The impact of forests on the evolution of water resources in the mid-altitude Alps from the middle of the 19th century (Chartreuse massif, France)

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1   Coherent management of the water resources of a mountain range requires precise knowledge of the precipitation that actually reaches the ground. An area's forest cover intercepts and retains a certain percentage of the rainfall through its foliage, thereby reducing the amount of water actually reaching the soil and thus available to reach the river system and karstic aquifers (Llorens and Gallart, 2000). The amount of water available for runoff (Boulangeat, 1978; Bultot *et al.*, 1990) and groundwater reserves is therefore less than that calculated simply on the basis of meteorological records (Aussenac, 1975, 1981; Saugier *et al.*, 1; Carlyle-Moses, 2004; Pieffer *et al.*, 2005). This study attempts to determine the water losses related to interception by the forest cover at the scale of a mountain massif, that of the Chartreuse in the French Pre-Alps, an area that receives substantial precipitation (about 2000 mm on average).

2   More specifically, the present study, which follows on from earlier work on forest interception of rainfall in the Chartreuse massif (Dumas, 2008), seeks to determine the influence of the extension of the forest cover since the middle of the 19th century on the amount of water actually reaching the ground. The average rates of interception by forest cover determined in the 2008 study (Dumas, 2008) are used to evaluate the respective influence on the massif's water resources of changes in both the forest cover and precipitation levels since the middle of the 19th century.

Influence of forest cover on the amount of water reaching the ground

3   The Chartreuse massif is characterised by altitudes ranging from 300 m to more than 2000 m, with an average altitude of close to 1060 m, and covers an area of about 400 km² (Fig. 1). It is delimited to the east by the Grésivaudan valley, to the north and south by the transverse valleys of Grenoble and Chambéry, and to the west by the hills of the Lower Dauphiné. Like all of the Pre-Alpine massifs, the Chartreuse has substantial forest cover. Around 65% of its area is under forest, representing some 260 km² (IFN, 2006).

Figure 1. Location of the Chartreuse massif and the study area. The limits used to define the massif are those of the Chartreuse Regional Natural Park.
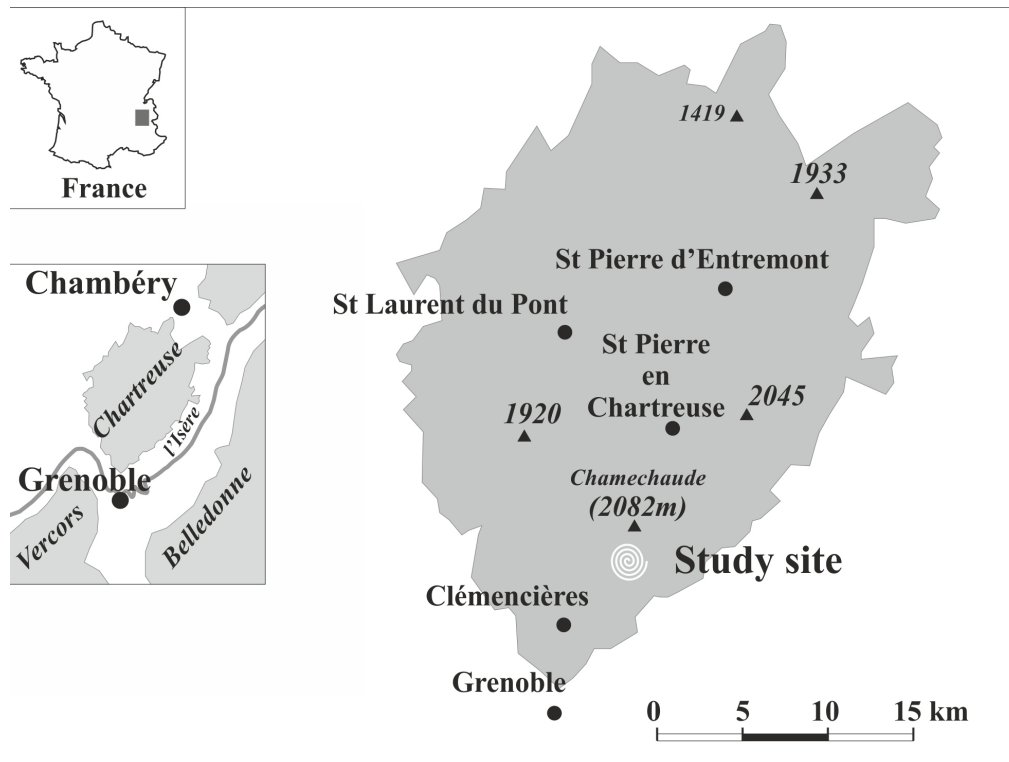
4   There is a clear layering of vegetation characterised mainly by a vast climax stand, a fir-beech forest, while above 1500m the forest cover is dominated by spruce (Tonnel and Ozenda, 1964; Richard and Pautou, 1982). With around 66% of the total tree cover, the fir-beech forest, where spruce and fir gradually become mixed with beech, is the most dominant over the massif as a whole. Lower down, "pure" beech represents almost 10% (Tonnel and Ozenda, 1964; Richard and Patou, 1982; IFN, 2006). At higher altitudes, the spruce stand, composed mainly of *Picea excelsa* and *Abies alba*, represents the massif's second most important forest stand, accounting for about 33% of the tree species in the Chartreuse.

