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HYDROLOGICAL REGIME IN THE ALPINE FORESTS EXPLAINED THROUGH TREE AGES, FOG PRECIPITATION, RAINFALL AND CANOPY INTERCEPTION

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Abstract: This manuscript presents a comprehensive analysis of the eco-hydrology of an Alpine mountain forest. The data series contains monitoring aspects to find effects of the role of fog during mixed rain-fog situations and particularly in an old-grown forest with presence of lichens. This research is a contribution to eco-physiology of forests and their role in regional climate change. The water balance was evaluated of the 2 systems: old forest and young forest. Diverse environmental components were directly measured and calculated to evaluate the effects of fog in old and young forests. The parameters of evapotranspiration were applied separately using time scales and eddy covariance.

***Key words**: Fog, water balance, temperate mountain, precipitation, soil, canopy interception, evaporation, throughfall, old forest, rainfall*

INTRODUCTION

Mountain regions are of essential importance for water provision with an impact extending far wider than their actual range [1-5]. However, they are also strongly affected by climate change with past and projected warming exceeding the global average [6-8]. The vegetation of mountain regions, whose distribution is driven by the change of climatic and soil conditions along elevation gradients [6-8] but also influenced complex (micro) topography [9-11], is an important, but often neglected factor in the mountain water balance. In the Alps and other high mountains, the subalpine elevation belt is mostly covered by forests dominated by conifers [12-14].

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Mountain forests have a high capacity to influence the water balance by intercepting water through the canopy and releasing it back to the atmosphere as vapor, which keeps the water cycle running. Besides, mountain forests reduce runoff and increase infiltration.

Warmer temperatures may have very distinct consequences for alpine forests, such as an increase in radial growth, which may depend on sufficient water availability to compensate for the increased evapotranspiration [15-17] Thus, moisture availability needs to be considered to predict the consequences of future climate change. Forest overuse and degradation can lead to environmental problems, such as soil erosion, landslides, rockfalls, increased water runoff or reduced water storage, the drying of springs, and biodiversity loss, and have severe impacts on livelihoods or even cause human deaths. However, there are still gaps in the understanding of water redistribution in forests and its consequences for land-use management, water policies, and the climate system.

Measurements of the water balance components are usually surrounded by uncertainties and, in hydrological approaches, widely accepted oversimplifications. In ecohydrology, the latter is overcome by separating evapotranspiration into evaporation from surfaces inside the forest and transpiration by the vegetation. While tree transpiration and soil evaporation can be measured directly through sapflow sensors and for instance canopy chambers, evaporation from canopy interception can still only be estimated indirectly or modelled. Thus, there are still major uncertainties, for example, concerning the rate of wet canopy evaporation estimated from eddy covariance measurements or as the differences between precipitation, throughfall and stemflow, or those using the conventional Penman-Monteith-equation by a factor of two or more.

The aim of this study was to estimate, for the first time, the annual water balance and all of its components of a subalpine forest in South Tyrol (Central Italian Alps). Thereby we especially aimed to better understand the potential influence of fog and tree age and the associated abundance of lichens on the water balance. To estimate the water balance, we measured the relative contribution of the water components in the balance at the catchment level.

MATERIAL AND METHODS

The experiment was conducted at the Renon site, South Tyrol, in the Italian Alps (1735 m a.s.l., 46°35′11″N, 11°26′00″E). The site, IT-Ren, provides data for several monitoring networks, including Fluxnet, ICOS (https://www.icos-cp.eu/), and Lter (https://www.lter-europe.net/). The catchment has an area of 0.44 km^2. The water basin was measured on the local digital elevation model using ArcGIS software (ESRI, Redlands, CA, USA). The tree layer (diameter at breast height (DBH) >5 cm) consisted of 85% spruce [*Picea abies (L) Karst.*], 12% Swiss stone pine *(Pinus cembra L.)*, and 3% European larch (*Larix europea L.*) trees. Scots pine (*Pinus sylvestris L.*) and European rowan (*Sorbus aucuparia*) individuals were also present sparsely. The dominant tree height was approximately 29 m. The understory consisted mainly of alpenrose (*Rhododendron ferrugineum L.*) and blueberry (*Vaccinium myrtillus L.*). Intervening grasslands, which refer to the forest gaps covered by herbaceous specie were dominated by wavy hair-grass [*Deschampsia flexuosa (L.) Trin*].

