/S0169-8095(01)00067-9)
- Brechtel HM (1989). Monitoring wet deposition in forest - quantitative and qualitative aspects. In: "Monitoring Air Pollution and Forest Ecosystem Research: Commission of the European

- Communities, Air Pollution Reports" (Bresser AHM, Mathy P eds). RIVM, Bilthoven, Netherlands, pp. 39-63.
- Cape JN, Kirika A, Rowland AP, Wilson DR, Jickells TD, Cornell S (2001). Organic nitrogen in precipitation: real problem or sampling artefact? *The Scientific World Journal* 1: 230-237. - doi: [10.1100/tsw.2001.278](https://doi.org/10.1100/tsw.2001.278)
- Dawson TE (1998). Fog in the California redwood forest: ecosystem inputs and use by plants. *Oecologia* 117: 476-485. - doi: [10.1007/s004420050683](https://doi.org/10.1007/s004420050683)
- Delleur JW (1989). Atmospheric deposition. International Association of Hydrological Sciences, Wallingford, Oxfordshire, UK, pp. 288.
- Golterman H (1969). Methods for chemical analysis of fresh waters. F.A. Davis Company, Philadelphia, PA, USA, pp. 172. [online] URL: <http://eric.ed.gov/?id=ED064114>
- Hildebrandt A, Eltahir EAB (2008). 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* 113: 1-11. - doi: [10.1029/2008JG000727](https://doi.org/10.1029/2008JG000727)
- Holder CD (2003). Fog precipitation in the Sierra de las Minas Biosphere Reserve, Guatemala. *Hydrological Processes* 17: 2001-2010. - doi: [10.1002/hyp.1224](https://doi.org/10.1002/hyp.1224)
- Holen S, Wright R, Seifert I (2013). Effects of long range transported air pollution (LRTAP) on freshwater ecosystem services. ICP-Waters report 115/2013, NIVA - Norwegian Institute for Water Research, Oslo, Norway, pp. 43. [online] URL: <http://brage.bibsys.no/xmlui/handle/11250/216428>
- Igawa M, Matsumura K, Okochi H (2002). High frequency and large deposition of acid fog on high elevation forest. *Environmental Science* 36: 1-6. - doi: [10.1021/es0105358](https://doi.org/10.1021/es0105358)
- Ingwersen JB (1985). Fog drip, water yield, and timber harvesting in the Bull Run municipal watershed, Oregon. *Journal of the American Water Resources Association* 21: 469-473. - doi: [10.1111/j.1752-1688.1985.tb00158.x](https://doi.org/10.1111/j.1752-1688.1985.tb00158.x)
- Kim M-G, Lee B-K, Kim H-J (2006). Cloud/fog water chemistry at a high elevation site in South Korea. *Journal of Atmospheric Chemistry* 55: 13-29. - doi: [10.1007/s10874-005-9004-8](https://doi.org/10.1007/s10874-005-9004-8)
- Kopáček J, Procházková L (1993). Semi-micro determination of ammonia in water by the rubazoid acid method. *International Journal of Environmental Analytical Chemistry* 53: 243-248. - doi: [10.1080/03067319308045993](https://doi.org/10.1080/03067319308045993)
- Kreček J, Hořícká Z (2006). Forests, air pollution and water quality: influencing health in the headwaters of Central Europe's "Black Triangle". *Unasylva* 224: 46-49.
- Kreček J, Hořícká Z (2010). Recovery of Headwater Catchments and Lakes Affected by the Acid Atmospheric Deposition. In: "Integrated Watershed Management" (Beheim E, Rajwar GS, Haigh M, Křeček J eds). Springer, Dordrecht, Netherlands, pp. 200. - doi: [10.1007/978-90-481-3769-5_17](https://doi.org/10.1007/978-90-481-3769-5_17)
- Kreček J, Krčmář V (2015). Landsat imagery applications to identify vegetation recovery from acidification in mountain catchments. *Hungarian Geographical Bulletin* 64: 121-126. - doi: [10.15201/hungeobull.64.2.3](https://doi.org/10.15201/hungeobull.64.2.3)
- Kreček J, Palán L (2015). Effects of fog precipitation on water resources and drinking water treatment in the Jizera Mountains. *Civil Engineering Journal* 24: 1-7. [online] URL: http://www.civilengineeringjournal.cz/archive/issues/2015/2015_2/010-palan_2-2015.pdf
- Krečmer V, Fojt V, Kreček J (1979). Fog precipitation and fog drip in forests as an item of water balance in a mountain region. *Meteorological Bulletin (Meteorologické zprávy)* 32: 78-81. [in Czech]
- Krečmer V, Páv B (1982). Methodology to estimate the number of rain gauges under the forest canopy. *Journal of Hydrology and Hydromechanics (Vodohospodársky časopis)* 479-490. [in Czech]
- Kroll G, Winkler P (1989). Influence of meteorological parameters on interception of cloud droplets in a coniferous forest. *Beiträge zur Physik der Atmosphäre* 62: 265-274.
- Lovett GM, Reiners WA (1986). Canopy structure and cloud water deposition in subalpine coniferous forests. *Tellus B* 38: 319-327. - doi: [10.3402/tellusb.v38i5.15140](https://doi.org/10.3402/tellusb.v38i5.15140)
- Lovett GM (1988). A comparison of methods for estimating cloud water deposition to a New Hampshire (USA) subalpine forest. In: "Acid Deposition at High Elevation Sites" (Unsworth MH, Fowler D eds). Springer, Netherlands, pp. 309-320. - doi: [10.1007/978-94-009-3079-7_16](https://doi.org/10.1007/978-94-009-3079-7_16)