5   The presence of the forest makes it considerably more complicated for precipitation to reach the ground. Foliage intercepts and retains a certain proportion of the water, which is then susceptible to varying rates of evaporation (Bultot *et al.*, 1972; Aussenac, 1975). Evaluation of rainfall interception based on some 50 rainfall gauges installed on a study site in the commune of Le Sappey-en-Chartreuse has already been the subject of a first publication, which provided insights into the respective roles of rainfall in a forest environment (Dumas, 2008). These observations showed that variability in interception rates in areas of forest cover mainly depends on the amount of incident precipitation. The rate of interception is highest for very low rainfall amounts and decreases during episodes of heavier rainfall. When daily rainfall is slight (a shower of less than 5 mm), interception can exceed 50% whatever the type of tree cover in question. This might appear considerable but is in line with those values suggested in the literature (Aussenac, 1981; Petit and Kalombo, 1984; Nizinski and Saugier, 1988; Gash *et al.*, 1995). Interception then decreases fairly rapidly when rainy episodes become more marked (exceeding 15 mm), to reach only 10% in fir-beech forests, and about 20% in spruce stands (Dumas, 2008).

6   Improved knowledge of these relationships has made it possible to assess, for an average year, the amount of precipitation lost through interception and to calculate from this the average interception rate. An assessment of annual interception was the subject of an earlier publication (Dumas, 2008) for the three main tree stands present in the Chartreuse mountains. Estimated annual interception rates in this study were as follows:

- For a fir-beech forest, the average yearly interception rate is 130 mm, or 15.6% of annual incident rainfall,

- For a pure beech forest, an average of 164 mm is intercepted, or 19.7% of annual precipitation,
- And for a spruce forest, interception is more pronounced at 320 mm, or 38.5% of annual precipitation.

7   These results enable us today to evaluate the impact on water resources of the extension of the forest since the middle of the 19th century. First, however, it is important to determine if there have been any changes in the annual precipitation received by the Chartreuse massif during this same period.

Precipitation in the Chartreuse massif and its evolution since 1850

8   In the northern Alps, the Chartreuse massif is an area of heavy precipitation. This is related to its external westerly position in relation to the other Alpine massifs, a position that means that it bears the brunt of humid westerly winds. Since the middle of the 19th century, it has been possible to monitor precipitation levels in the Grenoble region on the basis of several long series of rainfall records.

9   Five meteorological stations, located within or near the Chartreuse massif and possessing precipitation data over a sufficiently long period, were selected with a view to examining in greater detail the precipitation received by the area for a period of more than a century (Tab. 1).

Table 1. Location of rainfall stations used

Station	Longitude	Latitude	Altitude	Observation period
Grenoble	5°47′	45°10′	210 m	1847 - 1953 1970 - 2000
St Genis-Laval	4°47′	45°42′	290 m	1881 - 1972
St Laurent du Pont	5°44′	45°23′	415 m	1907 - 2000
St Pierre d'Entremont	5°52′	45°25′	644 m	1920 - 1991
St Pierre de Chartreuse	5°49′	45°20′	945 m	1921 - 2000

10   The Grenoble station, despite being located just outside the Chartreuse massif, provides data that can be used to assess precipitation levels at the base of the massif. The data was statistically analysed and adjustments made so as to obtain values for the entire period from 1845 to 2000 (Dumas, 2004). The station at Saint-Genis-Laval was used exclusively to reconstitute missing data. This reconstitution, conducted using a yearly time step, was also made easier by the fact that there was a good level of correlation between values. Moreover, for the 1845-2000 period, the reconstituted annual values only slightly modify the averages calculated from the initial series.

11   These four series can thus be used to examine annual fluctuations in rainfall over more than a century in the Chartreuse massif. Naturally, estimating the average annual rainfall at the scale of the mountain range as a whole would require precise knowledge of rainfall distribution over the massif for each year. The spatial distribution of rainfall in areas of relief is governed by laws whose influence is difficult to calculate in detail but which result in considerable variations in the amounts of precipitation received by areas that are in close proximity (steep altitudinal and longitudinal gradients). Furthermore, even at the annual scale, it remains a difficult task to map precipitation in mountainous areas with any precision, since the climatological data measurement network is generally insufficient, if not totally lacking. Trying to monitor rainfall over a long period is also a difficult task, as the number of stations with available data is even more deficient.

12   In the present study, however, our objective remains to determine the evolution of annual rainfall over more than a century and not just to evaluate rainfall amounts. This approach, which seeks to identify modifications and possible trends, necessarily involves comparing annual values over more than a century. It therefore requires having access to values that are homogenous and obtained using the same methodology for the entire study period.

13   Thus mean rainfall values were determined by referring to a gradient calculated on the basis of rainfall observations. The gradient was used to apply an extrapolation of observed rainfall measurements to each year, in an analogous and systematic manner. Numerous regional distributions of annual precipitation are based on a hypothesised linear relationship between

increasing rainfall and increasing altitude. Using a monthly or annual time step, an assessment of rainfall at a given altitude is often based on the local rainfall gradient. Using a gradient means implicitly integrating a linear relationship between rainfall and altitude.

