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First data on rainfall interception in an Atlas cedar forest (*Cedrus atlantica* Manetti) in the Aurès (eastern Algeria)

Erste Daten zur Niederschlagsinterzeption in einem Atlaszederwald (*Cedrus atlantica* Manetti) im Aurès (Ostalgerien)

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Keywords: semi-arid forests, stemflow, interception, throughfall, climate change

Schlüsselbegriffe: semi-aride Wälder, Stammabfluss, Interzeption, Kronendurchlass, Klimawandel

Abstract

With climate change, data on throughfall, stemflow and rainfall interception in forests are much needed by hydrologists throughout the world, including the Mediterranean region. Such data are rare for Algeria, especially for cedar forests. Thus, the present study is interested in analysis of throughfall, stemflow and rainfall interception in a cedar forest dominated by *Cedrus atlantica* Manetti in the province of Batna (Eastern Algeria) and establishing models for forecasting the different rainfall fractions in this forest type. Specific containers (plastic bottles and collars) were installed at stems of 30 trees, under tree crowns and in an open area not covered by tree crowns between January 2018 and December 2019 to collect the different studied fractions of water (rainfall, throughfall and stemflow). Our results reveal that throughfall was with 65.41% of the total rainfall the greatest fraction in the studied cedar forest. Stemflow represented only a very small fraction of total rainfall with 3.86%. The mean rainfall interception was 30.72 % of the total rainfall. The relationships between rainfall, throughfall and stemflow were assessed by linear regressions. We found strong correlations between throughfall, stemflow and rainfall with coefficient of determination

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R² ranging between 0.92 and 0.99. The equations developed by this study revealed that the studied cedar forest must receive at least 1.70 and 4.46 mm of rainfall, to trigger throughfall and stemflow, respectively.

Zusammenfassung

Angesichts des Klimawandels sind Daten über Kronendurchlass, Stammabfluss und Interzeptionin Wälder für Hydrologen auf der ganzen Welt, einschließlich der Mittelmeerregion, sehr gefragt. Dennoch sind solche Daten in Algerien, insbesondere für Zedernwälder, nicht verfügbar. Diese Studie beschäftigt sich mit der Quantifizierung des Kronendurchlass, des Stammabflusses und der Interzeption von Niederschlag in einem Zedernwald dominiert durch *Cedrus atlantica* Manetti in der Provinz Batna (Ostalgerien) und mit der Entwicklung von Modellen zur Vorhersage der verschiedenen Niederschlagsfraktionen in diesem Waldtyp. Zwischen Januar 2018 und Dezember 2019 wurden spezielle Behälter (Plastikflaschen und -manschetten) installiert an 30 Bäumen, unter Baumkronen und auf Freiflächen ohne Kronenbedeckung um die verschiedenen untersuchten Niederschlagsfraktionenzu sammeln.

Die Ergebnisse zeigten, dass der Kronendurchlass 65.41 % des Niederschlags im untersuchten Zedernwald betrug. Der Stammabfluss stellte nur einen sehr kleinen Teil des Gesamtniederschlags dar mit 3.86 %. Die mittlere Interzeption betrug 30.72 % des Gesamtniederschlags. Die Beziehungen zwischen Niederschlag, Kronendurchlass und Stammabfluss wurden mit linearen Regressionen analysiert. Wir beobachteten starke Korrelationen zwischen Kronendurchlass, Stammabfluss und Niederschlag mit Bestimmtheitsmass R² zwischen 0.92 und 0.99. Die in dieser Studie entwickelten Gleichungen ergaben, dass der untersuchte Zedernwald mindestens 1.70 bzw. 4.46 mm Niederschlag erhalten muss, damit Kronendurchlass bzw. Stammabfluss messbar ist.

1 Introduction

Rainfall is one of the most important sources of water in forest ecosystems and it is responsible for forest productivity, especially in seasonally dry forests (Tague *et al.* 2019; Missaoui *et al.* 2020; Yang *et al.* 2022; 2023; Zhao *et al.* 2023). Rainfall is the main input to the soil water balance and plays an important role in the water cycle and the plant-soil-atmosphere system (Biniak-Pieróg 2017; Klamkowski *et al.* 2011; Levia *et al.* 2017; Schwingshackl *et al.* 2017; Han *et al.* 2018; Magliano *et al.* 2019; Sun *et al.* 2022; Treder *et al.* 2022). The distribution of rainfall by trees is an important hydrological process, particularly in the context of climate change (Llorens & Domingo, 2007; Sadeghi *et al.* 2018; Yang *et al.* 2022; Zhao *et al.* 2023). The two main processes, evapotranspiration and interception, are strongly influenced by vegetation and its composition (Vicente *et al.* 2018). With climate change, any alterations in the precipitation or temperature regimes will directly affect the dynamics of the interception of rains by forests. Previous studies pointed out that with climatic variations, rainfall may be concentrated in a shorter time period with more intense rainfall events and in consequence higher drought risks (Benhamiche *et al.* 2014; Zhao *et al.* 2023). It is increasingly recognized that a better understanding of water use patterns and their response to climate change depends on our ability to better quantify the dynamics of rainfall fractions (Yang *et al.* 2023).