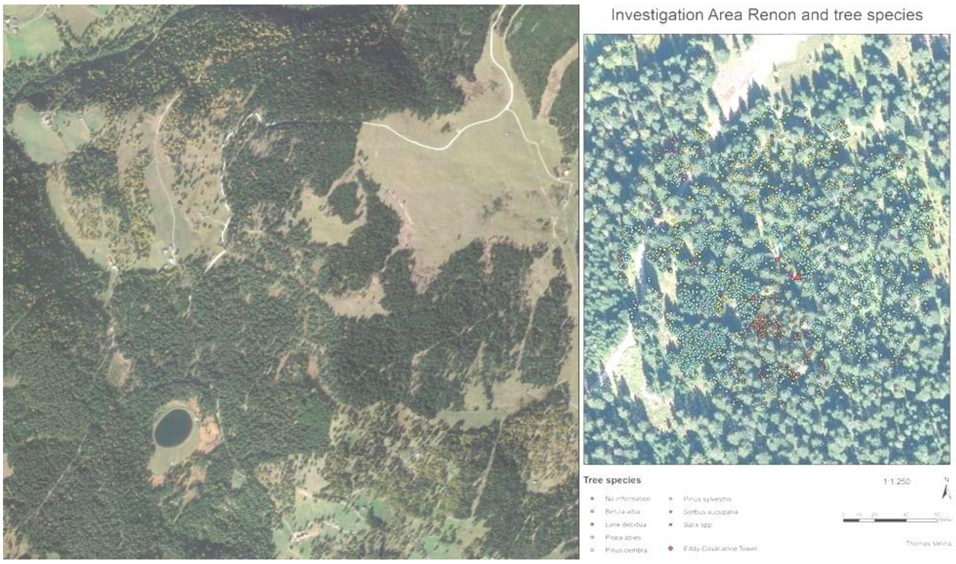

Figure 1. Study area, tree distribution and canopies from above, young and aged: UAV mounted laser estimation of canopy structure of the Renon forest site. Red triangles define the two portions of the research site selected as representative of young (blue tones) and old-growth sections (yellow tones) of the forest. In the centre of the image, the Eddy covariance tower is a red circle.

The forest is of natural origin and managed for wood production. The traditional harvest method creates small gaps, approximately 50 m wide, and involves the thinning of surrounding trees. The result is a heterogeneous vegetation structure, with groups that are almost even-aged forming an uneven-aged structure at a larger scale. A large group of dominant spruce trees with an age of approximately 200 years, and a second group of young, about 30 years-old trees were present at the study site. In both stands, parts of the living crown frequently reached the ground, irrespective of age.

The diameters and heights of the trees in the research area have been measured every ten years since 1990, while the diameter of a subset of trees is measured annually by manual dendrometers (UMS, München, Germany). The most recent inventory (tree height, size, and position) was performed in 2020 with the TruPulse sensor (TruPulse 360 B laser range-finder; Laser Tech, Centennial CO, USA). In addition, tree size was assessed during the summer of 2020 using a laser technique involving a UAV mounted laser scanner flight. Local trees and spruces were characterised by an almost columnar shape. This shape and the high leaf area index (LAI) (4.74 ± 0.88 for the 200-year-old stand and 4.65 ± 0.86 for the 30-year-old stand, as measured by hemispherical images), created peculiar microclimatic conditions within the crown, favouring lichen growth.