14   The determination of rainfall-altitude gradients in the Chartreuse on the basis of four measurement stations naturally remains somewhat approximate. However, taking into account a greater number of rainfall stations, whose data series would in any case be for a shorter period, would lead to relatively similar results when extrapolating rainfall at altitude, since Saint-Pierre-en-Chartreuse is still the highest established rainfall station in the Chartreuse massif. Consequently, it has a very strong influence on the relationship between rainfall and altitude, and would continue to do so even if additional observations were introduced.

15   Analysis of recorded data for the altitudinal layer between 200 m and almost 1000 m reveals a mean annual rainfall gradient of 131 mm for 100 m of altitude (Fig. 2: linear relationship, P=1.31Z + 867). Although this rate of increase in precipitation is interesting, it must nevertheless be used with caution in summit areas, despite a strong correlation coefficient ($r^2 = 0.92$). Indeed, strict application of this relationship would result in mean annual precipitation figures of close to 3500 mm at 2000 m altitude, values that are highly improbable (Fig. 2).

16   In some years, this amount of water might possibly be observed in certain locations in summit areas, but the average is closer to 2300-2500 mm per year (Dobremez, 2001; Arques, 2005). Annual precipitation maps of the region published by Météo France always show values of about 2000 mm for the summit areas of the massif.

Figure 2. Increase in annual precipitation with altitude, and extrapolation of observations using 3 different models
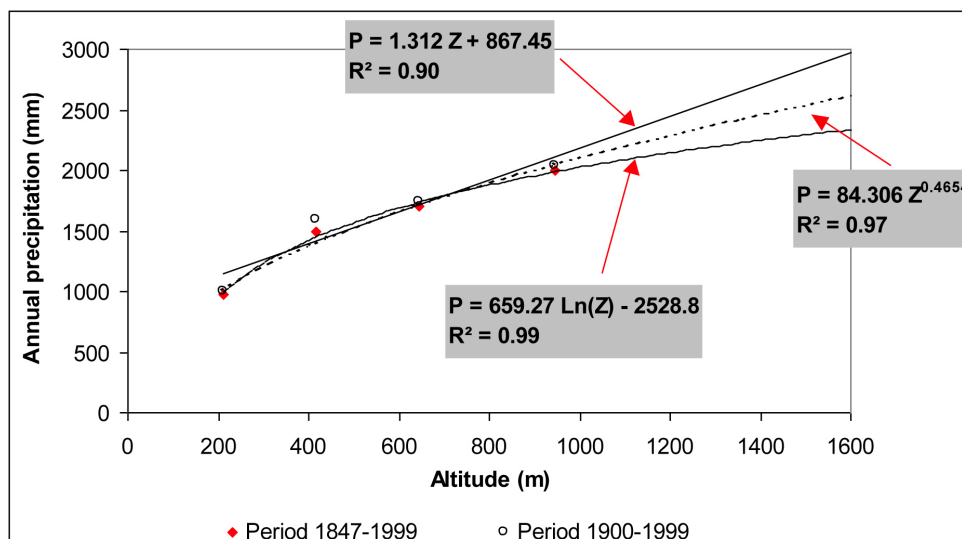
17   In the Chartreuse, the most realistic relationship for evaluating precipitation at a given altitude (Z en m) therefore appears to be the logarithmic relationship, written as follows:

18   P (mm/an) = 546.3 ln (Z) – 1819.7 $r^2 = 0.91$ *Equation 1*

19   Mean annual precipitation values likely to be observed at a given altitude can be estimated from this relationship. The values are naturally approximations but are largely sufficient to provide an estimate of the influence of the forest on incident precipitation. In order to obtain precipitation values that are representative of the massif, the four rainfall series analysed earlier are used to estimate precipitation for the median altitude of the massif, i.e. 1065 m. For the remainder of the estimates, this precision of altitude is of course somewhat illusory, but it nevertheless has the advantage of clearly indicating the basis of this value, and of avoiding any confusion with a value that might be thought completely arbitrary.

20   Consequently, equation 1 can be used to correct the rainfall figures recorded at the four stations by adjusting all the annual observations to an altitude of 1065 m (Fig. 3). For each year, readings from the stations of Grenoble, Saint-Laurent-du-Pont, Saint-Pierre-d'Entremont and Saint-Pierre-en-Chartreuse are corrected by taking into account the rainfall difference between

the annual precipitation and the rainfall for this same year calculated at 1065 m. To define the annual mean rainfall at the scale of the massif, the mean value is then calculated from the corrected readings of the four stations. By integrating the four readings in this way, a new rainfall estimate is thus established which is representative of the average precipitation received by the Chartreuse massif as a whole (Fig. 4).