Therefore, an understanding of the redistribution of rainfall by the action of the forest cover is very useful to understand the water balance and the nutrients of the ecosystem, but also to develop the silvicultural practices, that mitigate the effects of climate change (Jeong *et al.* 2019; Tague *et al.* 2019; Shi *et al.* 2022; Zhao *et al.* 2023). During a rainfall event, the forest cover causes, on the one hand, a reduction in the rainfall amount reaching the forest floor, and on the other hand, a redistribution of the latter into three fractions, throughfall, stemflow and interception (Dohnal *et al.* 2014; Sadeghi *et al.* 2020; Jančo *et al.* 2021; Zhao *et al.* 2023). Throughfall penetrates the tree crowns, while stemflow is water running along the surface area of tree trunks (Lévia *et al.* 2017). The amounts of rainfall, that is captured by forest canopy and then returned to the atmosphere by evaporation, are often referred to as interception (Šraj *et al.* 2008; Dohnal *et al.* 2014; Jančo *et al.* 2021).

The Mediterranean area is more strongly affected by climate change than other regions globally (GIEC 2014; Lionello *et al.* 2018; IPCC 2021). The expected changes include hotter and drier summers as well as a general decrease in rainfall as large as minus 40% in certain regions (Barros *et al.* 2014; Peñuelas *et al.* 2017; Arar *et al.* 2020; Tuel *et al.* 2020).

The Atlas cedar, *Cedrus atlantica* Manetti, is endemic to North African mountains and constitutes the southwesternmost species of the genus *Cedrus* (Bouahmed *et al.* 2019). In Algeria, it constitutes a much values forest asset of remarkable ecological, economical and cultural importance (Médail & Quézel 2003). It is also classified as an endangered species and carries the status of a rare plant (Yahi *et al.* 2007; Touati *et al.* 2021). The Algerian cedar forests occupy an area of about 2089 km^2, where the stands located in the Aurès regions are the most xeric in Algeria (Arar *et al.* 2020) and they have suffered from tree mortality linked to drought and climate change for several years (Allen 2009; Yahi & Djellouli 2010; Kherchouche *et al.* 2012; Bezzih *et al.* 2021). Bouahmed *et al.* (2019) indicated that the decline of Algerian cedar forests is driven by a shift of climate towards drier conditions. This is problematic as Atlas cedar is characterized by strong height growth, that is highly sensitive to drought (Ladjal *et al.* 2007).

Growth-climate relationships for Atlas cedar showed a significant positive, cumulative and stable temporal effect of precipitation variability (Slimani *et al.* 2014). A negative growth shift was triggered by a climate shift towards drier conditions in the 1980s (Navarro-Cerrillo 2019). A very high decrease in suitable areas of Atlas cedar was forecasted based on the predictions of Arar *et al.* (2019) for 2070; which indicates that the species has little chance to survive under the conditions of future climate change scenarios. More arid conditions would raise Atlas cedar mortality rates and trigger compositional shifts toward forests dominated by species better able to tolerate drought, such as *Quercus ilex* (Navarro-Cerrillo 2019).

Studies of rainfall interception have long received considerable attention worldwide (Gash *et al.* 1980; Llorens & Domingo 2007; Muzylo *et al.* 2009; Zhao *et al.* 2023) and remains an important topic for future environmental studies (Zhang *et al.* 2023). Many researchers have already recommended continuing studies on the redistribution of rainfall by forests, particularly for semi-arid and arid regions, to better understand the interception process in the context of climate change and to balance the water demands of humans and the ecosystem (Friesen & Van Stan 2019; Jeong *et al.* 2019; Ma *et al.* 2019; Levia *et al.* 2019; Yang *et al.* 2022; Zhao *et al.* 2023). It is noticed that the majority of available studies on rainfall interception have focused on cumulative annual amounts and not on individual values of interception by rainfall events (Muzylo *et al.* 2009). Although semi-arid environments represent a third of the world's land area (Li *et al.* 2020; Mirzabaev *et al.* 2022), little is known from a point of view of rainfall interception compared to other climates (Llorens & Domingo *et al.* 2007; Muzylo *et al.* 2009; Magliano *et al.* 2019).

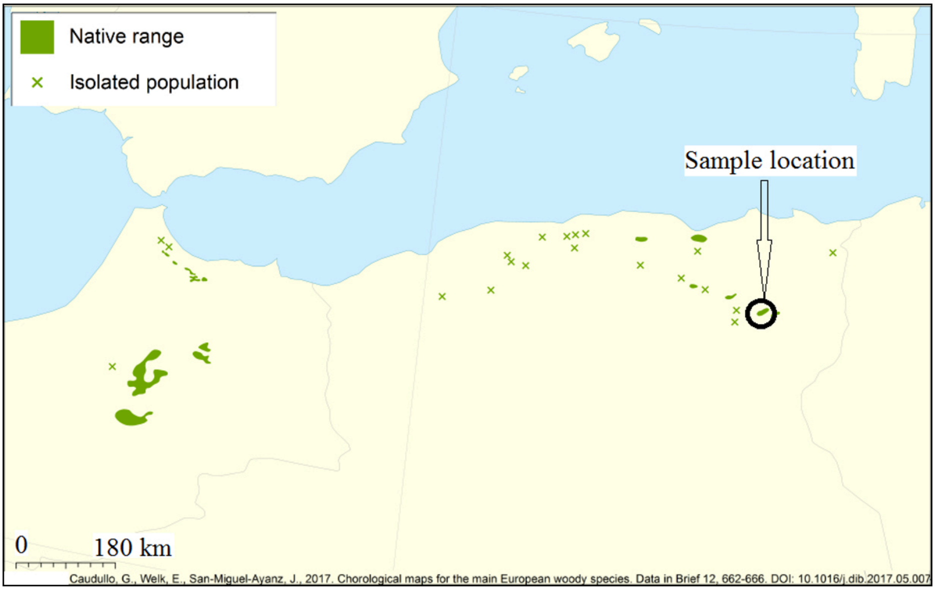
Despite the obvious significance of this topic, there is currently no data on the interception of rainfall in Algeria by the action of the Atlas cedar. Our study aims fill this gap and to provide models to predict the interception of rainfall by traa canopies for the first time for the Atlas cedar. A novel aspect of our study is exploring rainfall interception for single events for an endemic species in a semi-arid climate.