The soil has developed above a layer of glacial till, with a depth of approximately 1 m, placed on top of a porphyry bedrock. The soil was classified as Haplic Podzol according to the FAO soil taxonomy and on average consisted of 49% sand, 39% silt, and 12% clay.

Prediction of fog based on meteorological conditions was performed during days with rain, fog and mixed precipitation.

Meteorological variables measured during 2015 and 2019 were analysed to understand the meteorological conditions during dry and wet conditions, and especially during days with fog presence (visibility below 1 km). The ratio of diffuse to the total global radiation, the VPD, and relative air humidity (RH) were selected to characterize hours and days without precipitation, with fog-only, with rain-only and with mixed precipitation (fog and rain) during the first half of 2015 when half-hourly photos were available from a phenological camera directly at the site.

The relation between precipitation type and these three meteorological drivers were then used to predict the occurrence of fog and mixed precipitation during the study period 2019. These predictions were compared to fog observations from a public webcam (www.foto-webcam.eu/webcam/ritten/) located at 3 km and 300 m lower in elevation than the study site.

The periods characterized by dry conditions were compared, with fog and with rain, for 2015 and 2019, by including both the observation (obs) and the prediction (pred) periods to assess the accuracy of our predictions. The number of days characterized by dry conditions, fog, precipitation (rain or snowfall), and mixed precipitation for both years, 2015 and 2019, were calculated and discussed. Three representative time periods from late May to early July, from mid- July to early September and from mid-September to early November during 2019 were selected to study meteorological conditions (global radiation: total global radiation in the top row, diffuse global radiation in the middle, ratio of diffuse to total radiation, temperature and relative humidity) during dry, fog and precipitation periods and times with mismatches between observed and predicted fog.

Tree transpiration was estimated by measuring the sap flow of five spruce trees with a DBH ranging from 23 cm to 57 cm. The sap flow measurements of up to 10 trees going back to 2016 showed a representative behaviour of these trees for their size classes. To minimise errors due to incoming shortwave radiation, one sensor of the tissue heat balance sensor (Table 1) was installed at the north side of the trees. The measuring system provided sap flow rates integrated for the whole sapwood depth per unit trunk circumference (kg h-1 cm-1). The measured values were logged tat 10-min intervals and then scaled them to the tree level by multiplying them with stem circumference (minus the bark and phloem thickness measured during sensor installation) and integrated them to 30-min and daily sums per tree (L day-1).

When a sensor was installed for more than a year, we checked whether wound reaction and/or an accumulation of resin led to a decrease in sap flow by comparing the 95th percentile (P95) of 30-min sap flow rates for 2019 and the previous years. For the two smallest trees, we found a considerable decrease in the P95 sap flow and consequently corrected sap flow for 2019 by multiplying it with the ratio of P95. Minor data gaps caused by power outages or temporary sensor malfunction were filled by using a linear correlation of the respective tree's sap flow with eddy covariance evapotranspiration (R^2 = 0.57 to 0.66 at a 30-min resolution).

To estimate the canopy interception (I), we used the water balance at canopy level on a daily scale during periods with rainfall-only and mixed precipitation,

$$I = Pr + Pm - Tf - St \quad (1)$$

Where,

I is canopy water storage or interception (mm),

Pr is rainfall (mm),
Pm is mixed precipitation (rainfall during days with the presence of fog) (mm),
Tf is throughfall (mm) and St is stemflow (mm).

The accuracy of the equipment of the measured variables and the systematic error of I in Eq.2 are shown in Table 1. Data gaps owing to logger failure were filled by linear correlation with working gauges, as the correlations between them were high ($R^2 > 0.87$). The data for the manual gauges were missing for the last sampling interval and were added via a linear correlation with the results from the automatic gauges ($R^2 > 0.77$).

Stemflow was measured at one tree each at the old and young stand. Water running downwards around the tree trunk was collected into a funnel, and measured with a tipping bucket pluviometer (Table 1). The measured volume of stemflow was divided with the projected crown area of the trees to convert the data into mm. Missing values owing to logger failure were added via linear correlations with automatic throughfall measurements ($R^2 = 0.81$ for the old forest and 0.55 for the young forest).