Figure 3. Rainfall measured at different stations in year$_i$ and correction to average altitude of massif (values are in mm)
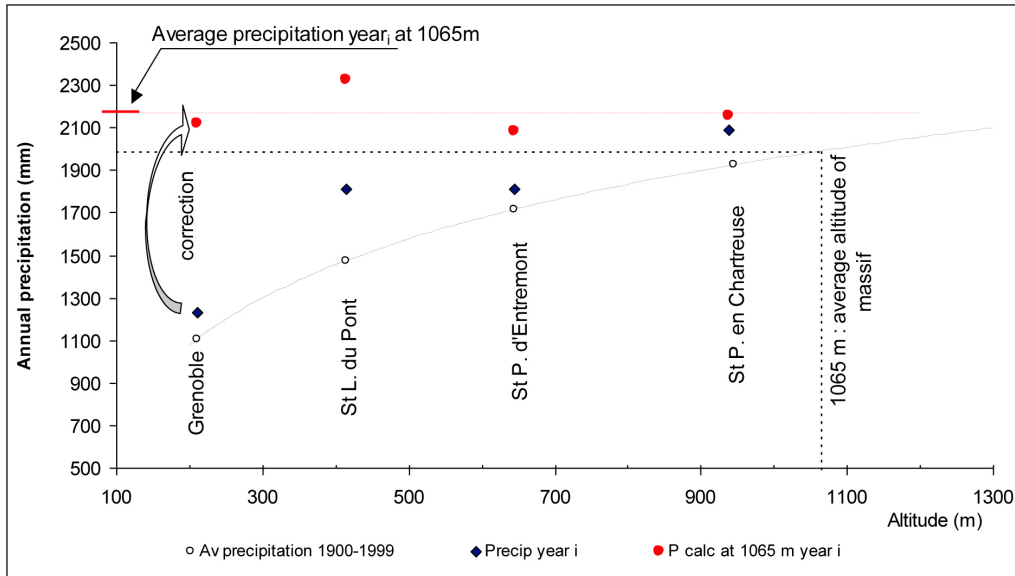
Figure 4. Evolution of mean annual rainfall of massif (at 1065 m altitude) calculated from four stations selected for this study (7-day curve of moving means)
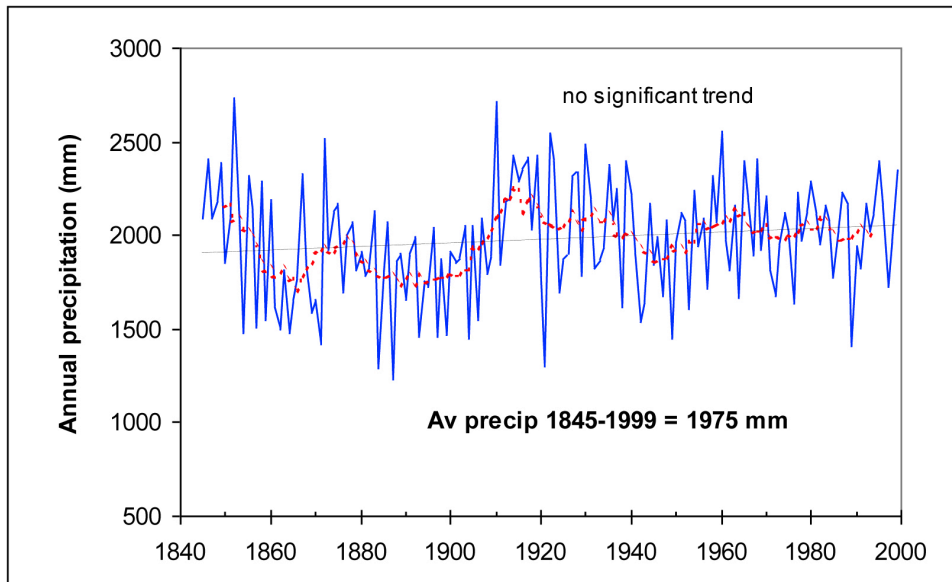
21   Rainfall figures recorded at the Grenoble, St-Laurent-du-Pont, St-Pierre-d'Entremont and St-Pierre-en-Chartreuse stations do not show any significant trend in rainfall since the middle of the 19th century, or even during the 20th century. Nevertheless, some wetter and some drier periods can be observed:

Three relatively wet periods: 1840-1850, 1910-1940 and, to a lesser extent, 1960-1980,

Three drier periods: 1860-1870, 1890-1910 and 1940-1955.

22   Several rainfall phases appear, but the amounts of rainfall received by the Chartreuse massif as a whole, reconstituted from these four stations, do not reveal any significant rising or falling

trends since the middle of the 19th century. Climate changes observed at the scale of the planet therefore do not seem to influence rainfall in the Chartreuse massif. Climate changes observed in the Alps mainly concern temperatures, and there is hardly any impact on total annual rainfall (Durand *et al*., 2009). From a statistical point of view, precipitation received by the Chartreuse massif over the past century may therefore be defined as stable, without any significant trends.

23   Despite this observation, the following question may still be asked: Has the water available for runoff decreased over this period and, if it has, in what proportions? To answer this question, we must now try to determine whether the forest cover in the Chartreuse massif has changed since the middle of the 19th century.

Evolution of forest cover

24   Since the Industrial Revolution, advances made in the high-yield agriculture of lowland areas and the socio-economic changes affecting mountain areas have resulted in a large part of the farmland in highland areas being abandoned. In France, the forest has spread at a rate of 20 to 30,000 hectares per year, at the expense of heathland and meadows (Périgord, 1996). This general trend has been observed in all France's mountain areas, and the Chartreuse is no exception. Photographs 1 and 2 are illustrative of this change. The first photograph, taken at the end of the 19th century, shows a landscape with little forest, while the second photograph reveals an area with about one fifth forest cover.