2 Materials and methods

2.1 Measurements of rainfall, throughfall, stemflow and interception

The study was conducted on the interception of rainfall by the action of Atlas cedar, in an area located in the northeastern part of Algeria in the province of Batna (Fig. 1). More precisely, the Atlas cedar forest was located in the Larbaa mountains (35°39'50''N, 6°12'31''E) at an altitude of 1680 m with average tree density of 600 trees per hectare and an estimated leaf area index (LAI) between 1.7 and 2.5. We estimated LAI based literature (Breda 1999; Breda *et al.* 2002) and the observation that the canopy of our studied forests is relatively sparse and suffered from drought effects. The tree height ranged between 14 and 18 m and their age was approximated 90 years. Tree diameter at breast height ranged between 26 and 32 cm and the basal area of the studied cedar forest was 32 m^2/ha.

The data provided by the meteorological station of Ain Skhouna (35°75'79''N, 6°30'57''E), about 43 km in the northeast of the study site, revealed that the average rainfall in the Batna region over 25 years (1989-2013) was 332.83 mm with an average air temperature of 15.58 °C.



Caudullo, G., Welk, E., San-Miguel-Ayanz, J., 2017. Chorological maps for the main European woody species. Data in Brief 12, 662-666. DOI: 10.1016/j.dib.2017.05.007

Figure 1: The location of the study site and distribution of Cedrus atlantica (Caudullo et al. 2020).

Abbildung 1: Der Standort des Untersuchungsortes und die Verbreitung von *Cedrus atlantica* (Giovanni et al. 2020).

The collectors used to measure rainfall, throughfall and stemflow were deduced from previous studies (Gash *et al.* 1980; Molina & del Campo 2012; Llorens & Domingo 2007; Attarod *et al.* 2015). Because of its adaptability to forecast rainfall interception, particularly for coniferous forests in semi-arid climates, the Gash model was chosen (Llorens & Domingo 2007; Muzylo *et al.* 2009). Water volumes (rainfall, throughfall and stemflow) were measured continuously (after each rainfall event) for two years from January 2018 until December 2019.

The different fractions of water were collected, just after a rainfall event finished, using plastic bottles with the upper part cut and turned into a funnel (Fig. 2). The receiving area for each bottle was 0.0227 m^2. Throughfall was quantified by four bottles installed under the central and peripheral parts of each tree. Previous works have stated, that rain gauges should be placed not only in the central area of the crown, near the trunk of the trees, but also in the periphery to ensure more reliable results (Bartík *et al.* 2016; Dohnal *et al.* 2014; Minďáš *et al.* 2018). The bottles used to measure the throughfall were installed under crowns of 30 Atlas cedar trees, for a total of 120 bottles. Our overall surface for receiving throughfall water (2.72 m²) is considered sufficient to correctly estimate this fraction of rainfall (Rodrigo & Avila 2001; Llorens & Domingo 2007). On a bare plot further 20 bottles were placed identical to those used to measure the throughfall and in approximately eight meters distance from the Atlas cedar trees, to measure rainfall undisturbed by tree canopies.

Figure 2: Devices for collecting stemflow (A) and throughfall (B).

Abbildung 2: Geräte zum Sammeln von Stammabfluss (A) und Kronendurchlass (B).

Stemflow was measured using plastic collars fixed around the trunks of 16 trees and sealed with mastic. These collars were connected with a plastic container using a pipe. The collected rainfall volumes are converted into mm using the formula (Vialard-Goudou & Richard 1956):

$$\mathrm{P} = 10 \times \mathrm{V}/\mathrm{S} \qquad (1)$$

with P rainfall (mm), S reception surface (cm^2) and V volume of water collected (cm^3).

Stemflow was calculated by dividing the collected volumes by the crown surface (Livesley *et al.* 2014). The interception in mm were estimated according to (Llorens & Domingo 2007; Moreno-Pérez *et al.* 2018):

$$\mathrm{I} = \mathrm{P} - \mathrm{Tf} - \mathrm{Sf} \qquad (2)$$

with I interception (mm), P rainfall (mm), Tf throughfall (mm) and Sf is stemflow (mm).