Soil water content was measured continuously within the study site (Table 1) and the change of soil water content was calculated as the difference between the start and end of the measuring period and the hydrologic year, respectively. Water discharge at the catchment scale was measured using a combination of a water stage sensor and flow velocity measurements. The water stage sensor was placed at the lowest spot of the catchment, just above an artificial water basin (46°35′00″N, 11°26′02″E, 1,675 m a.s.l.) and continuously measured the height of the water table in the stream (S in cm). Discharge (DC in l s^{-1}) was calculated as

$$DC = a * S^b \qquad (2)$$

Where,

a and b are empirical parameters according to the salt method, [19].

Precipitation below the canopy as throughfall was measured with sixteen manual rain gauges, arranged in two groups of eight in the two main forest formations, the 200-year-old section and the 30-year-old section. These pluviometers, with a 10-cm diameter orifice, were arranged in rows with a 5-m distance between each pluviometer and data were recorded almost on a weekly basis. Additionally, six tipping bucket pluviometers (with a Hobo data logger; Onset) arranged 5 m apart in two groups of three continuously recorded the below canopy precipitation at a 10-min resolution. To increase their collection representativeness, funnels with a diameter of 30 cm were placed above the orifice of each pluviometer

RESULTS

The average monthly precipitation, represented as a monthly sum and maximum daily sum, showed the importance of convective rainfall events in the warm summer, while the cold winters were comparatively dry (Tab. 1).

In 2019, the precipitation in the study area was generally in accordance with the 20-year average, except for a drier June and October and November, which were 1.5- and more than 3-fold, respectively, wetter than the average. These aberrations were also evident in the maximum daily precipitation.

In fact, an exceptional snowfall event starting on 8 November, causing a considerable snow break especially in the young forest, effectively ended our measuring season. Also, air temperature deviated from the 20-year average in 2019, mainly during the first half of the year: February and June were too warm and May was too cold.

Table 1. Days with dry conditions, fog and precipitation (rain- or snowfall) and mixed precipitation of fog plus rain-or snowfall for the whole observed period in 2015 and 2019 and the common period observed in both years.

	2015 all		2015 common period		2019 all		2019 common period	
period	1.1. - 30.8.2015		25.5. - 30.8.2015		25.5. - 7.11.2019		25.5. - 30.8.2019	
time	9-17		9-17		0-24		0-24	
	days	%	days	%	days	%	days	%
dry	123	50.6	40	41.2	79	47.3	46	47.4
fog	72	29.6	31	32.0	9	5.4	2	2.1
rain/snow	11	4.5	6	6.2	34	20.4	31	32.0
mixed precipitation	37	15.2	20	20.6	45	26.9	18	18.6
total	243	100	97	100	167	100	97	100

Tree transpiration was calculated by dividing sap flow by the projected crown area of the respective tree, thereby converting units from kg per tree to mm. The projected crown area was estimated from the mean crown radius measured in the four cardinal directions. The average tree transpiration of the two smaller trees (DBH 23 cm and 32 cm, respectively) was used to represent the young stand, while the average of the three larger trees (DBH 43 cm, 50 cm, and 57 cm, respectively) was used to represent the old stand. All the selected trees were dominant or codominant.

Throughfall rates relative to precipitation were higher in the young than in the old stand (Tab. 2) even though the LAI in both stands was similar. Throughfall variability was higher in the manual gauges than in the automatic ones as they covered a higher small-scale variability of PAI/LAI. A strong linear correlation ($R^2 > 0.93$) was found between throughfall, precipitation and precipitation for both stands and no clear increase in throughfall ratio with P, Tab. 2.