Photo 1. View of Chamechaude, the highest summit of the Chartreuse, from the commune of Le Sappey-en-Chartreuse, around 1880-1890 (source ASFAMM)

Photo 2. Similar view in 2003 (photo by R. Binard)

25   The predominance of conifers (firs and spruce) on the massif can be explained by the earlier exploitation of the forest for charcoal. For this activity, deciduous trees were more sought after than conifers. Regular cutting of deciduous trees made way for the gradual development of conifers. Then, in the 20th century, the foresters implemented a reforestation policy in favour of conifers: their re-growth is more rapid, and there was less need for charcoal.

26   By using photographs, cadastral documents (1820 et 1994) and vegetation maps (1956 and 1993), it is possible to retrace the major trends in the evolution of the massif's forest cover. In order to determine this evolution during the 20th century, it was decided to examine more closely the area around Le Sappey-en-Chartreuse, between the massifs of Chamechaude, St Eynard and Ecoutoux, an area covering more than 3000 hectares. Above this area can be found the successive vegetation levels of the Collinean, Montagnard and Subalpin of the Chartreuse massif (Dumas, 2008). The study provides valuable insights into forest dynamics.

27   In this area, the vegetation maps of 1956 and 1993 clearly show the gradual evolution of the forest landscape. In 1956, the forest represented more than 70% of the study area, but only 37 years later, the trend towards closure of the landscape was already visible. Between these two dates, the forest gained ground, increasing its cover by about 4%. The cadastral documents and aerial photographs complete and confirm this evolution. They reveal the vegetation spreading down the slopes and the appearance of clumps of trees in the flatter areas. Hedges also developed considerably during the 20th century.

28   The major stages in the spread of the forest cover can thus be retraced (Tab. 2). Of course, the values calculated provide only an indication, revealing no more than the general trend in the development of the massif's forest cover. In addition, it is obvious that the evolution of the landscape over almost two centuries has not been totally homogenous over the massif. It would be expedient to follow this up by examining the evolution of the tree cover in more detail over the massif as a whole and not only in the control area.

Table 2. Estimated percentage of the main forest stands in the study area, and extrapolation of their areal extent to the scale of the massif (according to Binard, 2003)

	1820	1900	1950	2000
Estimation in study zone				
Forest cover	59%	67%	69%	70%
Fir-beech	46%	49%	54%	58%
Beech	44%	24%	13%	8%
Conifers	10%	27%	33%	34%
Extrapolation to scale of massif (in km²)				
Forest cover over massif	235	269	278	280
Fir-beech	108	133	150	162
Beech	103	64	36	22
Conifers	24	72	92	95

29   Based on these first results, and by interpolation between the dates for which information exists, it is possible to retrace the evolution of tree cover for each year, and then to compare this with precipitation levels. The distribution of the forest stands according to altitude is based on several contemporary cartographic and documentary sources (Tonnel and Ozenda, 1964; Richard and Patou, 1982; Pache, 2000; Girard, 2003; Binard, 2003; IFN, 2006) and determined with the help of a numerical terrain model. For the year 2000, the values were then refined and adjusted to the areas recently proposed by the IFN (2006) for the different tree stands covering the Chartreuse massif.

Changes in amounts of water reaching the ground since the middle of the 19th century

30   The methods developed to evaluate the role of interception and define the average values of rainfall components at the scale of the Chartreuse massif have been described in an earlier publication (Dumas, 2008). Estimates were made for an average year, calculated on the basis of rainfall values observed for the period 1900-1999, and for an average distribution of the forest cover for this same period (Tab. 3). In order to better identify and define the evolution of water resources over several decades, the rates of interception for the three forest stands are now examined for each year since 1845.

31   Thus, for each altitude layer of the massif for which the surface area is known (SZ), the annual precipitation reaching the ground (Ps) can be calculated, taking into account the respective surface areas (Sfai) of the different tree stands (fai) and their rates of interception (Infai). The average rainfall reaching the ground (Tab. 3) is thus calculated for each altitude layer by weighting to take account of surface areas, using the following formula:

$$P_{sol} = \left(\frac{S_{non\,arboree}}{S_{Zalt}}\right) P_{meteo} + \sum_{i=1}^{3} \left[\left(\frac{S_{fa_i}}{S_{Zalt}}\right)(P_{meteo} - Int_{fa_i})\right]$$

32   For the Chartreuse massif as a whole, the average precipitation, calculated for the 1900-1999 period, is 1951 mm per year. The amount of water reaching the ground is somewhat less, estimated at 1634 mm per year (Tab. 3). Over an average year, the average amount of water lost through forest interception is close to 300 mm. This interception value, however, remains relatively modest in relation to the total amounts of precipitation received, which are considerable at the scale of the massif.