2.2 Data analysis

The results of rainfall, throughfall, stemflow and interception were subject to analysis of variance (ANOVA) at the 5% error threshold, using SPSS software version 10.0.5 (SPSS Inc.). The relationships between the different fractions studied (P, Tf, Sf, I) were estimated by linear regressions using Microsoft Excel 2013. We calculated the amount of rainfall needed to trigger Tf and Sf by reformulating the linear functions for Sf and Tf equal 0.1 mm.

3 Results

3.1 Rainfall

The results of two years of measurements showed that the cumulative daily rainfall was 773.6 mm, created by 118 days with rainfall. The year 2018 received more rainfall with 436.6 mm, compared to year 2019 with 337 mm.

Daily rainfall fluctuated between 0.9 and 56 mm with an average of 4.28 mm per day of rainfall. The distribution by rainfall class ranging from 0 to 60 mm and their frequencies are available in Table 1.

Table 1: Classes, frequencies and accumulations of daily rainfall.

Tabelle 1: Klassen, Häufigkeiten und Anhäufungen der täglichen Niederschläge.

Daily rainfall	**2018**			**2019**			**Cumulative rainfall during both years (mm)**
	Frequencies (Days)	**Cumulative rainfall**		**Frequencies (Days)**	**Cumulative rainfall**		
		mm	**%**		**mm**	**%**	
]0-5 mm]	43	122.2	27.99	30	76.5	22.70	198.7
]5-10 mm]	14	104.4	23.91	10	71.2	21.13	175.6
]10-20 mm]	6	82.0	18.78	11	155.3	46.08	237.3
]20-30 mm]	0	0.0	0.00	0	0.0	0.00	0.0
]30-60 mm]	3	128.0	29.32	1	34.0	10.09	162.0
Total	66	436.6	100	52	337.0	100	773.6

Table 1 demonstrated the dominance of rainfall less than or equal to 5 mm per day, throughout the study period. In 2018, most rainfall was created by rainfall events with 30-60 mm per day, while in 2019 most rainfall originated from events with 10-20 mm per day. It should be noted that only about 16% of days in the measurement period received rainfall greater 0 mm. From these 118 days with rainfall, 73 days has rainfall between 0 and 5 mm and the number of days with rainfall greater 30 mm was very low with 4 days out of 118. Surprisingly, the cumulative rainfall of these four days was 162 mm (19.66 % of the total rainfall).

3.2 Throughfall

Our results revealed that among 118 rainy days, only 92 events could trigger throughfall, penetrating the crowns of the Atlas cedar forest. Accumulation throughfall over two years was 509.32 mm, which represents an average of 65.41% of total annual rainfall. We note that the highest throughfall rate (68.69%) was recorded in year 2018 (Fig. 3), which was also received more rainfall compared to the year 2019 (436.6 and 337 mm, respectively).

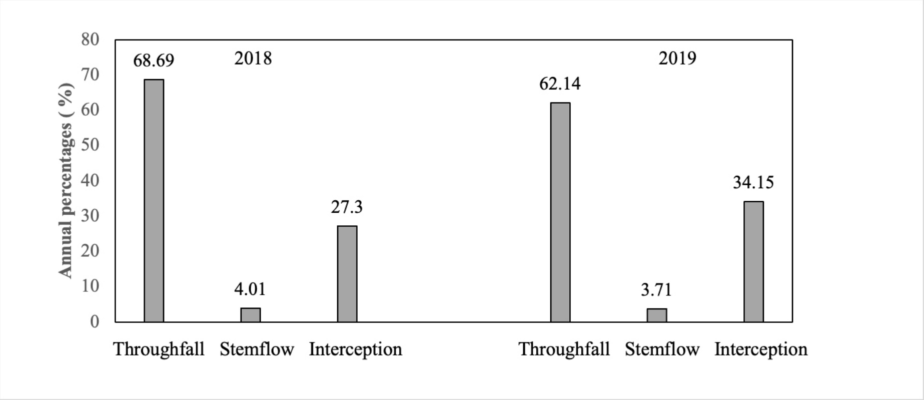


Figure 3: Annual percentages for throughfall, stemflow and interception during the study period.

Abbildung 3: Jährliche Prozentsätze für Kronendurchlass, Stammabfluss und Interzeption während des Untersuchungszeitraums.

The average daily throughfall for 2018 (0.82 mm/day) was much greater compared to the throughfall for the year 2019 (0.54 mm/day). It should also be noted that during the year 2019, the throughfall for the two months of June and July was nil. Throughout the study period, the largest amounts of throughfall were recorded between March and May. Figure 4 presents the monthly variations for the two years 2018 and 2019.