Only the last data point with the highest amount of throughfall and P was clearly above the linear regression line, indicating that the limits of the canopy's interception capacity were reached. The correlation between old and young stand throughfall was very high (Tab. 2).
Throughfall was not captured during days with fog-only. In subtropical cloud forests with a high frequency of fog, fog-only contributed with only 6% of throughfall. The high wind speed and humidity in the Japane Alps to measure up to 35% of the fog-only contribution in throughfall. Variations in height and air temperature could be explained by the Alpine forest's reduced contribution. This finding supports our theory that fog may very slightly affect the seasonal and annual water budget.

Table 2. Water components from 2019-5-30 (DOY 150) until 2019-11-07 (DOY 311) at canopy level based on daily data divided into dry and precipitation periods. Precipitation measured inside and outside the forest (minor amount of precipitation during "dry" period because periods were defined based on the outside climate station alone), throughfall and stemflow measured with automatic tipping gauges, storage/interception calculated as P - Tf - St.

Period	nr of days	P	ET	Throughfall	Stemflow	Interception
			young forest			
dry	78	1.3 ± 1.8	350.2	2.62 ± 3.31	0.002	-1.34 ± 3.28
fog	8	0.1 ± 0.2	26.2	0.16 ± 0.00	0.000	-0.01 ± 0.16
Mixed fog+P	42	459.7±35.2	109.6	291.86 ±25.59	1.030	166.84 ±35.59
rain/snow	34	132.4 ±20.9	146.8	47.03 ± 11	0.055	85.31 ±18.97
			old forest			
dry	78	1.3 ± 1.8	350.2	0.58 ± 0.19	0.004	0.69 ± 1.41
fog	8	0.1 ± 0.2	26.2	0.06 ± 0.00	0.000	0.09 ± 0.17
Mixed fog+P	42	459.7±35.2	109.6	216.49 ±11.43	0.774	242.46 ±29.11
rain/snow	34	132.4±20.9	146.8	35.67 ± 2.81	0.178	96.54 ±16.41

Table 3. Water components for 5 months from 2019-5-30 until 2019-11-07 at canopy level roughly divided into months according to sampling dates of the manual throughfall gauges.

Days with mixed precipitation	young forest	old forest
P measured (mm, see Table 2)	459.7 ± 35.2	459.7 ±35.2
Total Tf measured (mm)	291.9 ± 25.6	216.5 ±11.4
Contin. Table 3. f estimated from rain only events (mm)	242.6 ± 6.7	184.1 ± 8.2
Fog contribution in mixed events (mm)	70.3 ± 14.9	52.9 ± 4.7
measured Tf/P (%)	63.5	47.1
estimated rain-only Tf/P (%)	52.8	39.6
estimated fog Tf/P (%)	15.3	11.5
rain contribution to Tf (%)	83.1	84.1
fog contribution to Tf (%)	24.1	24.4

Throughfall rates were much greater on days with mixed fog and rain precipitation (Tab.3), whereas interception rates (I/P) were lower on days with rain only. This was discovered by examining throughfall rates at a daily resolution and differentiating by precipitation type. Fog was blamed for this Tf excess (Tf/P = 0.28 for the young stand and Tf/P = 0.27 for the old stands. Cloud forests have also shown a greater percentage of Tf on days with mixed precipitation. Days with mixed precipitation contributed the same amount of fog to Tf as days with mixed precipitation in the Spanish forests (23%). The amount of fog that contributed to throughfall during mixed precipitation did not differ considerably between the stands, and it was similar to the partition in the Spanish cloud forest (24.2%). Less than 1% of precipitation in both stands was attributed to stem flow, which was similarly noted in cloud forests.

DISCUSSION

In this study, we quantified the frequency of fog events in a subalpine coniferous forest in the Italian Alps and assessed the hydrological balance at basin and canopy scales by combining different measurement approaches. The difference between water input in rain and snow forms (fog not included) and water output as evapotranspiration and water discharge, plus the variation in the soil water content, was 25 mm, within the uncertainty range of the measurements. Thought fog has been not included in past water balance studies, our study revealed that fog combined with rainfall the same day, as mixed precipitation, contributed to higher throughfall, which in turn contributes to higher net precipitation (soil water recharge, in absence of runoff) and evaporative conditions inside the canopy.