Table 3. Surface areas, current land use, annual rainfall interception values and average annual precipitation (1900-1999) per altitudinal layer. Precipitation values Pi are calculated from equation 1

Altitude layer	Surface (km²)	Precipitation calc (mm)	Fir-beech superficie (km²)	Fir-beech interception 14.4% (mm)	Beech superficie (km²)	Beech interception 18.3% (mm)	Spruce superficie (km²)	Spruce interception 37.2% (mm)	Precipitation reaching ground (mm)
[200 -400]	11,5	1296							1296
[400 - 600]	37,2	1575							1575
[600 - 800]	49,1	1759	6	253	10	322			1663
[800 - 1000]	63,4	1896	38	273	7	347			1694
[1000 - 1200]	94,2	2006	73	289					1782
[1200 - 1400]	72,8	2097	37	302			26	780	1665
[1400 - 1600]	42,7	2176					39	809	1436
[1600 - 1800]	23,6	2244					22	835	1466
[1800 - 2000]	4,3	2305							2305
[2000 - 2100]	1,2	2346							2346
Total	400		154		17		87		
Average weighted in function of surface area		**1951**		287		332		807	**1652**

33 The value of 300 mm also conceals an interception rate that varies considerably depending on the forest stands concerned. The fir-beech forest and the beech forest remove respectively 311 mm and 358 mm of water per year from the hydrological cycle. Despite occupying a smaller area, the spruce stand intercepts and retains a considerably greater proportion of rainfall through its foliage, accounting for 835 mm of water per year. This characteristic results from both a higher annual interception rate on conifers and more abundant precipitation in the area of the conifer stand, related to its higher altitude. Today, the 300 mm of water removed through forest interception represents about 16% of the mean annual precipitation of the Chartreuse massif as a whole. Has this value always been the same since the middle of the 19th century?

34 With the help of the model established at the yearly scale (Tab. 3), annual precipitation figures for the Chartreuse massif since 1845, estimates of the interception of this precipitation, and knowledge of the general trends in the evolution of the forest cover during this period can now be used to estimate the amount of water actually received on the ground since the middle of the 19th century. By integrating the differential evolution of forest stands and our knowledge of the interception rates of the three main forest formations present in the massif, it is possible to retrace and model, at the annual scale, the precipitation reaching the ground and the interception values. (Fig. 5).

Figure 5. Evolution of precipitation amounts reaching the ground and amounts intercepted since 1845. The values shown are obtained from annual incident precipitation values calculated for the massif as a whole, and from the areal extent of the three forest stands, calculated annually through interpolation between the four dates for which information is available (1820-1900-1950 and 2000).

$$\text{Interception} = 0.6246x + 243.79$$
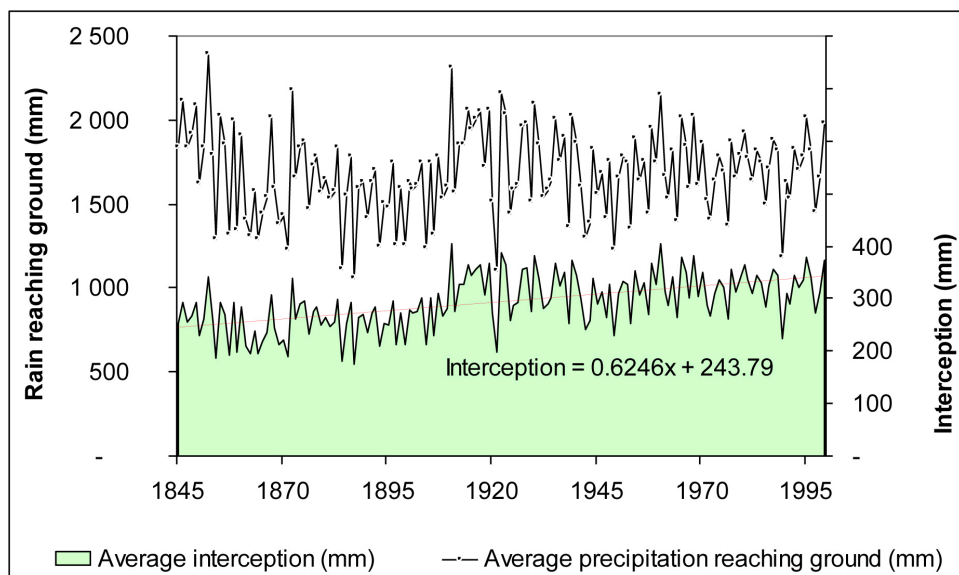
35   Since 1845, with the expansion of the forest cover, a slight rise in interception values has been observed (Fig. 5). The inter-annual variability of this interception, however, remains very pronounced, with fluctuations of the order of 100 mm. Over the study period as a whole, the first decade (of the data series) reveals an average interception value of 260 mm, while the last decade shows a value of almost 330 mm. Insofar as the precipitation values show no significant trends, this increase in the amount of water lost through interception is directly related to the extension of the forest cover.

36   In order to eliminate any possible bias related to a slight increase in the rainfall observed, but which would not be statistically significant, the quantity of water reaching the ground since 1820 has also been simulated on the basis of constant annual precipitation figures, the value of which represents the mean of the rainfall recorded for the period 1845-1999. The earlier results showing an average water loss of around 100 mm are also confirmed (Tab. 4).