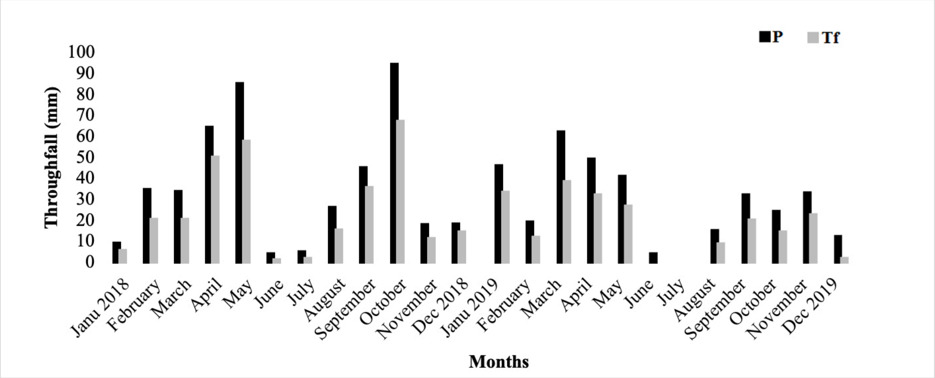


Figure 4: Monthly variation of throughfall during the study period.

Abbildung 4: Monatliche Variation des Kronendurchlasswährend des Untersuchungszeitraums.

3.3 Stemflow

The number of rainfall days that could trigger stemflows, through the cedar tree trunks, was only 37 days, that is a rate of 31.35% of the total number of rainfall days during our study period. The results also showed that the average stemflow rate was around 3.86%. The stemflow for 2019 was slightly higher than for 2018 (4.01 and 3.71%, respectively) (Fig. 3).

The average volume per rainfall event of water brought to the soils of the cedar forest through stemflow fluctuates between 0.03 and 0.05 mm for 2019 and 2018 respectively.

On an interannual scale, the two months of June and July were characterized by zero stemflow, while, the largest stemflows were recorded between March and May (2.2 - 3.4 mm) (Fig.5).

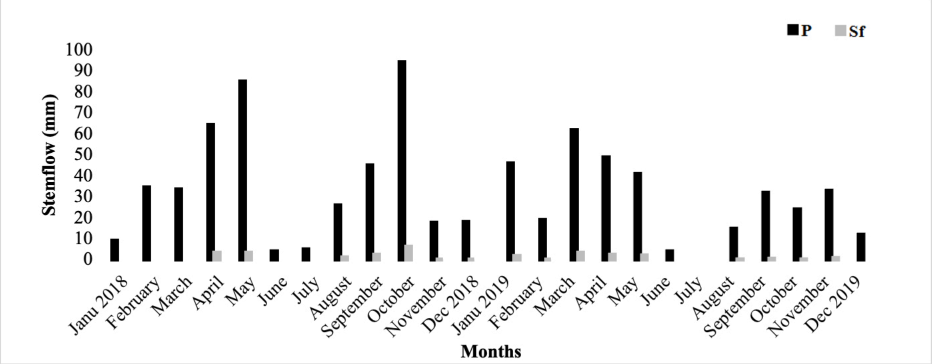


Figure 5: Monthly variation of stemflow volumes throughout the study period.

Abbildung 5: Monatliche Variation der Stammabfluss während des Untersuchungszeitraums.

3.4 Interception

The average interception rate found for this study is 30.72%. ANOVA analysis confirmed a significant difference between years (*p*= 0.010) (Table 2). The interception was higher in the least rainy year. It was 34.15% in 2019 (where the rainfall was 337 mm) and 27.30% in 2018 (where the rainfall was 436.6 mm) (Fig. 3). The mean interception varies between 0.32 and 0.33 mm per rainfall day throughout the study period.

As for the monthly variation, the ANOVA analysis revealed a significant difference (*p*= 0.002) (Table 2). The interception was much greater in March 2019 (20.2 mm) and May 2018 (24 mm) (Fig.6).

Table 2: ANOVA analysis of the studied parameters at an intra-annual and inter-annual scale. Asterisk indicate significant difference at $p < 0.05$.

Tabelle 2: ANOVA-Analyse der untersuchten Parameter auf einer inter- und intra-annualen Skala. Stern zeigt signifikante Unterscheide mit $p < 0.05$.

	P	**Tf**	**Sf**	**I**
Interannual variations	0.897	0.666	0.960	0.010 *
Intraannual variations	0.755	0.838	0.724	0.002 *

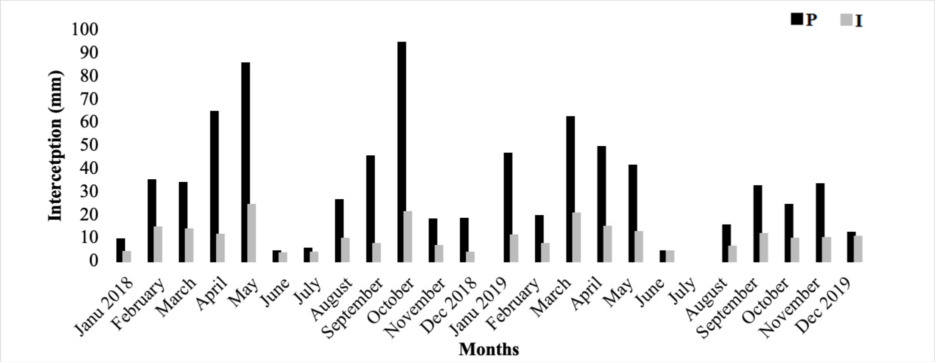


Figure 6: Monthly variation of rainfall interception throughout the study period.

Abbildung 6: Monatliche Variation der Niederschlagsinterzeption während des gesamten Untersuchungszeitraums.