- Merilehto K, Kenttämies K, Kämäri J (1988). Surface water acidification in the ECE region: regional acidification, current geographical extent of acidification in lakes, streams and reservoirs in the countries of the ECE region. Nordic Council of Ministers, Copenhagen, Denmark, pp. 156. [online] URL: <http://books.google.com/books?id=E2J5gHEqzvgC>
- Miller EC, Panek JA, Friedland AJ, Kadlecck J, Mohnen VA (1993). Atmospheric deposition to a high-elevation forest at Whiteface Mountain, New York, USA. *Tellus B: Chemical and Physical Meteorology* 45: 209-227. - doi: [10.3402/tellusb.v45i3.15725](https://doi.org/10.3402/tellusb.v45i3.15725)
- Mosello R, Barbieri A, Marchetto A (1995). Seasonal variations and trends of atmosphere-borne nutrient load to the alpine biosphere and pedosphere. In: "The role of the hydrological cycle in Mountain Ecosystems". University of Zurich, Zurich, Irchel, Switzerland, pp. 17-18.
- Motulsky HJ, Searle P (1998). *InStat guide to choosing and interpreting statistical tests*. GraphPad Software, Inc., San Diego, California, USA, pp. 154.
- Pahl S, Winkler P, Arends BG, Kos GPA, Schell D, Facchini MC, Fuzzi S, Gallagher MW, Colvile RN, Choulaton TW, Berner A, Krusiz C, Bizjak M, Acker K, Wieprecht W (1997). Vertical gradients of dissolved chemical constituents in evaporating clouds. *Atmospheric Environment* 31: 2577-2588. - doi: [10.1016/S1352-2310\(96\)00285-3](https://doi.org/10.1016/S1352-2310(96)00285-3)
- Prošková J, Hůnová I (2006). Assessment methods of fog and low cloud deposition. *Meteorological Bulletin (Meteorologické zprávy)* 59: 151-157.
- Ruiz G (2005). Characterization of fog water collection potential at Fort Ord and Glen Deven Ranch near Big Sur. Faculty of Science and Environmental Policy, California State University, Monterey Bay, CA, USA, pp. 27. [online] URL: http://digitalcommons.csumb.edu/caps_thes/5/5/
- Schell D, Georgii H-W, Maser R, Jaeshke W, Arends BG, Winkler P, Schneider T (1992). Inter-comparison of fog water samplers. *Tellus B: Chemical and Physical Meteorology* 44: 612-631. - doi: [10.3402/tellusb.v44i5.15573](https://doi.org/10.3402/tellusb.v44i5.15573)
- Schemenauer R, Banic CM, Urquiza N (1995). High elevation fog and precipitation chemistry in southern Quebec, Canada. *Atmospheric Environment* 29: 2235-2252. - doi: [10.1016/1352-2310\(95\)00153-P](https://doi.org/10.1016/1352-2310(95)00153-P)
- Schöpp W, Posch M, Mylona S, Johansson M (2003). Long-term development of acid deposition (1880-2030) in sensitive freshwater regions in Europe. *Hydrology and Earth System Sciences* 7: 436-446. - doi: [10.5194/hess-7-436-2003](https://doi.org/10.5194/hess-7-436-2003)
- Shaw EM, Beven KJ, Chappell NA (2010). *Hydrology in practice* (4th edn). CRC Press, London, UK, pp. 560. [online] URL: <http://books.google.com/books?id=z1qignvz7YkC>
- Tolasz R, Baštyřová H (2007). Climate atlas of Czechia. Czech Hydrometeorological Institute, Prague, Czech Republic, pp. 256.
- Verhoeven W, Herrmann R, Eiden R, Klemm O (1987). A comparison of the chemical composition of fog and rainwater collected in the Fichtelgebirge, Federal Republic of Germany, and from the South Island of New Zealand. *Theoretical and Applied Climatology* 38: 210-221. - doi: [10.1007/BF00867414](https://doi.org/10.1007/BF00867414)
- Vogelmann HW (1973). Fog precipitation in the cloud forests of Eastern Mexico. *BioScience* 23 (2): 96-100. - doi: [10.2307/1296569](https://doi.org/10.2307/1296569)
- Walmsley JL, Schemenauer RS, Bridgman HA (1996). A method for estimating the hydrologic input from fog in mountainous terrain. *Journal of Applied Meteorology* 35: 2237-2249. - doi: [10.1175/1520-0450\(1996\)035<2237:AMFETH>2.0.CO;2](https://doi.org/10.1175/1520-0450(1996)035<2237:AMFETH>2.0.CO;2)
- Weathers KC, Lovett GM, Likens GE (1995). Cloud deposition to a spruce forest edge. *Atmospheric Environment* 29: 665-672. - doi: [10.1016/1352-2310\(94\)00317-E](https://doi.org/10.1016/1352-2310(94)00317-E)
- Whitman CD (2000). *Mountain meteorology: fundamentals and applications*. University Press, Oxford, UK, pp. 355.
- WHO (2004). Guidelines for drinking water quality (3rd edn). World Health Organization, Geneva, Switzerland, pp. 515.
- Wrzesinsky T, Klemm O (2000). Summertime fog chemistry at a mountainous site in central Europe. *Atmospheric Environment* 34: 1487-1496. - doi: [10.1016/S1352-2310\(99\)00348-9](https://doi.org/10.1016/S1352-2310(99)00348-9)

Supplementary Material

Tab. S1 – Coefficients a , a_0 (eqn. 2) and Pearson's correlation coefficients (r) between the deposited fog water and elevation.

Tab. S2 – Coefficients b , b_0 (eqn. 3) and Pearson's correlation coefficients (r) between the deposited acidic substances and elevation.

Tab. S3 – Regression coefficients k , q and Pearson's correlation coefficients (r) between pH of the fog water and elevation.

Link: Palan_2319@suppl001.pdf