Table 4. Precipitation reaching the ground in the Chartreuse massif in 1820 and during the 20th century with incident precipitation assumed to be constant (Pmoy$_{1845-1999}$ = 1975 mm)

		1820	1900	1950	2000
Average rainfall (mm)			1975,0		
Volume of water (million m^3)			790,0		
	In (%)	Volume of water lost by interception (million m^3)			
Fir-beech	14,0%	29,6	36,1	41,2	44,5
Beech	17,6%	35,5	22,0	12,4	7,7
Conifers	38,7%	17,9	54,8	69,7	72,4
Total		83,0	112,9	123,3	124,6
Volume of water reaching ground		707,0	677,1	666,7	665,4
Average rainfall reaching ground (mm)		1767	1693	1667	1664
Interception (mm)		208	282	308	311

37   Table 4, shown for information purposes, also indicates the annual water losses through interception by the forest cover. These losses thus increase from about 80 Mm^3 in 1820 to almost 125 Mm^3 at the end of the 20th century. It is clear that, independently of the inter-annual rainfall variations, it is indeed the closure of the landscape by the forest, observed throughout the 20th century, that results in this decrease in the amount of water reaching the ground (Tab. 4).

Conclusion

38   The forest is a vital element of the Chartreuse massif, from both an economic and ecological point of view. The results of this study provide insights into the influence of the forest on the water cycle. Water losses through interception by the forest cover are estimated at more than 100 Mm^3 per year for the Chartreuse massif, information that constitutes an important input in evaluating the renewal of groundwater resources, for example, or in seeking to optimise the management of these resources. Such information is also important to our understanding of the relationship, sometimes modelled using complex algorithms, between precipitation and surface runoff.

39   The study underlines the fact that forests considerably reduce the water resources of catchment basins. Water intercepted by the forest cover is in large part removed from the water cycle. It would seem that only a very small proportion of this water is absorbed by the vegetation, with most of it being evaporated (Aussenac, 1981). Moreover, recent studies have shown that most of the water intercepted must be considered a loss in the water balance (Morton, 1984; Bultot *et al.*, 1990; Humbert and Najjar, 1992; Carlyle-Moses, 2004; Pieffer *et al.*, 2005; Cosandey, 2006). The interception of precipitation involves complex processes, which even today are not fully understood. Interception results from the interaction of numerous factors: influence of tree species, saturation capacity of foliage, degree of defoliation, runoff along trunks, spatial distribution, type of precipitation, season. The combination of all these factors, and their interrelationship, determines the amount of water finally reaching the ground.

40   Since the Industrial Revolution, advances made in the high-yield agriculture of lowland areas and the socio-economic changes affecting mountain areas have resulted in a large part of the farmland in highland areas being abandoned, giving way to mostly woodland formations.

Based on the interception values estimated in this study, the spread of the forest cover in the Chartreuse since the middle of the 19th century has increased these values by almost 100 mm per year, equivalent to around 40 Mm³ of water for the entire Chartreuse massif. This clearly shows the importance of taking into account the interception of rainfall by the forest in addressing questions relating to hydroclimatology, particularly in mid-altitude mountain areas, which are often heavily wooded. The hydrological balance is modified, resulting in less water being available for runoff or groundwater reserves than the amount traditionally defined on the basis of meteorological readings. However, since the Chartreuse massif receives abundant precipitation, with average values of around 2000 mm per year, the amount of water reaching the ground after interception remains considerable. The impact of increased interception here through the spread of the forest cover since the middle of the 19th century is therefore limited, if not imperceptible.

Bibliographie

ARQUES S., 2005. – *Géodynamique, colonisation végétale et phytodiversité des talus d'éboulis dans le massif de la grande chartreuse (Préalpes françaises du nord). Caractéristiques géo-écologiques et sensibilité aux changements environnementaux.* Thèse, Université Joseph-Fourier, Grenoble.

AUSSENAC G., 1975. – *Couverts forestiers et facteurs du climat : leurs interactions, conséquences écophysiologiques chez quelques résineux.* Thèse Doct. Sci. Nat., Univ. Nancy.

AUSSENAC G., 1981. – « L'interception des précipitations par les peuplements forestiers ». *La Houille Blanche*, 7/8, 531-536.

BINARD R., 2003. – *L'interception des précipitations par la forêt sur le massif de la Grande Chartreuse sur l'ensemble du XXe siècle.* Mémoire de maîtrise, Institut de Géographie Alpine, Univ. Joseph Fourier, Grenoble.

BOULANGEAT C., 1978. – *Influence de la forêt sur le cycle de l'eau : étude comparative de l'interception et de l'évapotranspiration d'un peuplement feuillu (Fagus silvatica) et de quatre peuplements de Douglas (Pseudotsuga).* Mémoire ENITEF, Nancy.

BULTOT F., DUPRIEZ G., BODEUX A., 1972. – « Interception de là pluie par la végétation forestière ; estimation de l'interception journalière à l'aide d'un modèle mathématique ». *J. of Hydrol.*, XVII, 3, pp. 193-223.

BULTOT F., DUPRIEZ G., GELLENS D., 1990. – « Simulation ofland use changes and impacts on the water balance. A case study for Belgium ». *J. of Hydrol.*, 114, pp. 327-348.

CARLYLE-MOSES D.E., 2004. – « Measurement and modelling of growing season canopy water fluxes within a mature mixed deciduous forest stand southern Ontario, Canada ». *Agricultural and Forest Meteorology*, 124, pp. 281-284.

COSANDEY C., 2006 – « Conséquences des forêts sur l'écoulement annuel des cours d'eau ». *Revue forestière française*, LVIII, 4, pp. 317-327.