3.5 Relationship between rainfall and throughfall

The results relating to the relationship between rainfall and throughfall during both years, under the Atlas cedar, are presented in Figure 7. The latter shows a positive linear relationship between throughfall (Tf) and rainfall (P) ($R^2 = 0.99$). There is a proportional relation between these two parameters.

The equations presented in Figure 7 show that Atlas cedar trees must receive at least 1.70 mm of rain to allow the rain to pass to the forest soils and subsequently feed the groundwater.

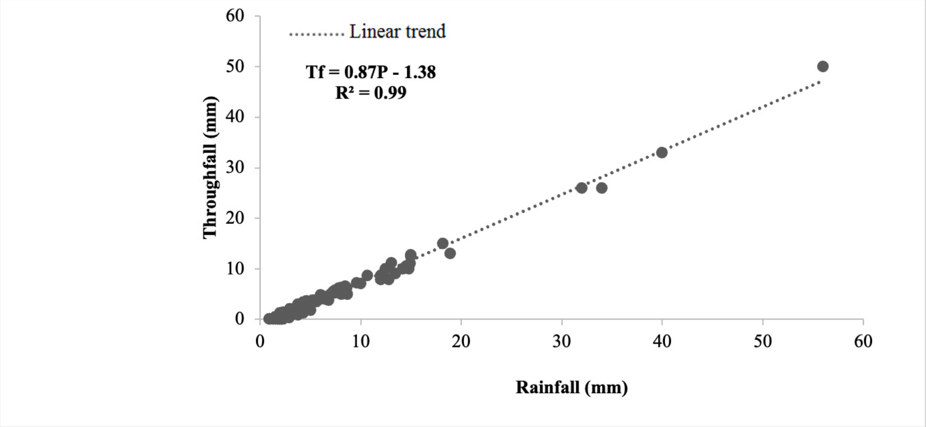


Figure 7: Relationship between rainfall and throughfall in the studied cedar forest.

Abbildung 7: Zusammenhang zwischen Niederschlag und Kronendurchlass im untersuchten Zedernwald.

3.6 Relationship between rainfall and stemflow

Figure 8 shows that stemflow is positively correlated with rainfall amounts (R^2 =0.92). The relationships between the rainfall and stemflow using a linear trend function are presented in Figure 8. By rearranging equation 8, we can conclude that the stemflow is triggered once 4.46 mm of rain is exceeded.

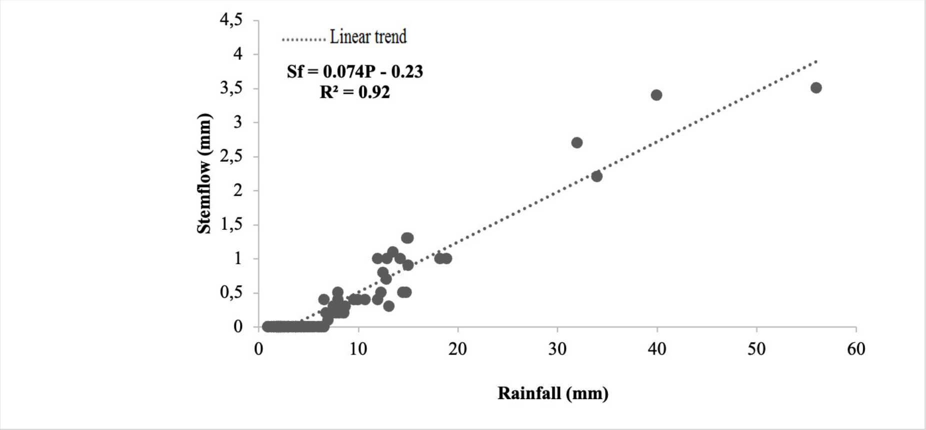


Figure 8: Relationship between rainfall and stemflow in the studied cedar forest.

Abbildung 8: Zusammenhang zwischen Niederschlag und Stammabfluss im untersuchten Zedernwald.

3.7 Relationship between rainfall and interception

Figure 9 shows that the volumes of interception are negatively correlated with the volumes of rainfall with coefficient of determination R2 varies between 0.18 and 0.63.

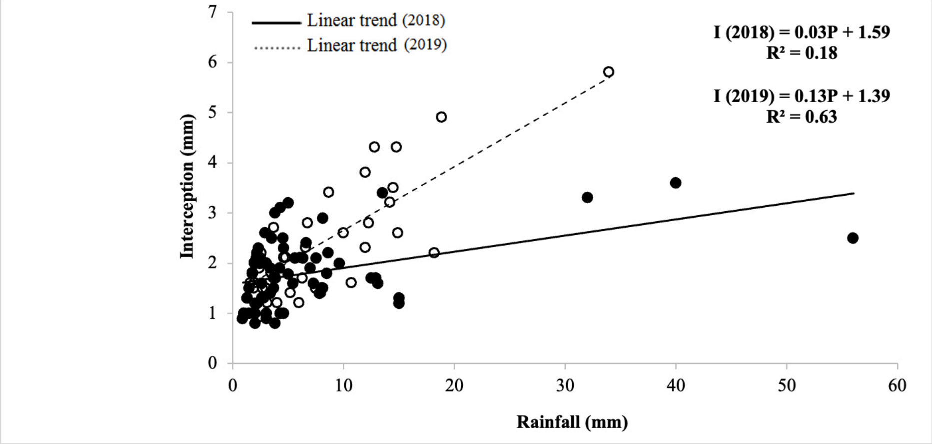


Figure 9: Relationship between rainfall and interception.