Therefore, fog plays an important role in the water balance during numerous days with mixed precipitation, maintaining for several days a high relative humidity inside the dense coniferous crowns composing the forest. This helped the trees to maintain a large amount of leaf area, and the filamentous lichens to grow in the upper part of the canopy.

These two features led to a large capacity of the crown, particularly in the mature coniferous forest, to intercept liquid precipitation, release only a small amount of precipitation to the soil and eventually to runoff, sustaining local ET with an associated reduction of the sensible heat flux. However, how much fog was intercepted by the canopy remains open for further research.

According to the results, the juvenile stand had lower interception, which was determined by subtracting Tf from Sf and then subtracting total P. Interception was responsible for 64% of ET in the ancient forest and 33% in the young forest, as intercepted water eventually evaporates back into the sky.

This research complements, in a hydrological perspective, recent evidence that indicates that natural forests play a key role in dampening heat extremes above vegetated terrestrial ecosystems [15-17]. It also attributes to fog and cloudiness the role of linkage in the positive feedback between the presence of forests and cool and humid meteorological conditions.

CONCLUSION

The age, structure, and leaf type of the forest canopy all affect how much water it can absorb, but other elements like mosses and epiphytes can also have a significant impact. As a result, they maintain evapotranspiration, lower the Bowen ratio, raise air humidity, and store water within the forest. In this manner, rain and cloud forests preserve conditions of nearly zero water pressure deficit and provide minimal water stress to leaves, especially to epiphytes. In temperate mountain forests, where needles can survive for years and epiphytes grow on the boles and branches of old trees, this may also be the case.

In this study, the significance of the meteorological conditions (temperature, relative humidity, radiation, wind direction and speed, ratio of diffuse to total global radiation, and vapor pressure deficit) was compared during dry conditions (dry), fog (less than 1 km visibility), and rainfall in order to gain a better understanding of fog occurrence. By measuring and contrasting water interception, epiphyte composition, and temperature at various elevations with a nearby young canopy forest, the impact of older tree vegetation on the water balance was investigated. Using sap flow sensors, we determined the eddy covariance for transpiration and evapotranspiration. We assessed soil moisture in an old and young forest and made additional soil-level measurements. At the catchment level, water discharge was measured.

This study demonstrated a number of differences between the young and old stands in terms of ecosystem water partitioning at the catchment level during the course of the measurement period. In the young forest, there was more throughfall and transpiration. Rainfall water can return to the atmosphere more quickly by evaporation, which is a component of the water cycle, rather than via the soil or plant life.

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HIDROLOŠKI REŽIM ŠUMA U ALPIMA PRIKAZAN KROZ STAROST DRVEĆA, PADAVINA SA MAGLOM, I KIŠAMA U KROŠNJAMA DRVEĆA

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Apstrakt: Ovaj rukopis predstavlja sveobuhvatnu analizu eko-hidrologije planinske šume u Centralnim Italijanskim Alpima (Južni Tirol). Serija podataka sadrži aspekte praćenja kako bi se pronašli efekti uloge magle tokom mešovitih situacija sa kišnom maglom, a posebno u staroj šumi gde je registrovano prisustvo lišajeva.

Ovo istraživanje je doprinos eko-fiziologiji šuma i njihovoj ulozi u regionalnim klimatskim promenama. Ocenjen je vodni bilans dva sistema: stara šuma i mlada šuma. Različite komponente životne sredine su direktno merene i izračunate da bi se procenili efekti magle u starim i mladim šumama.

Parametri evapotranspiracije primenjeni su posebno korišćenjem vremenskih skala i kovarijanse.

Ključne reči: *magla, vodni bilans, umerena planina, padavine, zemljište, krošnje drveća, isparavanje, propust, stara šuma, padavine*

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