DOBREMEZ J.-F., 2001. – « La montagne du biologiste ». – *Revue de Géographie Alpine*, n°2, pp. 93-100.

DUMAS D., 2004. – *Rôle des changements climatiques et influence de l'extension de la forêt sur les ressources en eau dans le massif de la Chartreuse, depuis le milieu du XIXe siècle.* Rapport Parc Naturel Régional de Chartreuse, Université Joseph Fourier, Grenoble, Institut de Géographie Alpine.

DUMAS D., 2008. – « Estimation de l'influence de la couverture forestière sur les pluies en montagne : exemple du massif de la Chartreuse ». *Revue Forestière Française*, LX, 6, pp. 711-726.

DURAND Y., LATERNSER M., GIRAUD G., ETCHEVERS P., LESAFFRE B., MÉRINDOL L., 2009. – « Reanalysis of 44 Yr of climate in the French Alps (1958-2002): methodology, model validation, climatology, and trends for air temperature and precipitation ». *J. of Apllied Meteorology and Climatology*, vol. 48, pp. 429-449.

GASH J.H.C., LLOYD C.R., LACHAUD G., 1995. – « Estimating spares forest rainfall interception with an analytical model ». – *J. of Hydrol.*, 170, pp. 79-86.

GIRARD R., 2003. – *L'interception des précipitations par une couverture forestière : exemple de la Chartreuse.* Mémoire de DEA, Institut de Géographie Alpine, Univ. Joseph Fourier, Grenoble.

HUMBERT J., NAJJAR G., 1992. – *Influence de la forêt sur le cycle de l'eau en domaine tempéré. Une analyse de la littérature francophone.* Rapport, Univ. Louis-Pasteur, Strasbourg.

Inventaire Forestier National (IFN), 2006 – *Département de l'Isère ; résultats du troisième inventaire forestier.* 1997. Rapport, Min. de l'Agriculture et de la Pêche, Paris.

LLORENS P., GALLART F., 2000. – « A simplified method for forest water storage capacity measurement ». *J. of Hydrology*, 240, pp. 131-144.

MORTON F.I., 1984. – « What are the limits of forest evaporation ? ». *J. of Hydrol.*, 74, pp. 373-398.

NIZINSKI J., SAUGIER B., 1988. – « Mesures et modélisation de l'interception nette dans une futaie de chênes ». *Acta Oecologica, Oecol. Plant.*, 9 (3), pp. 311-329.

PACHE G., 2000 – *Guide simplifié de typologie de stations forestières. Massif de la Chartreuse et chaînons calcaires du pays « entre Jura-Savoie ».* Laboratoire des Ecosystèmes Alpins, Univ. Joseph Fourier, Grenoble.

PERIGORD M., 1996. – *Le paysage en France*. Presses Univ. de France, coll. Que sais-je ? Paris.

PETIT F., KALOMBO K., 1984. – « L'interception des pluies par différents types de couverts forestiers ». *Bull. Soc. Géogr. Liège*, 20, pp. 99-127.

PIEFFER M., LE GOFF N., NYS C., OTTORINI J.-M., GRANIER A., 2005. – « Bilan d'eau, de carbone et croissances comparées de deux hêtraies de plaine ». *Revue forestière française*, LVII, 2, pp. 201-215.

RICHARD L., PAUTOU G., 1982. – *Carte de la végétation de la France au 200 000ᵉ. Alpes du Nord et Jura méridional.* Notice détaillée des feuilles 48-Annecy, 54-Grenoble. Ed. CNRS.

SAUGIER B., HALLDIN S., PONTAILLER J.Y., NIZINSKI G., 1985. – « Bilan hydrique des forêts de chêne et de hêtre à Fontainebleau. Mesures et modélisation ». *Revue Palais Découverte*, Paris, 13, (130), 187-200.

TONNEL A., OZENDA P., 1964. – *Documents pour la carte de la végétation des Alpes.* Laboratoire de Biologie Végétale de Grenoble et du Lautaret, Univ. de Grenoble, Faculté des Sciences.

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Abstract

Since the Industrial Revolution, a substantial part of the land in mid-altitude mountain areas has been abandoned to woodland. The forest intercepts and retains a certain percentage of rainfall on its foliage, thereby reducing the amount of water actually reaching the ground. The gradual transformation of the landscape over recent decades has therefore had an impact on the transfer of atmospheric water into a form that can be used as a resource. The present study, conducted at the scale of the Chartreuse massif (Pre-Alps, France), examines annual precipitation, the role of the forest in intercepting this precipitation, and changes in the extent of the forest cover. The impact of the extension of the forest cover from the middle of the 19th century on the amount of water lost through runoff and on groundwater reserves can thus be evaluated. The study shows that since the middle of the 19th century the extension of the forest cover in the

Chartreuse massif has increased water losses through interception by almost 100 mm per year. It also reveals that over this same period water losses have not been compensated for by an increase in precipitation. In short, the hydrological balance has been considerably modified, with the amount of water available for runoff and groundwater reserves being less than that generally calculated simply from meteorological data records.

Keywords : evolution, climate change, forest, precipitation, interception, Chartreuse massif, France

Notes de la rédaction

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