Abbildung 9: Zusammenhang zwischen Niederschlag und Interzeption.

4 Discussion

4.1 Rainfall

The average annual rainfall of 386.8 mm is higher than the average rainfall (332.83 mm) of the Batna region for a period of 25 years (1989-2013). Nevertheless, hydrologists are interested not only in annual rainfall, but also in rainfall events, as the latter are more important for throughfall, stemflow and interception than annual rainfall sums. In the present investigation, rainfall events were dominated by rainfall below 5 mm with an average of 4.28 mm per event.

Similarly, Benhizia *et al.* (2020) found, forthe Aleppo pine in a semi-arid region, that the daily rainfall was low, as daily rainfall higher than 30 mm was rare, but when it occurs, it can constitute a very significant proportion of the annual rainfall (33.52%). Moreover, other researchers stated, that in semi-arid and Mediterranean climates, daily rainfall of less than 10 mm constitutes almost all of the rainfall (Pérez-Suárez *et al.* 2013; Llorens *et al.* 2018). Our results suggest that the rainy days that can pass through the canopy of the Atlas cedar and feed the soil and the water table are much reduced. Indeed, Andreu *et al.* (2001) indicated that only daily rainfall greater than 15 mm was capable of producing groundwater recharge.

Vicente *et al.* (2018) have already asserted that rainfall events will become less frequent, which directly affects the deep percolation to groundwater. Similarly, Barros *et al.* (2014) and Vicente *et al.* (2018) reported that drought conditions are also expected to intensify, which could trigger plant mortality and species replacement events and consequently the forest water balances will be affected.

4.2 Throughfall

Studies on throughfall under the action of the Atlas cedar in a forest environment are rare or even nonexistent. Sensoy and Tanyel (2022) published the only study on *Cedrus libani* in an urban environment. Unfortunately, these researchers worked on rainfall greater than 10 mm and they found a throughfall rate of 51%. This rate is considered low compared to the present study (65.41%).

The scarcity of work on the redistribution of rainfall under the action of the Atlas cedar in forest environments led us to compare our results with studies that have worked on other conifers. The throughfall rate of the present study remains high compared to the results of Benhizia *et al.* (2020) which found for an Aleppo pine forest, a throughfall that varies between 51.36 and 56.95%. However, rainfall volumes and their characteristics as well as forest cover are not the same. The rainfall volumes of the present study are higher than the results of the latter researchers (386.8 vs.

312 mm). This difference may be, on the one hand, responsible for the increase in the rate of throughfall in our cedar forest and, on the other hand, dead branches and cones are abundant in the pine forest studied by the aforementioned researchers; and they are not too abundant in our cedar forest. Thus, Jeong *et al.* (2019) have claimed that for conifers, the drainage is low for stands characterized by dead branches because of the additional gain of rainwater from dead branches.

Besides, several previous studies stated that the throughfall in coniferous forests varied between 48.5 and 85% (Rapp & Romane 1968; Cape *et al.* 1991; Barbier *et al.* 2009; Zhou *et al.* 2013; Fan *et al.* 2014; Sun *et al.* 2014; Aydın *et al.* 2018; Jeong *et al.* 2019; Magliano *et al.* 2019; Dong *et al.* 2020; Yan *et al.* 2022).

Because the intra-annual variation was considerable, it must be pointed out here that the low throughfall, between June and August in the studied cedar forest, can negatively affect the germination of the Atlas cedar. Furthermore, Bentouati and Oujehih (1999) mentioned that the growth of Atlas cedar forests in the Aurès is conditioned by the substrate and the rainfall. They indicated that the total production of cedar forests in the Aurès is between 31 and 1007 m³/ha depending on rainfall, density and age of the forest trees. In our case, it seems that cedar forests that rest on deep soils will benefit more from throughfall compared to stands that grow on soils not deep.

4.3 Stemflow

Studies on stemflow are not very abundant, particularly for conifers. Among these rare studies, some revealed a stemflow rate that fluctuates between 0.6 and 1.74% (Llorens *et al.* 1997; Llorens & Domingo 2007; Xiao *et al.* 2007; Ma *et al.* 2019; Dong *et al.* 2020). The stemflow rate found in the present study (3.86%) is relatively high compared to the results of the aforementioned researchers. The difference can be attributed to daily rainfall patterns and stand characteristics. Therefore, Fan *et al.* (2014) claimed that stemflow rate is closely related to daily rainfall amounts. Besides, the rate found by the present study can be very beneficial for cedar forests. Stemflow represents a minor proportion compared to throughfall, but it can concentrate 17.9 to 56.6 times the amount of precipitation in the soil profile adjacent to the root zone (Zhao *et al.* 2023).

Furthermore, other studies indicated that the stemflow represents only a very small proportion of rainfall and its rate ranges between 0.8 and 9.1% depending on precipitation, density, diameter and height of trees (Barbier *et al.* 2009; Saito *et al.* 2013; Pérez-Suárez *et al.* 2014; Aydın *et al.* 2018; Dong *et al.* 2020; Yang *et al.* 2022).

4.4 Interception

The interception rate of the present study (30.72%) is relatively low compared to the results of Benhizia *et al.* (2020) who found an average interception rate of 42.5% in an Aleppo pine forest, although Keim *et al.* (2006) found for *Pinus spp* an interception rate of 28.5%. Nevertheless, the average rainfall found in the present study (386.8 mm) is higher than that found by Benhizia *et al.* (2020) (311.95 mm). In addition, the cumulative rainfall between 30 and 60 mm in the present study, is greater than that in the study of Benhizia *et al.* (2020). Consequently, the low interception found in the present study can be attributed to rainfall concentrated on four days among 118 rainy events.

The other factor that probably reduced the interception rate in the present study, is the reduced number of dead branches and cones on the cedar trees compared to the pine trees where they were abundant. Indeed, some researchers have already reported that cones and dead branches can significantly modify the redistribution of rainfall by the action of conifers due to the additional water gain of rain by the latter (Shinohara et al. 2010; Jeong et al. 2019).

Besides, the time between two successive rainfalls can also influence the interception rate. Rodrigo and Avila (2001) have set the canopy drying time at 4 hours, whereas Cape *et al.* (1991) estimate it at 12 hours. Moreover, the rainfall regime of the Mediterranean is probably the first to be responsible for the interception rates (Bellot *et al.* 1999; Llorens *et al.* 2018).

Nevertheless, the interception rate found in our study remains, in general, close to the results recorded in coniferous forests. Thus, previous studies have reported interception rates between 8 and 81% under coniferous species (Llorens *et al.* 1997; Xiao *et al.* 2007; Barbier *et al.* 2009; Zhou *et al.* 2013; Fan *et al.* 2014; Aydın *et al.* 2018; Dong *et al.* 2020; Jančo *et al.* 2021; Yang *et al.* 2022).

Regarding the significant interannual variation, Moreno-Pérez *et al.* (2018) stated that the interception rate is higher during dry years.

4.5 Relationships with rainfall

The equations found in the present study, that elicit the relationship between rainfall, throughfall and stemflow are consistent with previous studies. Indeed, several researchers (Magliano *et al.* 2019; Dong *et al.* 2020; Zhao *et al.* 2023) have already reported these positive correlations between rainfall, throughfall and stemflow. They indicated that a major rainfall event tends to favor a higher percentage of throughfall and stemflow.

The volume necessary to trigger the throughfall in the Atlas cedar (1.70 mm), is close to that found by Benhizia *et al.* (2020). The latter found a volume of 1.9 mm, for the Aleppo pine in the Aurès (Eastern Algeria). Similarly, Dong *et al.* (2020) claimed that the rainfall capable of generating throughfalls in the *Pinus tabuliformis* stand is between 1.5 and 1.9 mm depending on the age.

On the other hand, the volume necessary for the initiation of stemflow (4.46 mm) is less compared to that found by Benhizia *et al.* (2020), which found a volume of 6 mm is required to start stemflow in Aleppo pine. Moreover, the volumes capable of triggering throughfall and stemflow in the present investigation are higher compared to those stated by Zhang *et al.* (2023) who claimed that the average rainfall required for the initiation of throughfall and stemflow, in the forest canopies, begins on average at 1.2 and 3.3 mm, respectively. This difference can be attributed to the bark properties of cedar but and to the hydrophobous dust accumulating on the needles and trunks of trees, especially after long drought periods.

Furthermore, the difference in rainfall volumes triggering the stemflow in cedar and pine forests is most likely due to the presence of dead branches on Aleppo pine trunks, especially for the first few meters from the level of the soil. Dead branches attached to the stem trunks will likely hinder the stemflow in Aleppo pine and Cedar forests.

Applying the developed equations suggests that rainfall exceeding 5 mm will contribute to the water supply of Atlas cedar forests.

5 Conclusions

Our study presents the first data on the redistribution of rainfall in an Algerian Atlas cedar forest. The results of the two years of measurements recorded a cumulative rainfall of 773.6 mm distributed over 118 events of rain, including only four events with rainfall above 30 mm. Moreover, the rate of rainfall that crossed the crowns of the Atlas cedar trees by throughfall and stemflow was 65.41% and 3.86% respectively, while the interception rate was 30.72%. Thus, the interception was considerable and varied between 0.32 and 0.33 mm per rainfall day throughout the study period.

The aforementioned data are important and they can help foresters for effective management, in particular to balance the water demand of a forest ecosystem and the demand for water by humans. Thinning and removal of dead branches in dense Atlas cedar forests may be beneficial by increasing the amount of rainfall reaching forest soils and increasing the groundwater recharge with positive effects on water supply to societies and ecosystems. This study of rainfall interception has theoretical and practical importance in providing insight into the roles of certain climatic variables and cedar stand traits in the redistribution of rainfall, which can help determine of the impacts of reforestation with cedar on the local water balance.

As a perspective and to bring new knowledge relating to rainfall interception under the action of cedar forests in Aures (eastern Algeria), it is recommended to consider the following rarely considered meteorological variables: rainfall intensity, wind speed and wind direction, vapor pressure deficit and the number of wetting/drying cycles within a given rainfall event.

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